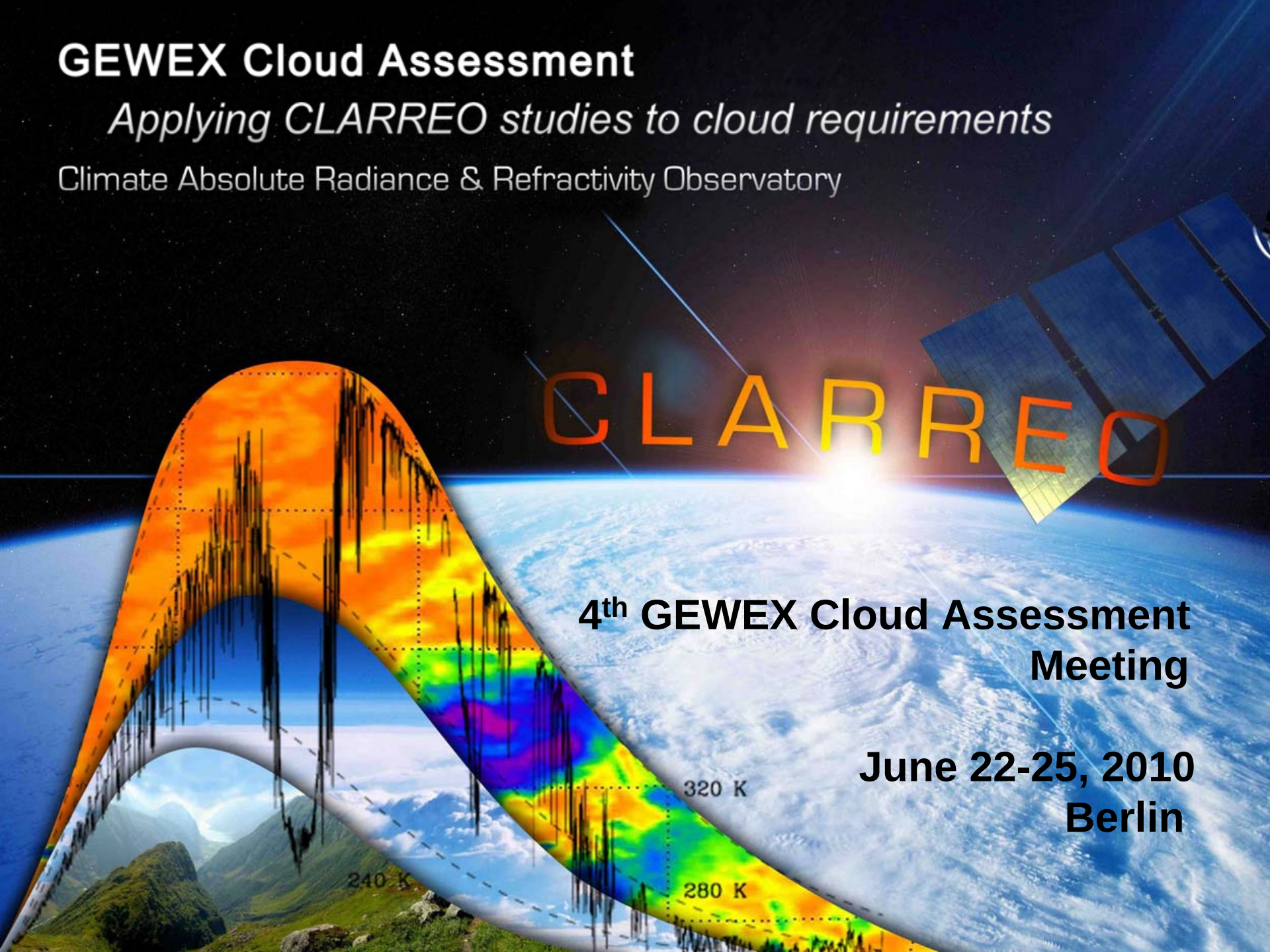
GEWEX Cloud Assessment

Applying CLARREO studies to cloud requirements

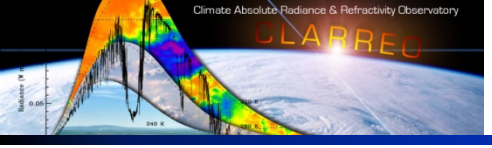
Climate Absolute Radiance & Refractivity Observatory



4th GEWEX Cloud Assessment Meeting

June 22-25, 2010

Berlin



Outline

- Use last 2 years of CLARREO studies to help clarify climate change observation requirements for GEWEX cloud assessment
- A brief summary of what CLARREO is and why its relevant
- CLARREO has clouds and cloud feedback as one of its key science objectives
- CLARREO has both solar and infrared spectra across all of the wavelengths relevant to passive cloud retrievals from current and future imagers and sounders, as well as broadband radiation observations
- CLARREO does NOT replace any of these instruments, but augments them with much higher calibration accuracy
- In defining its mission requirements, the CLARREO team has developed an approach that should be very useful to other climate change groups, including the GEWEX cloud group

- More Information on the CLARREO mission: **clarreo.larc.nasa.gov**

Use CLARREO climate change requirement studies to help GEWEX cloud.

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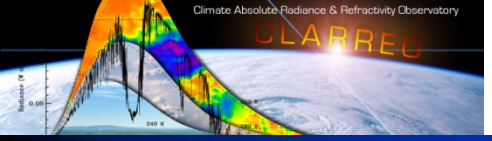
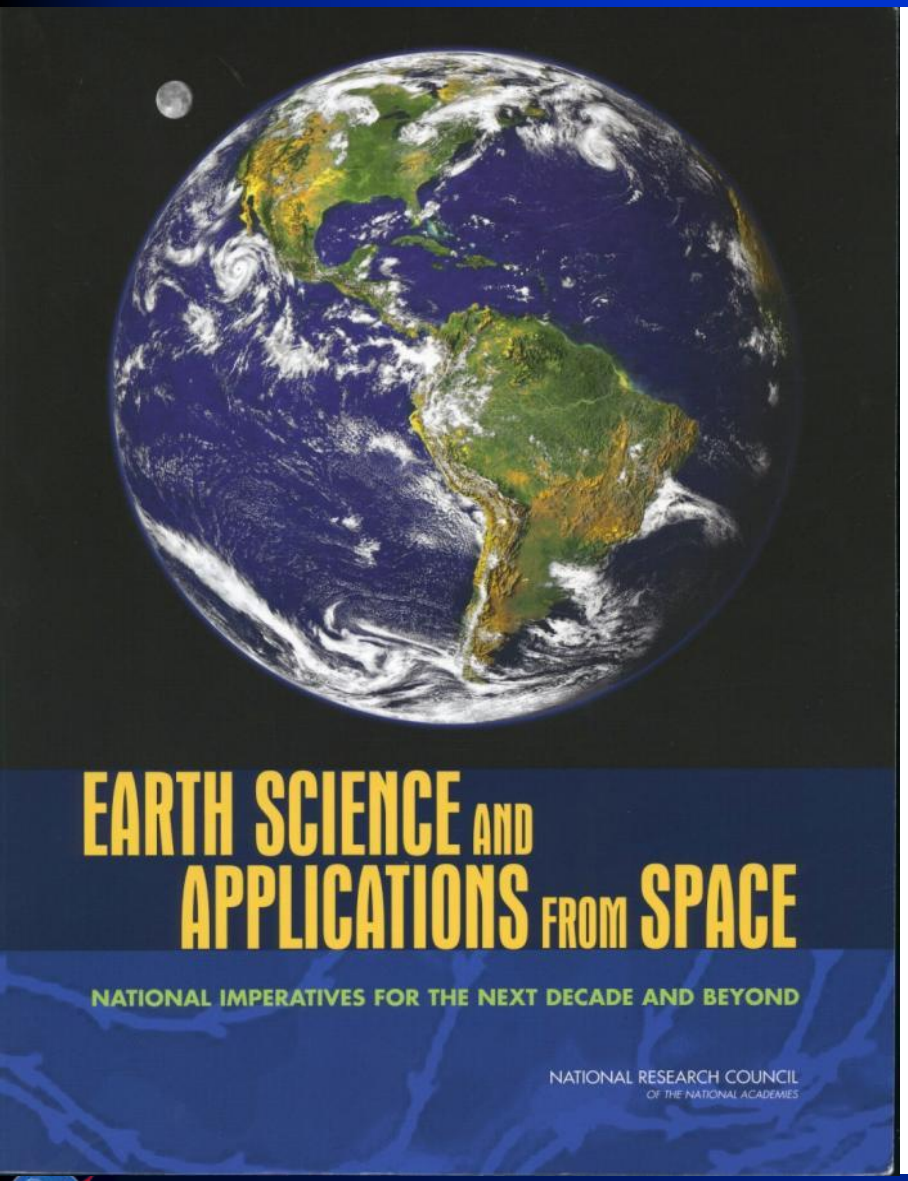


Decadal Survey defines CLARREO



NOAA CLARREO

- CERES (Clouds and Earth's Radiative Energy System)
- TSIS (Total Solar Irradiance Sensor)

NASA CLARREO

- Solar reflected spectra: SI traceable relative uncertainty of 0.3% (*k*=2)
- Infrared emitted spectra: SI traceable uncertainty of 0.1K (*k*=3)
- Global Navigational Satellite System Radio Occultation: SI traceable uncertainty of 0.1K (*k*=3).

CLARREO is a Cornerstone of the Climate Observing System

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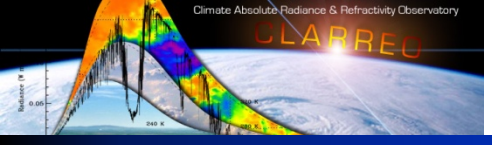
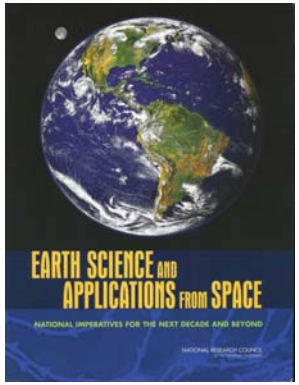


Decadal Survey defines NASA CLARREO



Societal Benefits

Enable knowledgeable policy decisions based on internationally acknowledged climate measurements and models through:

- Observation of high accuracy long-term climate change trends

- Use the long term climate change observations to test and improve climate forecasts.

Science Objectives

Make highly accurate and SI-traceable decadal change observations sensitive to the most critical but least understood climate radiative forcings, responses, and feedbacks

- Infrared spectra to infer temperature and water vapor feedbacks, cloud feedbacks, and decadal change of temperature profiles, water vapor profiles, clouds, and greenhouse gas radiative effects

- GNSS-RO to infer decadal change of temperature profiles

- Solar reflected spectra to infer cloud feedbacks, snow/ice albedo feedbacks, and decadal change of clouds, radiative fluxes, aerosols, snow cover, sea ice, land use

- Serve as an in-orbit standard to provide Reference Intercalibration for broadband CERES, and operational sounders (CrIS, IASI), imagers such as VIIRS, AVHRR, geostationary

A Mission with Decadal Change Accuracy Traceable to SI Standards

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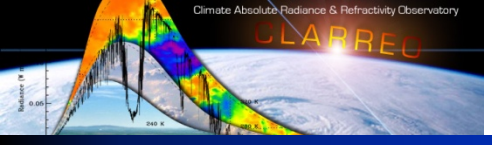

CLARREO Science Requirements: Process and Pre-Phase A Team

- **NRC Decadal Survey: original science community input and mission**
- **Requirements further developed over 30 months of science studies:**
  - 2 open science community workshops (3 days each)
  - 4 science team meetings (2 to 3 days each)
  - Weekly telecons for science review and input
- **Pre-phase A Science Team:**

Organization	Role	Relevant Expertise
NASA Langley	Mission Lead	FIRST/CERES/CALIPSO/SAGE, RS/IR intercalibration
	IR Inst Lead	RS/IR orbit sampling, RS fingerprinting, Radxfer Models
	Climate Obs	IIP for IR instrument.
Harvard Univ.	IR Science/Inst	INTESSA/IR Spectra fingerprinting, dec. change accuracy
	GNSS-RO	RO science, sampling, instruments, SI traceability, IR IIP
Univ. Wisconsin	IR Science/Inst	SHIS/CrIS/AIRS, IR intercalibration, SI traceability, IR IIP
GSFC/GISS	RS Lead/RS Inst	MODIS/VIIRS/APS/SeaWiFS lunar cal, SI traceability
CU-LASP	Solar Cal/RS Inst	SORCE/TSIS, RS SI traceability, IIP for RS instrument
NIST	SI traceability	IR and RS standards, SIRCUS, HIP, LUCI lunar cal
JPL	GNSS-RO/IR	AIRS/GNSS-RO
Univ. Maryland	IR orbit sampling	Diurnal sampling studies
GFDL/Berkeley	Climate Models	CLARREO climate OSSEs: Obs System Simulation Exp
UK	IR/Low Cal Interactions	TRUTHS RS SI traceability/GERB/IR interferometers

A diverse expertise science team to set requirements

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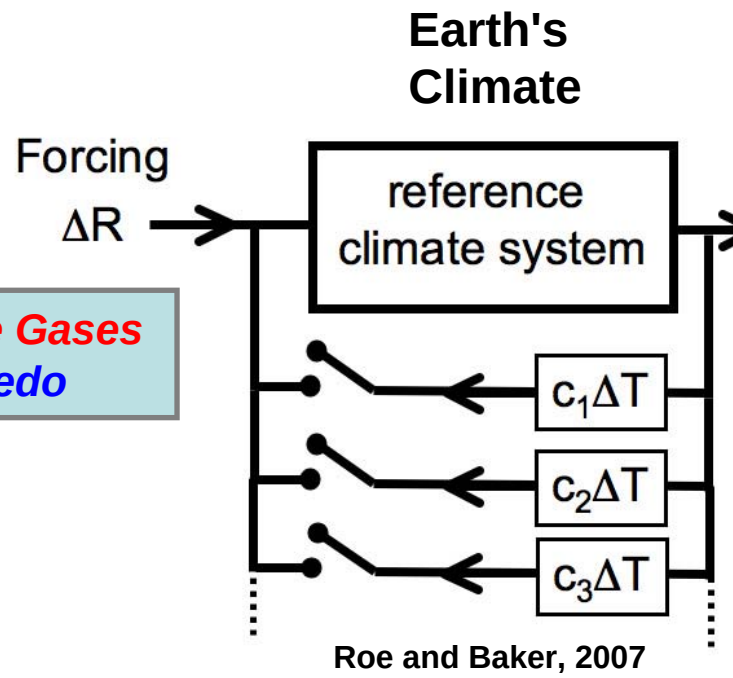
CLARREO Science Value
Climate Forcing, Response, Feedback

Blue = CLARREO Solar Reflected Spectra Science
Red = CLARREO IR spectra & GNSS-RO Science

- *Greenhouse Gases*
- *Surface Albedo*



Roe and Baker, 2007

- *Temperature*
- *Water Vapor*
- *Clouds*
- *Radiation*
- *Snow/Ice Cover*

Cloud Feedback

Water Vapor/Lapse Rate Feedback

Snow/Ice Albedo Feedback

50% of CLARREO Science Value is in Reflected Solar Spectra
50% of CLARREO Science Value is in Infrared Spectra & GNSS-RO

100% of CLARREO Science Value is in the Accuracy of the Data

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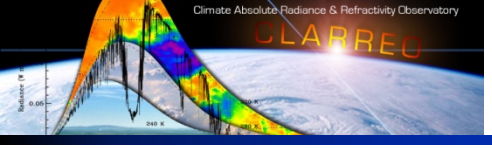
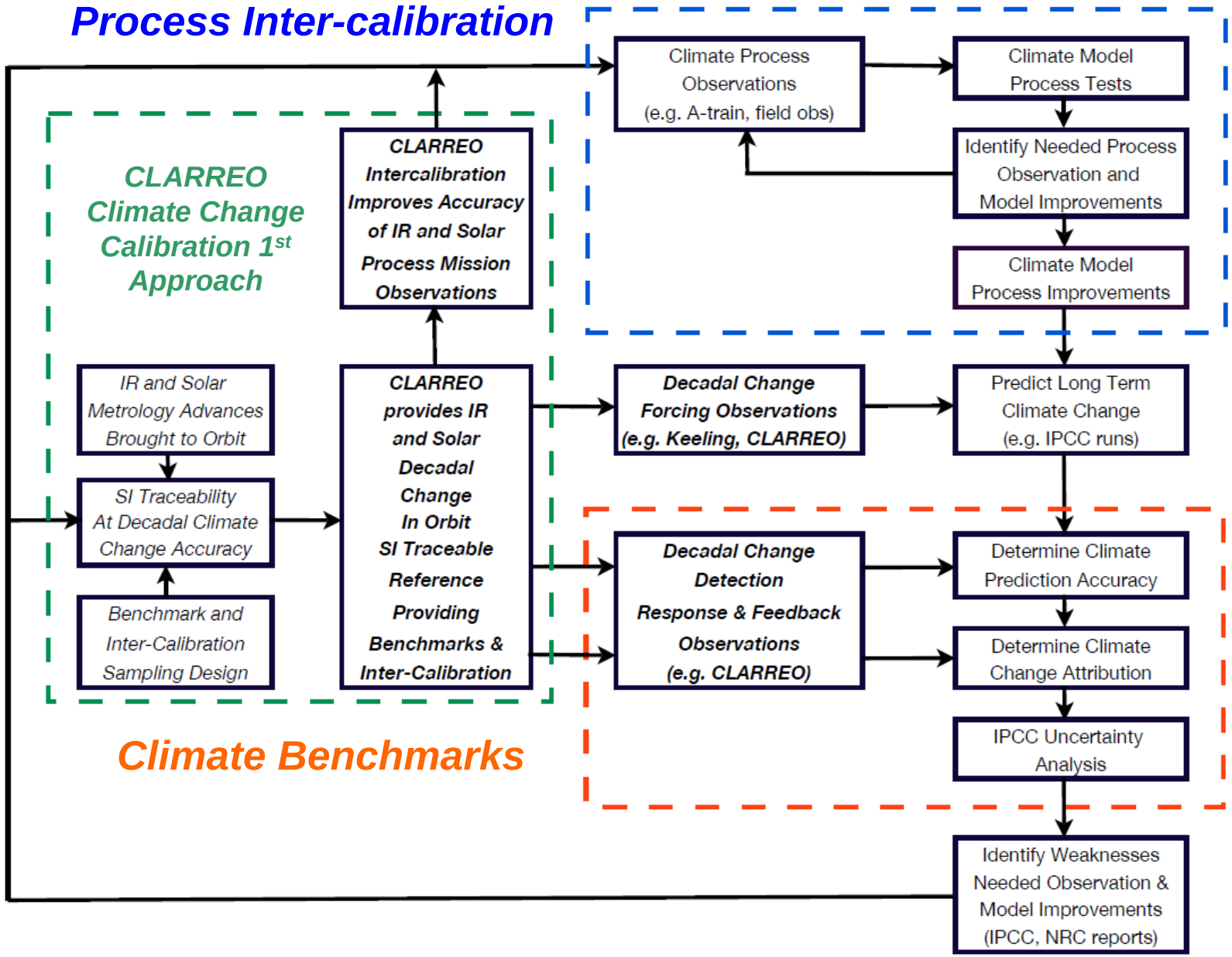
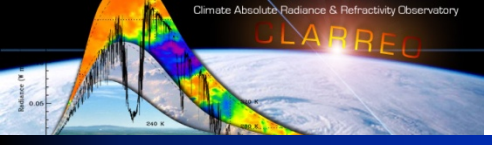
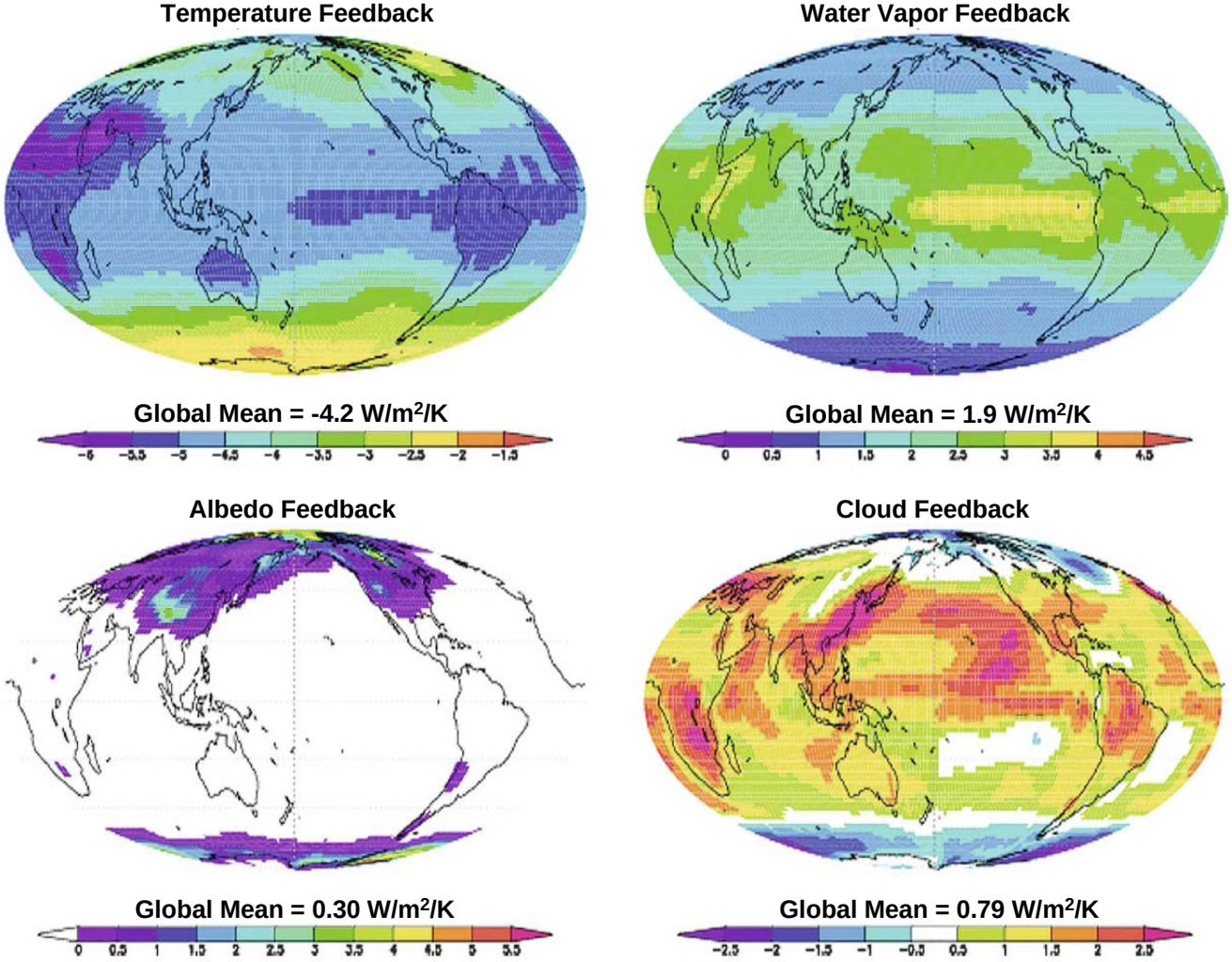


CLARREO and Climate Science





Feedbacks Drive Space/Time Sampling Requirements



Multi-model ensemble-mean maps of the temperature, water vapor, albedo, and cloud feedback, computed using climate response patterns from the IPCC AR4 models and the GFDL radiative kernels

Soden et al. 2008

- Land and ocean zonal annual means required for temperature lapse rate and water vapor feedbacks, surface albedo feedbacks
- 1000 km regional scale required for cloud feedbacks
- Seasonal cycle required for reflected solar: cloud feedback, snow/ice albedo feedback

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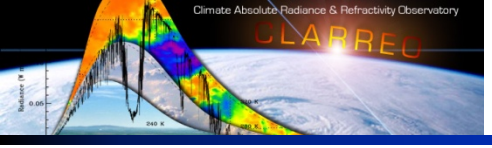

Tracing CLARREO Decadal Change Science Objectives to Mission Requirements

- CLARREO will create benchmark climate data records using two complementary approaches
  - Benchmarks using only CLARREO data
  - Benchmarks using CLARREO for reference calibration of operational sensors
- These two approaches provide a robust test of the CLARREO data records
  - Analogous to using independent measurements and analysis in metrology
- Climate benchmarks require
  - Accuracy for decadal trend detection
  - Unbiased sampling of the climate system
  - Information content sufficient for trend detection and attribution

CLARREO is a Climate Benchmarking Mission

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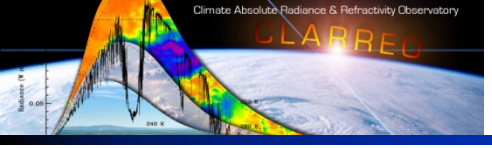

Determining the Accuracy of Decadal Change Trends and Time to Detect Trends

- A perfect climate observing system is limited in trend accuracy only by climate system natural variability (e.g. ENSO) (Leroy et al, 2008).
- Degradation of accuracy of an actual climate observing system relative to a perfect one (fractional error F_a in accuracy) is given by:

$$F_a = (1 + \Sigma f^2_i)^{1/2} - 1 \text{ , where } f^2_i = \sigma^2_i \, \tau_i / \sigma^2_{var} \, \tau_{var}$$

for linear trends where σ is standard deviation, τ is autocorrelation time, σ_{var} is natural variability, and σ_i is one of the CLARREO error sources.

- Degradation of the time to detect climate trends relative to a perfect observing system (fractional error in detection time F_t) is similarly given by:

$$F_t = (1 + \Sigma f^2_i)^{1/3} - 1$$

- *This simple equation leads to a simple rule of thumb for CLARREO error sources: error sources are required to be less than 1/3 natural variability so that in total, CLARREO degrades climate trend accuracy less than 20%.*

CLARREO Error Sources are required to be less than 1/3 natural variability

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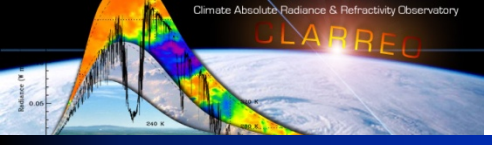

Accuracy of Decadal Change Trends Time to Detect Trends

- The CLARREO requirement is for climate change trend accuracy to be within 20% of a perfect observing system, and time to detect trends to be within 15%. To reach this goal, individual error sources must provide accuracy within 10 to 15% of a perfect observing system (e.g. orbit sampling, calibration).

- The accuracy of CLARREO observations is required *only at large time and space scales such as zonal annual, not at instantaneous field of view. Therefore all errors in the CLARREO error budgets are determined over many 1000s of CLARREO observations: never 1, or even a few.*

- *CLARREO requirements are very different than a typical NASA Earth Science process mission interested in retrievals at instantaneous fields of view at high space/time resolution.*

Degradation of Large Scale Decadal Change Trends by less than 20%

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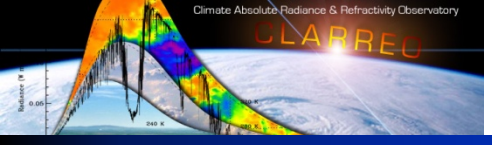
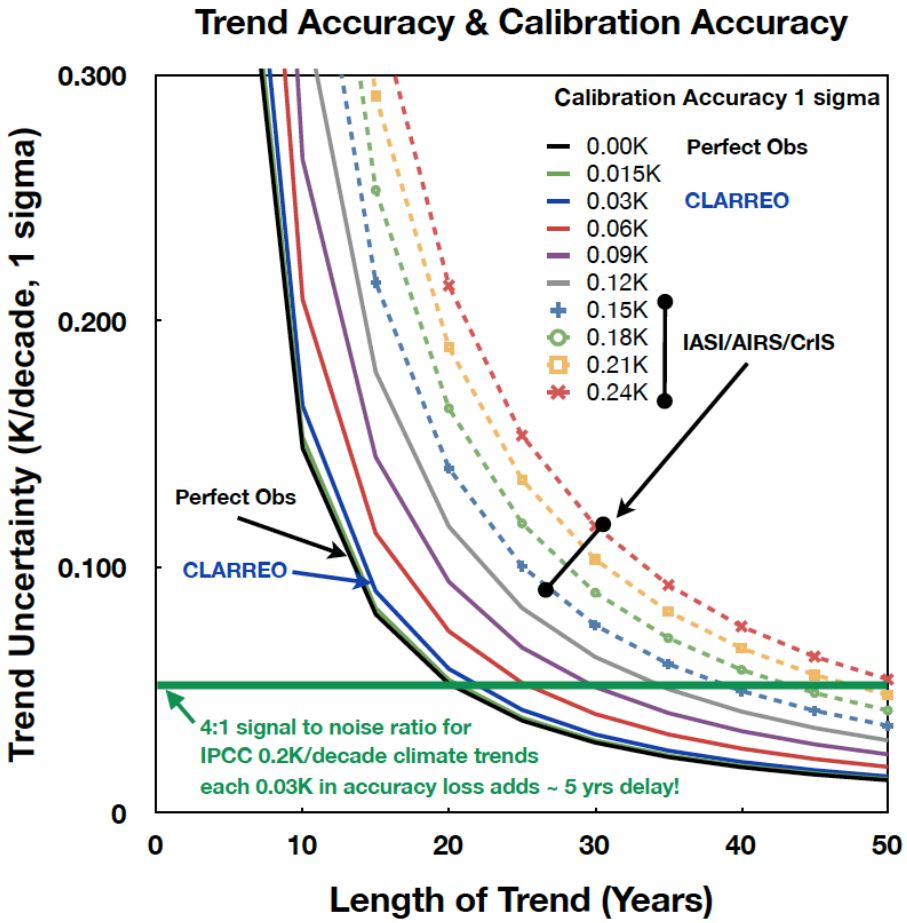


Goal of within 20% accuracy of an ideal climate observing system is critical!



Global average temperature trend results include all major error sources: natural variability, calibration error, orbit sampling (2 satellites), instrument noise. Results for Reflected Solar trends are similar.

- CLARREO 20% trend accuracy goal requires 0.03K (1σ) IR calibration absolute accuracy.
- 0.2K/decade IPCC prediction next 30 years
- 4:1 signal to noise ratio in that trend is needed to make rigorous policy decisions.
- CLARREO reaches this accuracy in 20 years
- Operational instruments require 40 years
- Every 0.03K loss in accuracy delays another 5 years when the information is available
- CLARREO represents the point of diminishing return: at higher accuracies, natural variability dominates and no further accuracy is achieved.
- **Similar result for Reflected Solar trends**.

- *CLARREO accuracy goals are optimal cost/value for climate change trends*
- *High confidence is critical when making global climate policy trillion dollar decisions!*
- *CLARREO is a breakthrough designed to provide that confidence.*

Climate Change Accuracy is Critical to Making Difficult Policy Decisions

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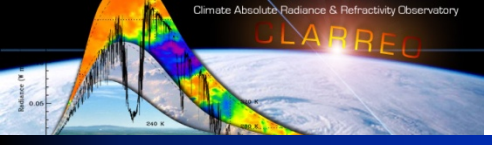
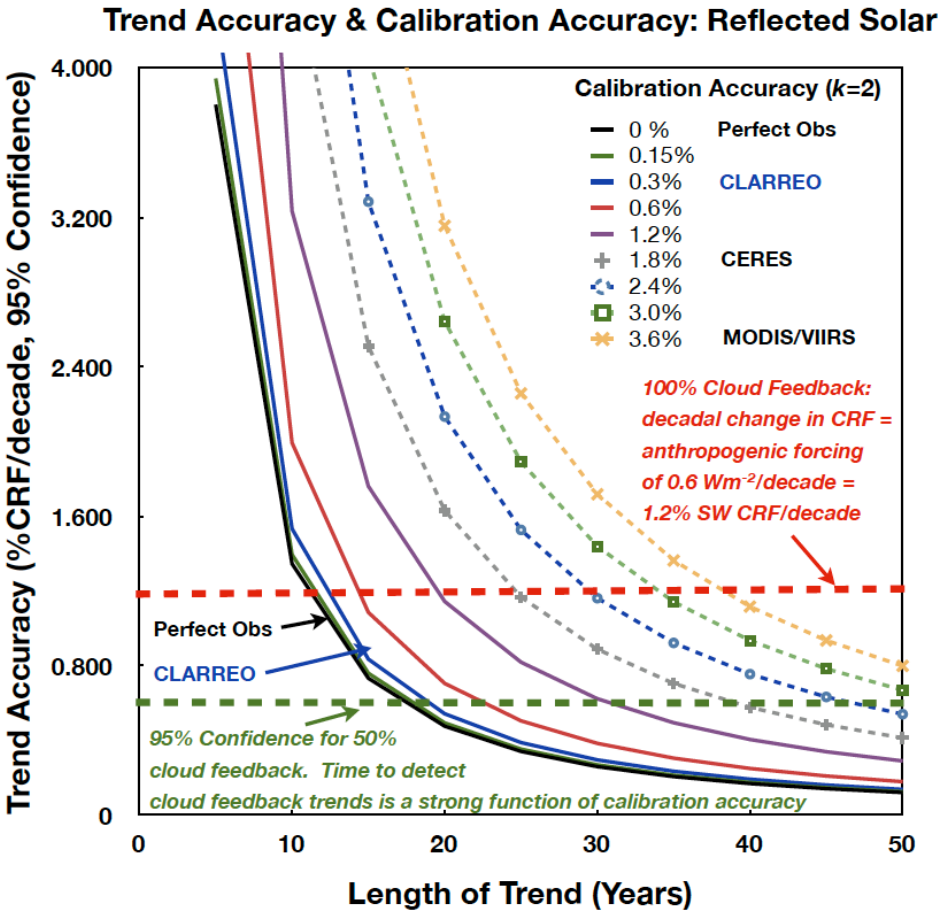


Goal of within 20% accuracy of an ideal climate observing system is critical!



Cloud Feedback trend results include all major error sources: natural variability, calibration error, orbit sampling (1 satellite), instrument noise.

- CLARREO 20% trend accuracy goal requires 0.3% (*k*=2) calibration absolute accuracy.
- 0.6 Wm^{-2} radiative forcing/decade (IPCC) next few decades
- 100% low cloud feedback is a change in SW CRF of 0.6 Wm^{-2} per decade, or 1.2% of SW CRF/decade
- Change from 0.3% (*k*=2) calibration accuracy to 1.2% (*k*=2) accuracy delays trend detection of cloud feedback signals by 10 years!
- CLARREO represents the point of diminishing return: at higher accuracies, natural variability dominates and no further accuracy is achieved.
- Similar result for Infrared temperature trends.

- *CLARREO accuracy goals are optimal cost/value for climate change trends*
- *High confidence is critical when making global climate policy trillion dollar decisions!*
- *CLARREO is a breakthrough designed to provide that confidence.*

Climate Change Accuracy is Critical to Making Difficult Policy Decisions

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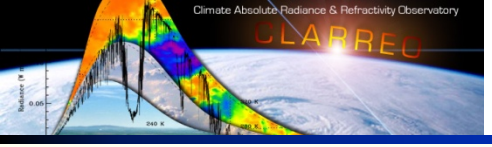
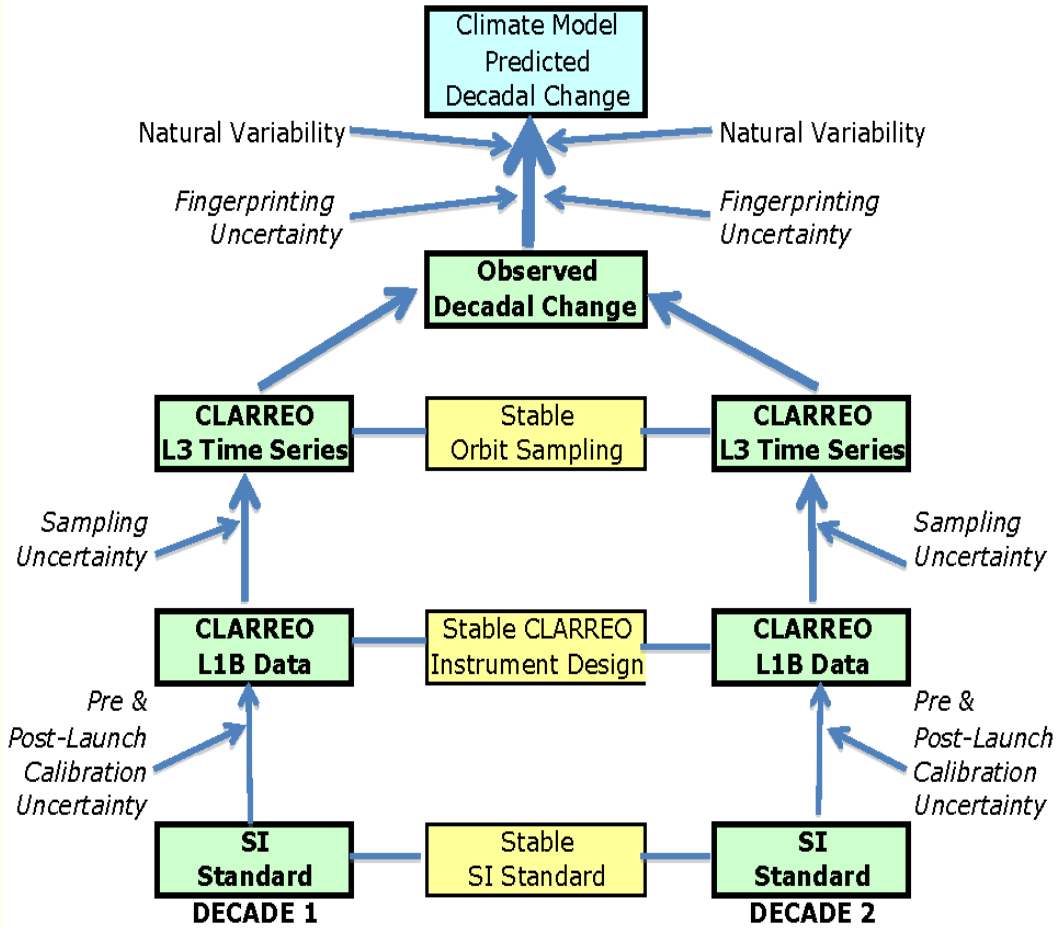


Tracing CLARREO Decadal Change Science Objectives to Mission Requirements

- Climate Model Decadal Prediction
- Tested against CLARREO decadal change observations
- Climate Model determined fingerprinting analysis
- CLARREO record length set to overcome noise from natural variability
- CLARREO sampling set to reduce error to < 1/3 natural variability
- CLARREO calibration accuracy, verification, traceability to SI standards achieve trend accuracy within 20%, time to detect within 15% of ideal system

Example of Observing Decadal Change
Through CLARREO Decadal Change Spectral Benchmark



Traceable uncertainties from decadal change observations to SI standards, *at decadal change accuracy*

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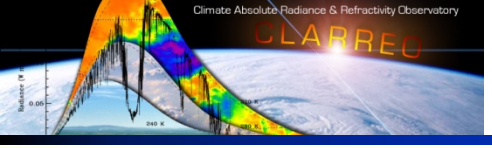
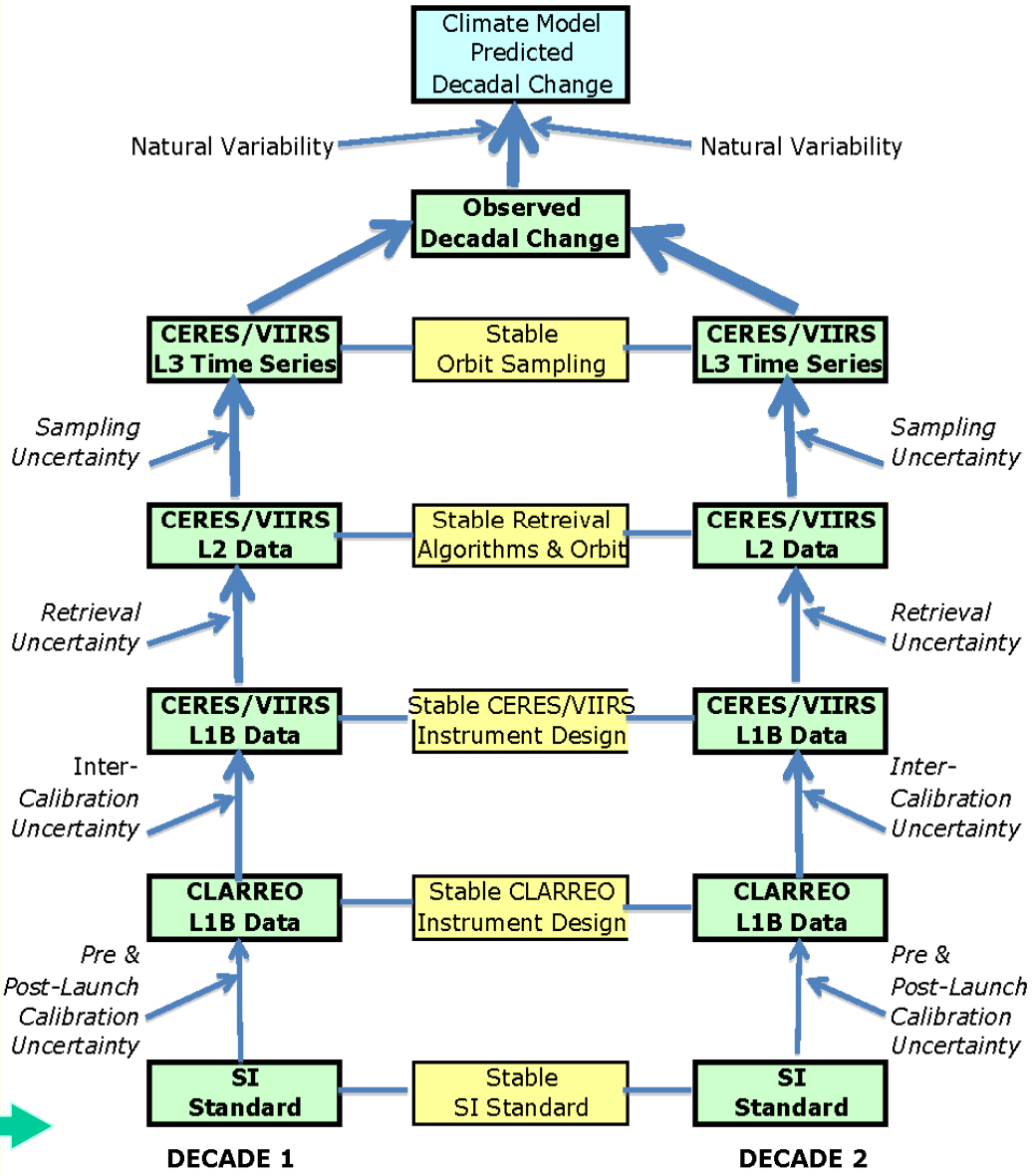


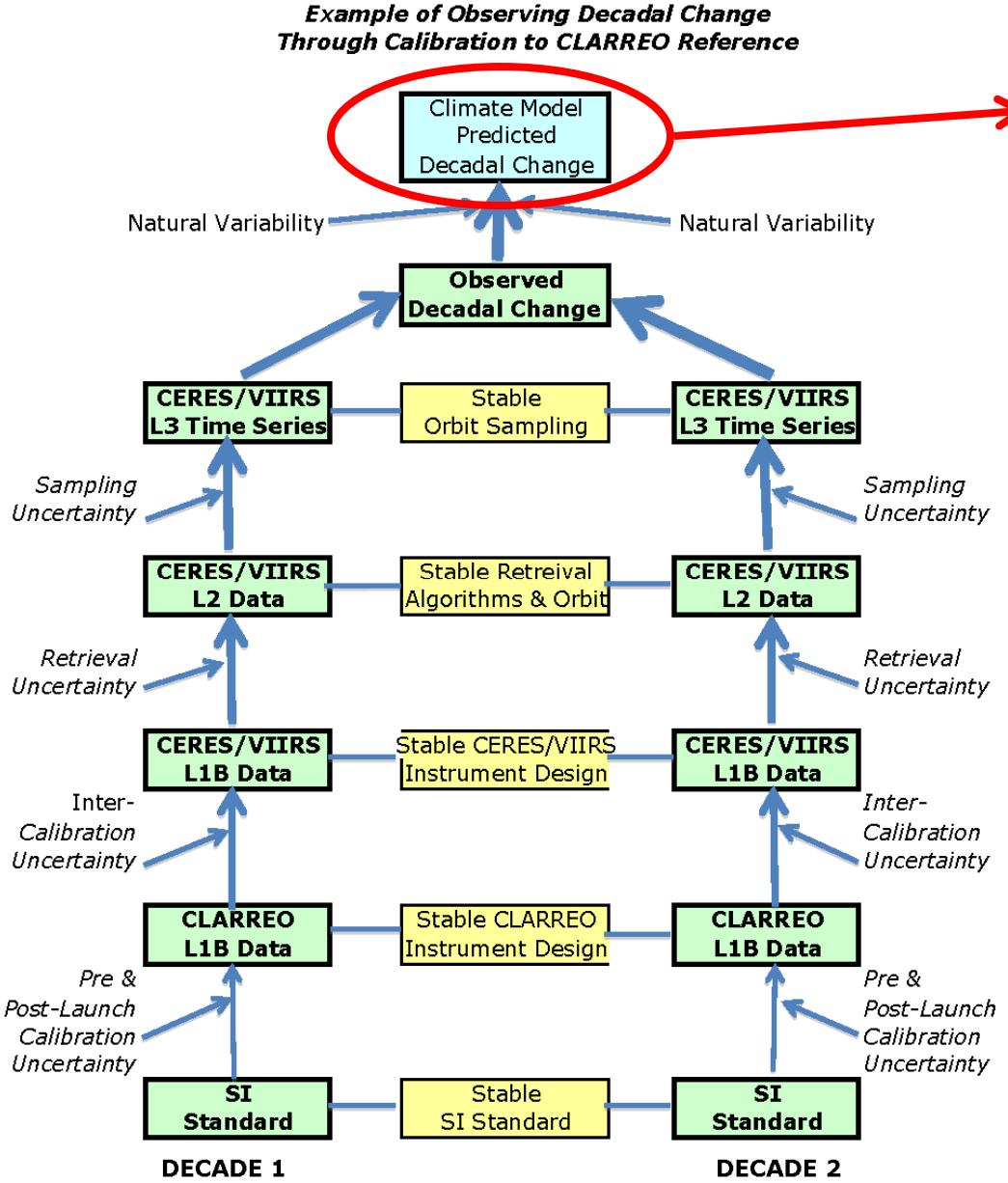
Tracing CLARREO Decadal Change Science Objectives to Mission Requirements

- Climate Model Decadal Prediction
- Tested against CLARREO decadal change observations
- CLARREO record length set to overcome noise from natural variability
- CLARREO sampling set to reduce error to < 1/3 natural variability
- Verify stability of retrieval algorithms for climate variables and for fingerprinting methods
- CLARREO orbits, pointing control set to accomplish reference calibration of operational sensors to 1/3 natural variability
- CLARREO calibration accuracy, verification, traceability to SI standards set to meet decadal change natural variability and signals

Example of Observing Decadal Change Through Calibration to CLARREO Reference



Tracing CLARREO Decadal Change Science Objectives to Mission Requirements



Climate Model Observing System Simulation Experiments (OSSEs):

- Information Content, Spectral Coverage, Spectral Resolution
- Accuracy of Spectral Fingerprinting Methods

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Climate OSSEs- Observing System Simulation Experiments

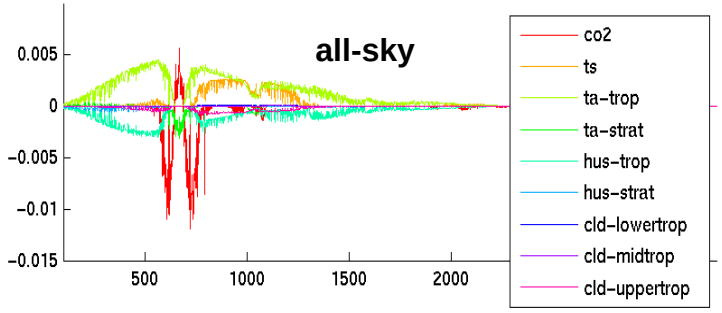
Climate modelers were identified by the Decadal Survey as primary users of CLARREO data

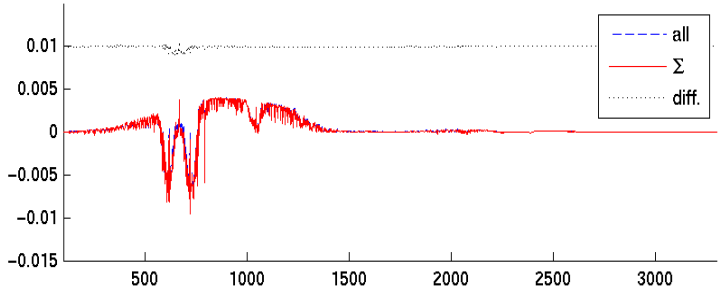
OSSEs were begun with 3 modeling groups (GISS, GFDL, U-Cal Berkeley) to determine measurement requirements

Studies include climate change fingerprinting methods using time/space averaged spectral data to define spectral resolution (IR 1 cm^{-1}, RS 15 cm^{-1})& spectral coverage (IR 200 to 2000 cm^{-1}, RS 300 to 2500 nm).

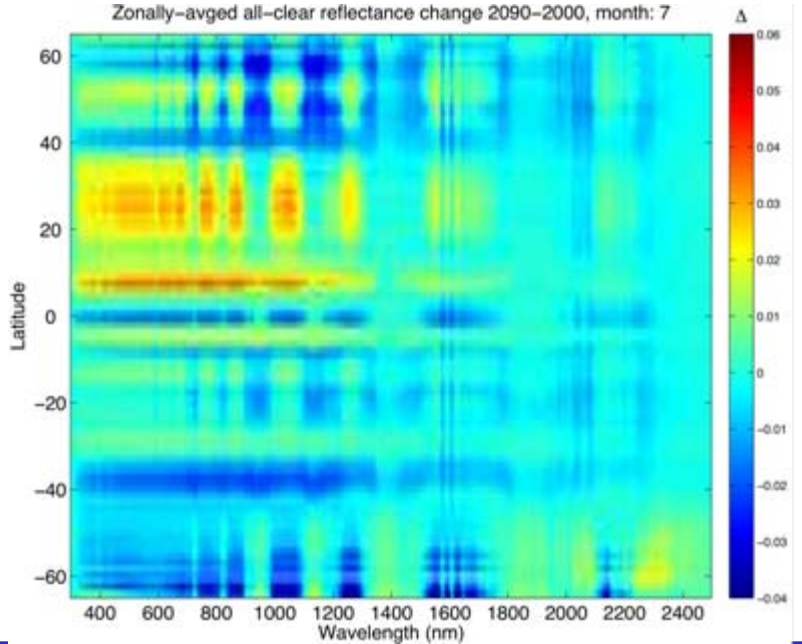
- Studies by GFDL/ Harvard demonstrate the linearity of all-sky decadal change IR signals

- Eliminates the requirement for global clear-sky observations (Huang and Leroy, 2009)



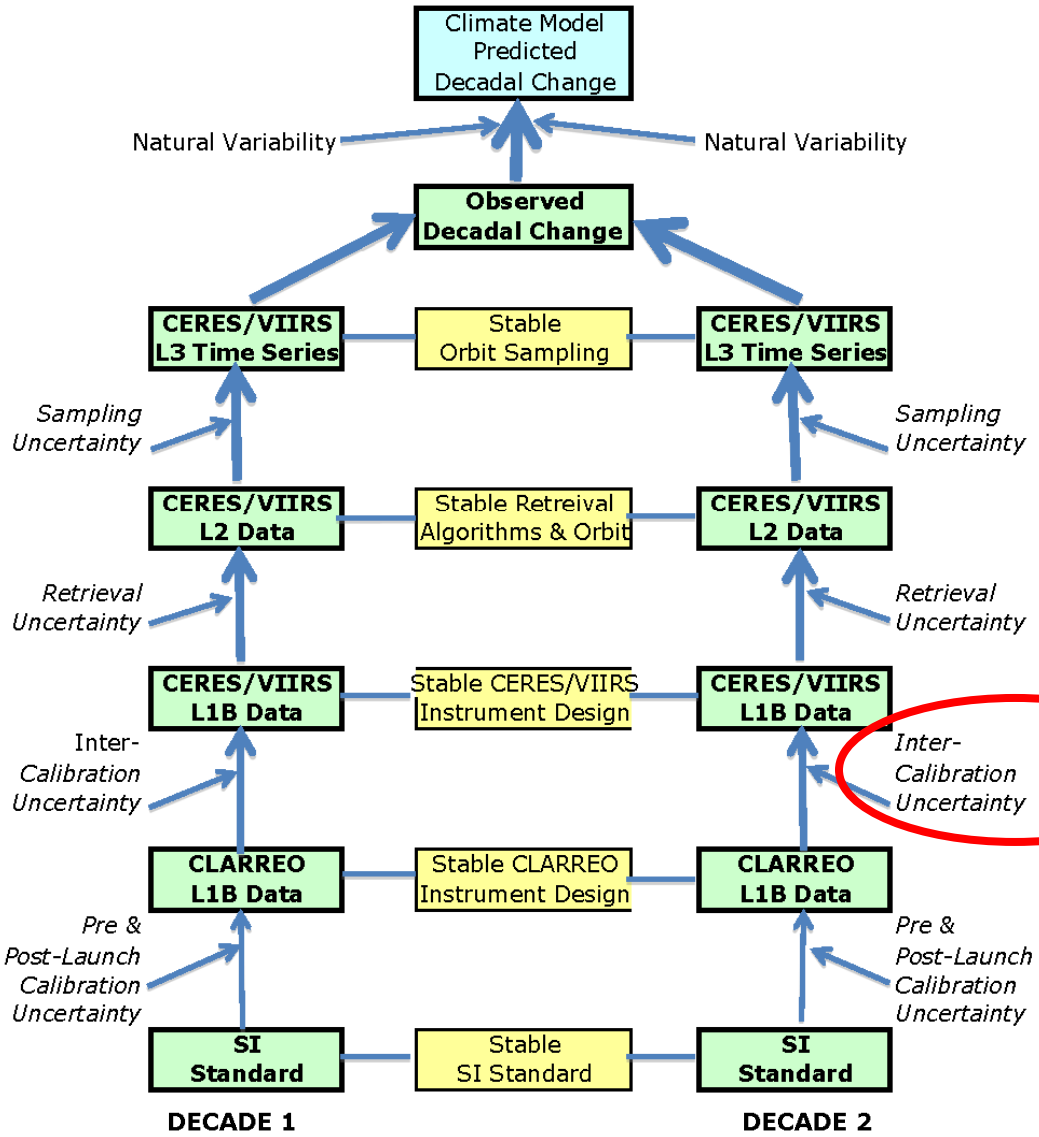


Studies by U-Cal Berkeley, LASP, and LaRC demonstrate the linearity and information content of the decadal change solar-reflected radiance signals. (Collins & Feldman, 2009)



Tracing CLARREO Decadal Change Science Objectives to Mission Requirements

Example of Observing Decadal Change Through Calibration to CLARREO Reference



Reference Inter-calibration Uncertainty

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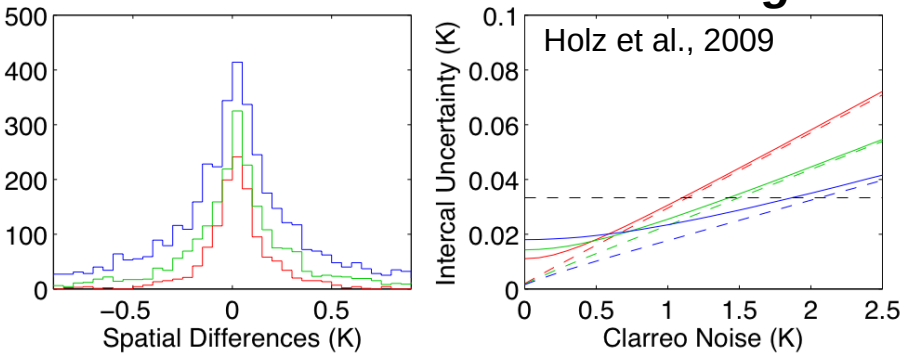
CLARREO Reference Inter-calibration Uncertainty: IR spectra

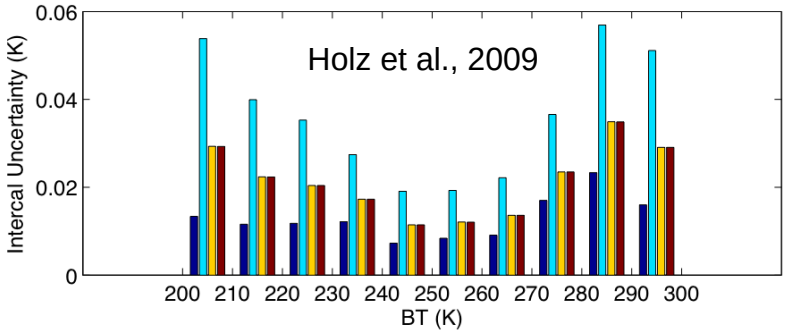
- Studies have answered outstanding questions concerning the accuracy of using CLARREO as a reference calibrator of operational IR sensors
- Nadir-only viewing provides sufficient sampling for IR intercalibration of gain, offset, and response nonlinearities.
- Sampling time and FOV will determine integration time for reference calibration

Conclusion: The inter-calibration goal of 0.1K (3-σ) for decadal change can be accomplished for a range of CLARREO FOV sizes 25km or larger.



100km (14s), 1276 pts, STDEV = 0.214 K spatial sampling noise
50 km (8s), 2286 pts, STDEV = 0.460 K spatial sampling noise
25 km (4s), 4474 pts, STDEV = 0.918 K spatial sampling noise

Conclusion: Instrument nonlinearities can be investigated using yearly averages for single channels or monthly using spectral averaging



CLARREO can provide IR reference intercalibration for CrIS, IASI, VIIRS, CERES

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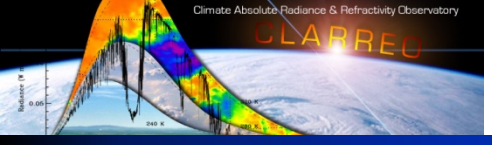

CLARREO Reference Inter-calibration Uncertainty: RS spectra

- Studies conducted by LaRC and GSFC have determined the ability of CLARREO to serve as a reference calibrator of operational sensors at decadal change accuracy.
- Demonstrated using SCHIAMACHY data to simulate CLARREO spectra. Determined the ability to distinguish and correct for changes in
  - Gain and Offset
    - Reference Inter-calibration of VIIRS narrowband leads to spectral sampling requirement of 4 nm and spectral resolution of 8nm.
  - Gain Nonlinearity
  - Spectral shape
    - Reference Inter-calibration of CERES broadband leads to spectral range requirement: 320 nm to 2300 nm
  - Polarization Sensitivity
    - Polarization sensitivity requirement for CLARREO RS spectrometer is less than 0.25% (k=2)
    - Scene dependent PARASOL spectral polarization data used to demonstrate intercalibration.
- Demonstrated requirement of angle matching to 1 degree, time matching to 5min, spatial averaging to 20km scale with 1km pointing knowledge (Wielicki et al. 2008).
- Demonstrated that any of the 90, 83, or 74 degree orbit inclinations have sufficient sampling for RS Reference intercalibration as long as either a gimball or spacecraft pointing system is capable of matching viewing zenith/azimuth/solar zenith with 1.5 degree/second motion.

CLARREO can provide RS reference intercalibration for CERES, VIIRS

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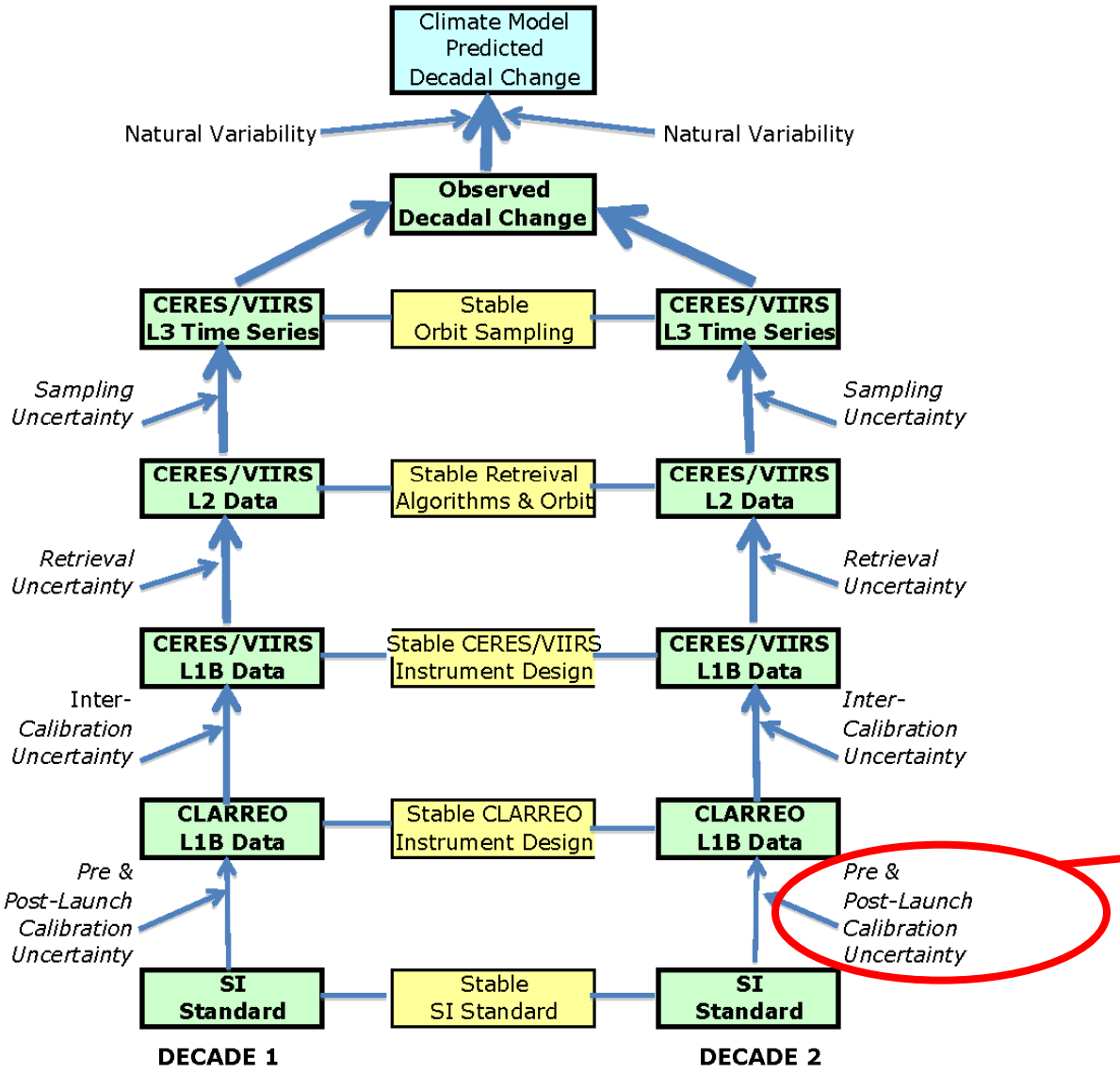
Tracing CLARREO Decadal Change Science Objectives to Mission Requirements

Example of Observing Decadal Change Through Calibration to CLARREO Reference



On-Orbit CLARREO Calibration Uncertainty

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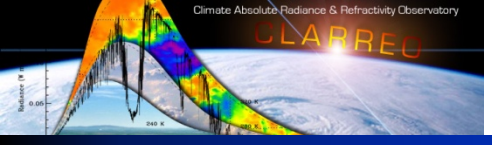

CLARREO Accuracy Requirements

- CLARREO instrument absolute accuracy requirements are derived consistent with the goal of achieving accuracy within 20% of a perfect climate observing system, and time to detect trends within 15% of a perfect observing system.

- 0.1K (*k*=3) for the IR spectra absolute accuracy required. Driven by natural variability of IR spectra.
- 0.3% (*k*=2) for the RS spectra (nadir reflectance) is required. Driven by natural variability of cloud radiative forcing, cloud fraction, cloud optical depth, particle size.
- 0.03% (*k*=2) refractivity, consistent with an accuracy of 0.1K (*k*=3) for temperature profile. Accuracy is for 5km to 20km altitudes.

- Achieving SI traceable observations with absolute accuracy at these decadal change levels enables the CLARREO mission to uniquely survive even short gaps in the climate record. Overlap becomes very important for a continuous climate record, but a gap does not break the climate record and cause a "restart".

Instrument Absolute Accuracy set for < 20% Trend Accuracy Degradation

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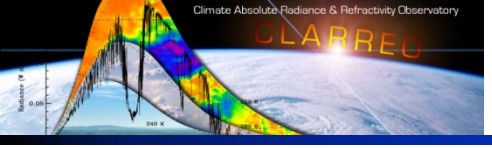

Application to Cloud Requirements

- Error budgets for decadal change accuracy and time to detect anthropogenic trends are general and can be applied to any climate observation: cloud fraction, optical depth, temperature, cloud radiative forcing, etc.

- Natural variability provides the limit of accuracy for a perfect observing system: choose a level of accuracy loss that is acceptable for a desired observing system: CLARREO has chosen accuracy within 20% of a perfect system, time to detect trends within 14% (the two are related).

- Estimate natural variability from multiple perspectives:
  - climate model control or nature runs (100 yrs, realism issues)
  - observations (5 – 30yrs, calibration/sampling aliasing issues)
  - varies with time/space scale: increases at smaller scales

- Include the complete set of errors from decadal change in a cloud variable to SI traceability and stability of radiances (see schematics for examples)

Requirements vs Perfect Observing System Limited by Natural Variability

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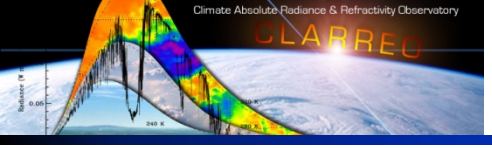

Application to Cloud Requirements

- A key error source for cloud properties will be the stability of retrieval biases
  - Currently this is just assumed for all satellite climate data
  - Studies needed to demonstrate stability in the face of 3-D cloud structure, thin cloud detection limits, etc.

- A second key error source for cloud properties will be the stability of sampling biases: e.g. sunsynch orbit diurnal sampling as well as geostationary subsatellite longitude (viewing angle).

- Requirements can vary with instrument type (VIIRS, CALIPSO, CloudSat), and sampling (scanning sunsynch, nadir sunsynch, geostationary)

- Natural variability is a function of time/space scale: increasing at smaller scales. This helps sampling requirements: CLARREO has found relatively similar ratio of sampling error/natural variability for nadir radiances in solar and infrared driven by cloud variability, from global to zonal to regional at 10 latitude by 30 longitude. But smaller scales require scanning instruments.

Showing stability of retrieval and sampling biases will be key for clouds

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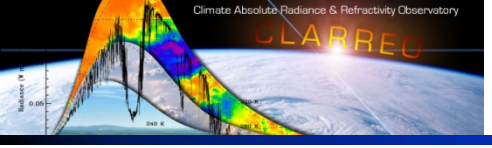

Application to Cloud Requirements

- CLARREO has found that decadal change accuracy error budget is dominated by instrument accuracy for nadir spectral radiances.

- CLARREO is using climate model OSSEs (Observing System Simulation Experiments) to simulate decadal change nadir high resolution spectral observations and ability to use spectral fingerprinting in determining decadal change: including cloud effects. These are extensions of radiative kernel methods.
  - Huang/Leroy/Anderson/Ramaswamy/Kato have had some success using all-sky IR spectral fingerprinting, spectral cloud effect tests in the next phase. Uses the GFDL climate model runs (200 to 2000 cm^{-1}, 1 cm^{-1} spectral resolution); A-train profile data + line by line RTM.
  - Collins/Feldman/Jin have had some success using spectral cloud radiative effect with reflected solar spectral fingerprinting. Uses NCAR climate model runs (300 to 2500 nm, 15 cm^{-1} resolution); CERES/MODIS/GEOS-4 surface and atmosphere data + Modtran.

CLARREO using climate model OSSEs to improve requirements

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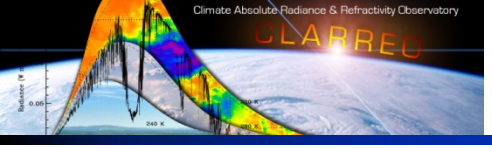

Application to Cloud Requirements

- What Space/Time Scales are required?
  - Soden et al. 2008 cloud feedback global maps suggest decadal change features down to ~ 1000km scale: suggests using global, zonal, regional to 1000km.
  - Taylor and Ellingson have extended the Soden et al. 2008 study to seasonal time scales: clouds showed significant seasonal signals especially for reflected solar (water vapor/lapse rate feedbacks did not).
  - CLARREO is suggesting reference intercalibration to calibrate leo and geo cloud retrieval instruments to cover full range of scales, with cloud retrievals and CLARREO spectra independently used at zonal/global scales.

- Decadal change accuracy is driven by the large ensemble of observations: not instantaneous accuracy of instrument noise or retrievals.
  - Ensemble distributions of small decadal changes tend to behave linearly: unlike instantaneous retrievals which are often very nonlinear. This is analogous to linear perturbation analysis of nonlinear systems.

Large ensembles and scales dominate for decadal climate change

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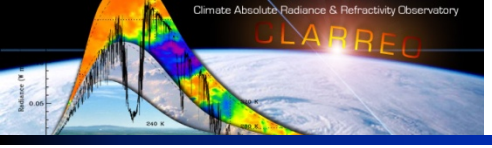

Application to Cloud Requirements

- Highly accurate decadal climate change data has requirements that have many analogies to international metrological standards

- Recent Geneva meeting of the international metrology groups (BIPM), and climate observation groups.

- Accepted international standards have 3 primary characteristics:
  - Peer reviewed observations and uncertainty analysis
  - Open documentation of observations, methods, uncertainty analysis
  - Comparison of independent observations each with quantified uncertainty

- GCOS climate observing principles are still missing two key principles:
  - Independent observations (metrology analogy)
  - Independent analysis and uncertainty (metrology analogy)

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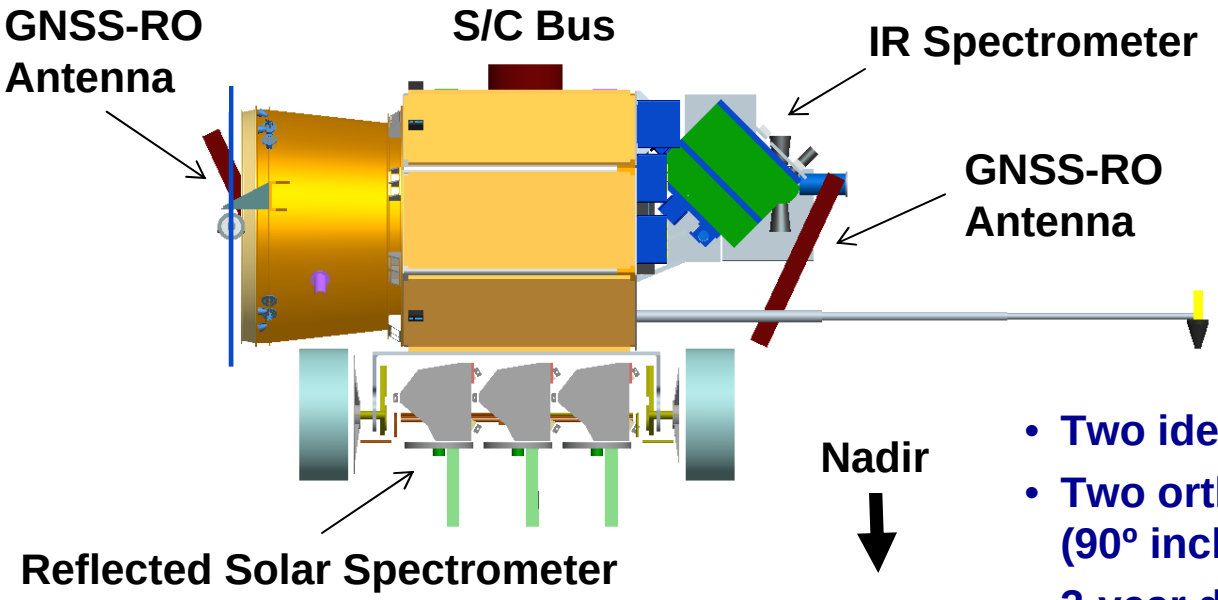
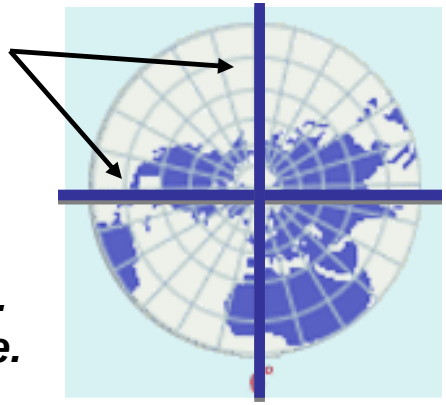
CLARREO Baseline Mission Concept

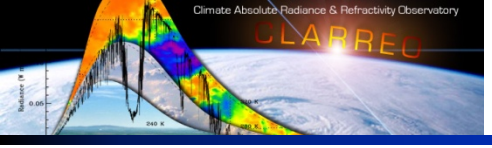


CBE Mass: 814 kg
OA Power: 691 W
~ ¼ the mass and
~ 1/7th the power of the Aqua spacecraft

- **Two identical observatories**
- **Two orthogonal 609 km polar orbits (90º inclination)**
- **3-year design life with spacecraft consumables to extend to a 5-year mission**
- **Instrument payload**
  - ***IR FTS spectrometer***
  - ***Reflected solar spectrometer suite***
  - ***GNSS RO***
  - ***Extensive on-orbit calibration verification***

2 - 90 degree polar orbits
- 6hrs apart local equator crossing time
- Samples full diurnal cycle once per 3 months.
- Precise repeat each year.
- Observes equator to pole.





CLARREO Mission Status

- The importance of high-accuracy, SI- traceable climate observations has been recognized by the NAS and now by NASA and the current US administration.
- CLARREO budget guidance calls for an initial launch target of 2017, second launch in 2020.
- Level 1and 2 requirements are set – generated by science team based mission studies (model and observational) over the past 2 years.
- Working closely with NIST on CLARREO metrology, SI traceability
  - We understand the fundamental connection between the climate science and metrology for this type of measurement
  - Working to extend standards where necessary (e.g. >15μm IR, >1600nm RS).
- BIPM forum to expand the connection to international NMIs/science.
- CLARREO is working with the UK – agreement with NCEO, key contacts Nigel Fox (Reflected Solar), John Harries (IR). CLARREO contributions to recent TRUTHS proposal to ESA for reflected solar spectra.
- NASA ROSES Science Definition Team (SDT) proposals due July 1.
- CLARREO mission concept review October, 2010.

CLARREO ready to move into phase A

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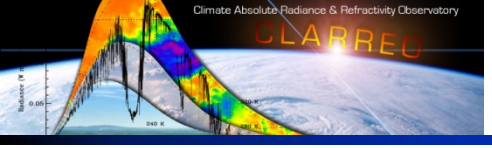
Summary of CLARREO Advances

- **CLARREO provides the S.I. traceable absolute accuracy in infrared and solar reflected spectra needed to observe decadal climate change and verify climate predictions.**
- **The CLARREO full spectra extend and expand the information content to a wide range of climate variables at climate change accuracy.**
- **CLARREO anchors the research and operational solar and infrared sensors at climate change accuracy through inter-calibration, providing the first "Standards Lab in Space".**
- **CLARREO provides the first full IR spectra by including the far infrared which is half of the Earth's emitted radiation, and is the bulk of the earths water vapor greenhouse effect .**
- **CLARREO provides the first full solar reflected spectra from the Earth at climate change accuracy.**



Backup Slides

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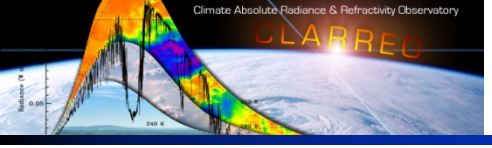
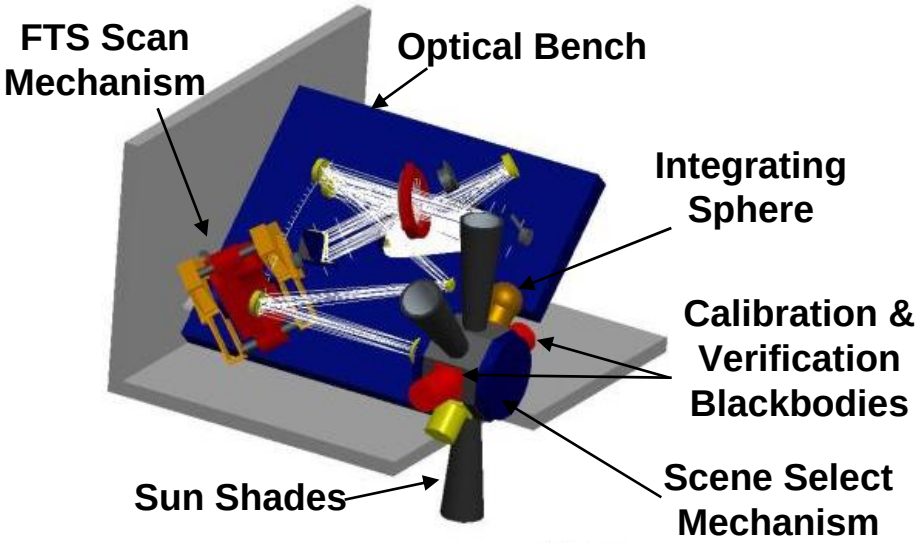
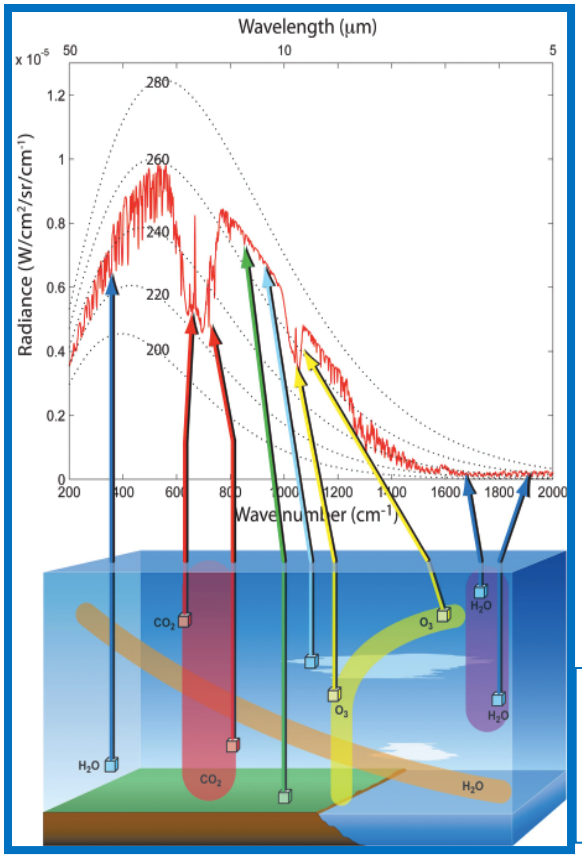
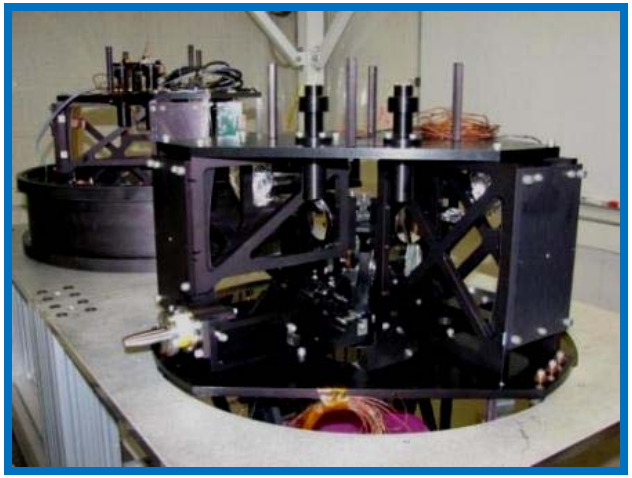


Infrared Instrument Suite





Courtesy of J. Anderson Harvard University



- 200-2000 cm^{-1}, 0.5 cm^{-1} unapodized resolution
- Mass: 87 kg, Power: 210 W
- Dimension: 42x65x70 cm^3
- Data Rate: 220 kb/sec
- IFOV: 25 km footprint (nadir only)

SI Traceable Accuracy 0.1K (*k*=3) all Earth Scene Temps (200 to 300K)

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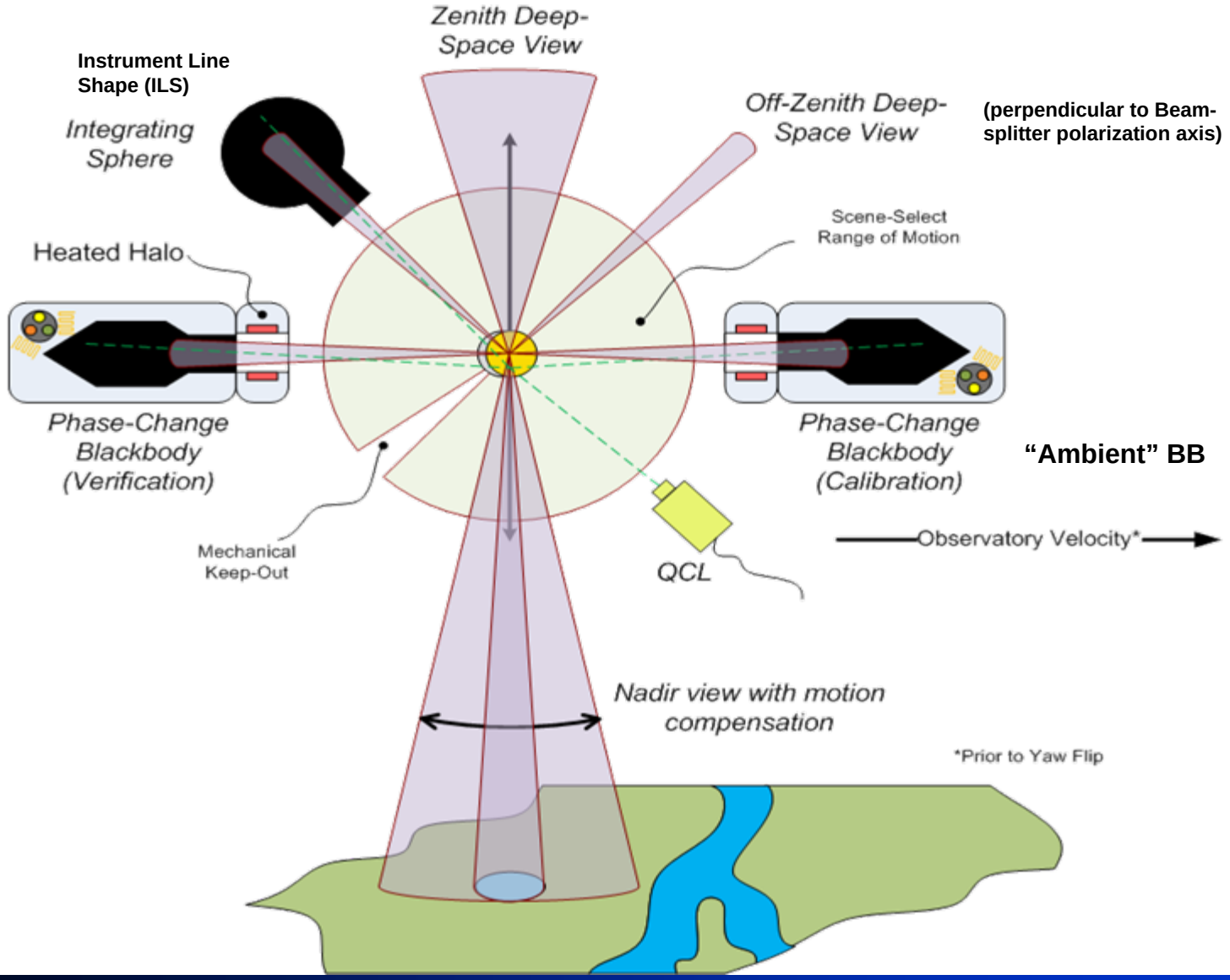
Calibration is the foundation of CLARREO



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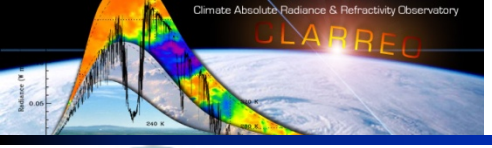
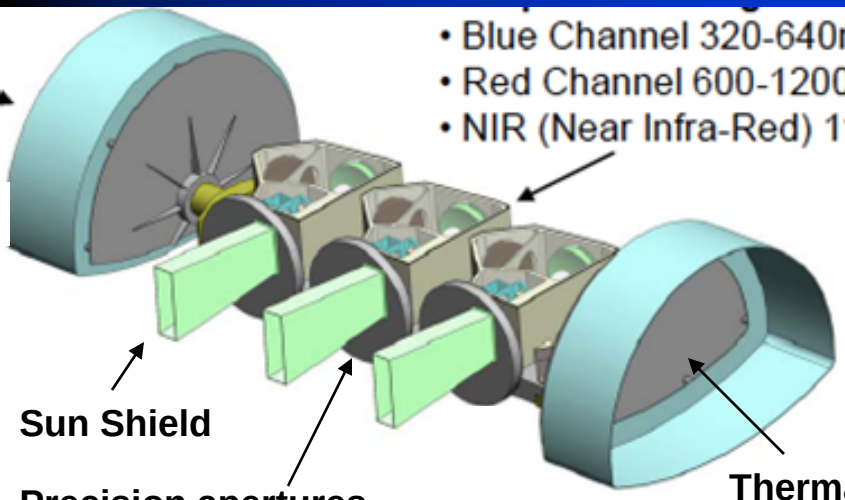
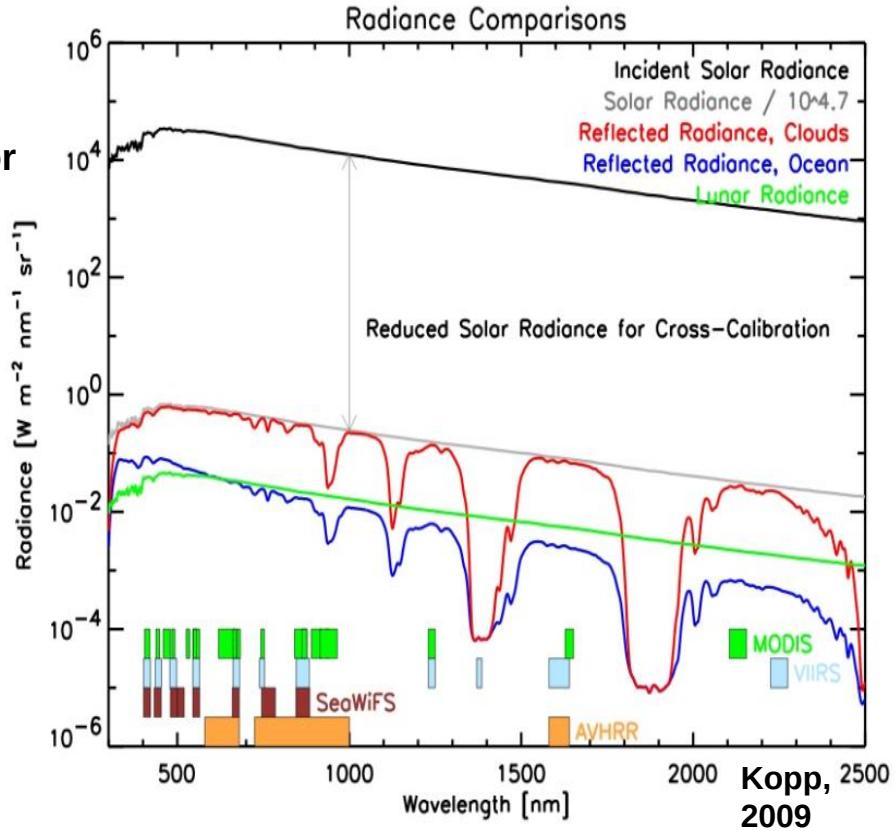


Reflected Solar Instrument Suite

- Blue Channel 320-640nm
- Red Channel 600-1200nm
- NIR (Near Infra-Red) 1150-2300nm



Polarization sensitivity less than 0.25% (*k*=2)
Spectral resolution 8nm, sampling 4nm
S/N ratio > 33 for 0.3 reflectance at solar zenith=75



Kopp, 2009

- **Mass** — **64 kg CBE**
- **Power** — **94 W CBE**
- **Data Rate** — **11 Mbps**
- **Spatial swath** — **0.5km IFOV, 100km**
- **Nadir for spectral benchmarking**
- **Gimbal pointing for lunar/solar calibration & Reference Intercalibration**

SI Traceable Relative Uncertainty 0.3% (*k*=2) in Spectral Reflectance

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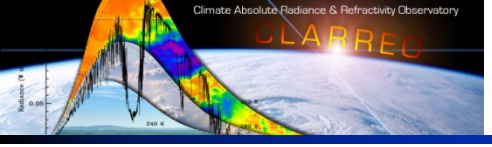
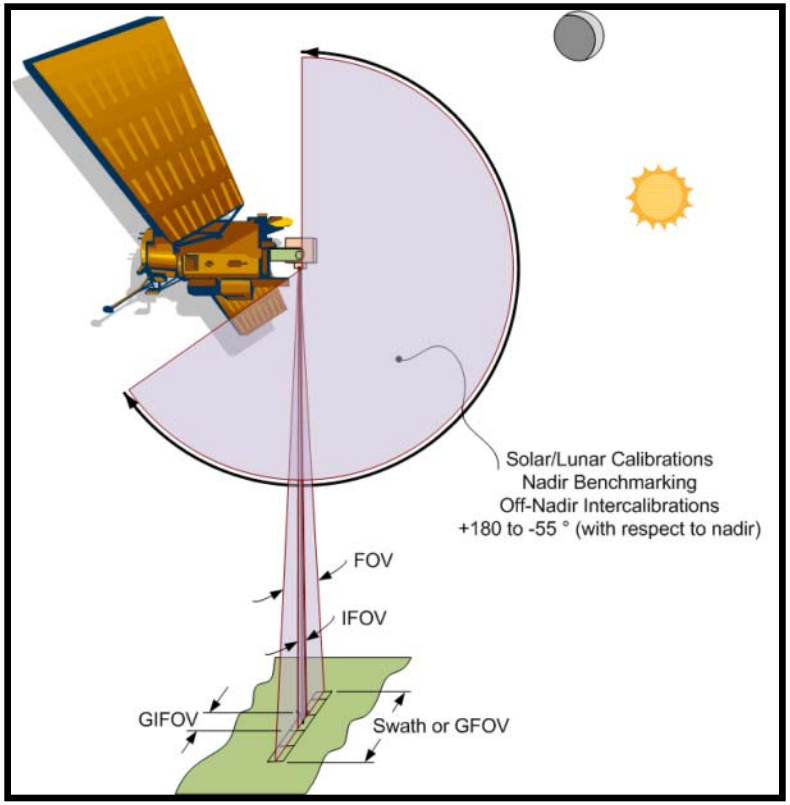


Calibration Approach: Reflected Solar

- One spectral order per spectrometer to simplify calibration: optimize detectors, optics, gratings, polarization sensitivity, precision apertures).
- Instrument dynamic range for solar, lunar, and Earth views with same spectrometer.
- Gimbal pointing to allow same optical path for solar, lunar, Earth view (no scanning or pointing mirrors).
- Lunar cal at constant phase angle of 7 to 9 degrees once/month (e.g. SeaWiFS 0.1% stability), verify transmission of neutral density filters (in/out of optical path).
- Solar cal weekly to monthly: use with precision apertures, neutral density filters, varying detector dwell time for nonlinearity test over full dynamic range of Earth viewing reflectance.
- Stray light verification using Venus scanned in/out of field of view.
- Optics design and depolarizers to meet polarization sensitivity requirement.
- Earth reflectance relative to sun is the primary measurement required for climate change, but if add spectral solar irradiance, SI traceability to the Watt.



Sun, Moon provide sources at better than 0.1% stability (11-yr solar cycle, lunar phase angle/libration)
Monitor solar irradiance change at better than 0.1% (TSIS)
SI traceability of lunar reflectance can be done at any time.

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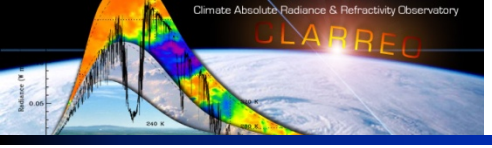
Societal Benefit	Science Objective	Level 1 Science Requirements	Level 2 Measurement Requirements	Level 2 Mission Requirements
Enable knowledgeable policy decisions based on internationally acknowledged climate measurements and models through: - Observation of high accuracy long-term climate change trends - Use the long term climate change observations to test and improve climate forecasts.	Highly accurate and SI-traceable decadal change observations sensitive to climate radiative forcings, responses, and feedbacks:	CL.PRJ.1.REQ.3000 •Verifiable on-orbit accuracy •Traceable to SI standards •Decadal climate change relevant time and space scales	CL.SYS.1.REQ.1005 Accuracy demonstrated to be SI traceable to the relevant NIST standard and maintained throughout the sensors lifecycle.	CL.SYS.1.REQ.4002 Observations from 2 Earth orbiting observatories
	<u>Infrared spectra</u> temperature and water vapor feedbacks cloud feedbacks decadal change of: •Temperature profiles •Water vapor profiles •Clouds, radiative fluxes •GHG radiative effects	CL.PRJ.1.REQ.3001 Infrared radiance spectra of the Earth and its atmosphere with: •Systematic error that corresponds to ≤ 0.1 K radiance calibration uncertainty (3σ) •Sampling to provide global coverage and degrade climate trend accuracy by <15%	CL.SYS.1.REQ.1001 Measurements in the Infrared Spectra: •Spectral range 200 – 2000 cm^{-1} •Spectral resolution 1 cm^{-1} apodized (0.5 unapodized) •NeDT < 10K (1σ) •Earth nadir direction, ± 0.2 deg •GIFOV >25 km across •Ground sampling interval <200 km •Systematic error < 0.100 Kelvin (3σ)	CL.SYS.1.REQ.4011 Observatories designed for a 3-year minimum lifetime.
	<u>Solar reflected spectra</u> cloud feedbacks snow/ice albedo feedbacks decadal change of: •Clouds •Radiative fluxes •Snow cover, sea ice, land use	CL.PRJ.1.REQ.3002 Solar spectral nadir reflectance of the Earth and its atmosphere relative to the solar irradiance spectrum with: •Absolute uncertainty ≤ 0.3% relative to global mean reflected solar energy (2σ) •Sampling to provide global coverage and degrade climate trend accuracy by <15%	CL.SYS.1.REQ.1002 Measurements in the Solar Reflected Spectra: •Spectral range 320 – 2300 nm •Spectral sampling ≤4 nm, resolution 8 nm •GIFOV <0.5 km by 0.5 km •SNR ≥ 33 for 380 to 900 nm, ≥20 elsewhere, for 0.3 reflectance, solar zenith angle 75° •Swath width ≥ 100 km •Polarization sensitivity ≤0.25% (2σ) <1000 nm, ≤0.75% elsewhere •Radiometric calibration uncertainty ≤0.3% of reflectance	CL.SYS.1.REQ.6001 Both observatories in near circular, polar orbits: •Orbit Period: 5820.6 ± 0.25 seconds (609 km ± 200m) •Inclination: 90± 0.1° •Eccentricity: ≤0.001 •Ground Track Repeat Cycle: 60.83 days (903 distinct paths) •Ground Track Error: ±12.5 km cross track at AN from target ground track established by the 60.83 day ground track repeat cycle. •Plane Separation: 90° in the Right Ascension of the Ascending Nodes (RAAN) •Time separation: No less than 10 minutes in polar crossing times
	<u>GNSS-RO</u> decadal change of temperature profiles	CL.PRJ.1.REQ.3003 Atmospheric refractivity with: •Uncertainty of 0.03% for 5-20 km altitude •Annual means in 10° latitude zones over all longitudes	CL.SYS.1.REQ.1003 Measure the phase delay rate of GNSS transmitted signal occulted by the atmosphere: •Altitudes 5-20 km, 200 m vertical resolution •Uncertainty ≤0.5 mm/sec CL.SYS.1.REQ.1004 Measure averaged microwave refractivity: •Over 1 year 10° latitudinal zones, over all longitudes, •Altitudes 5–20 km, 200 m vertical resolution •Uncertainty ≤0.03 %	
	<u>Reference inter-calibration</u> •Broadband CERES •Operational sounders (CrIS, IASI) •Operational imagers (VIIRS, AVHRR, Landsat)	CL.PRJ.1.REQ.3010 CLARREO shall enable inter-calibration with climate relevant operational sensors.		NOTE Orbit Definition considered science sampling requirements and reference intercalibration requirement



CLARREO: Why Now?

- The urgency of climate change science and the large uncertainties in climate prediction that remain.
- Advances in the understanding of the critical need for decadal change observations as the foundation of testing climate model predictions of future climate change (IPCC, 2007).
- The increased experience with high spectral resolution satellite observations (AIRS, IASI, SCHIAMACHY, GOME).
- The last decade of NASA EOS observations with greatly improved calibration but not yet to decadal change absolute accuracy, so that gaps are critical (SORCE, CERES, MODIS, AIRS).
- The last decade of NIST metrological advances at IR and solar wavelengths to support greatly improved calibration.

CLARREO is ready and is urgently needed by the climate community

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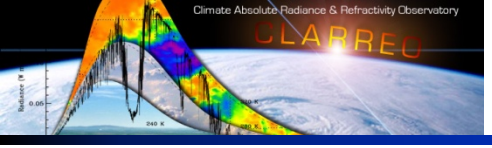

Science Payback in the First 3-5 Year Mission

- Establish a critical climate benchmark that can be compared rigorously to future decades of SI-traceable climate observations

- Improved climate model physics through direct spectral observations of the far-infrared water vapor greenhouse effect. This is 50% of the IR energy.

- Provide reference intercalibration to operational RS and IR sensors
  - Up to 10X accuracy improvement in the RS and 5X in the IR for science and applications: temperature, water vapor, radiation, cloud, surface
  - Greatly improved consistency across operational observing system

- Provide high absolute accuracy and high spectral resolution RS and IR climatologies for climate model testing and physics improvements.

- Demonstrate new calibration technologies to improve future operational and climate monitoring instruments

Initial CLARREO Mission Delivers High Science Value

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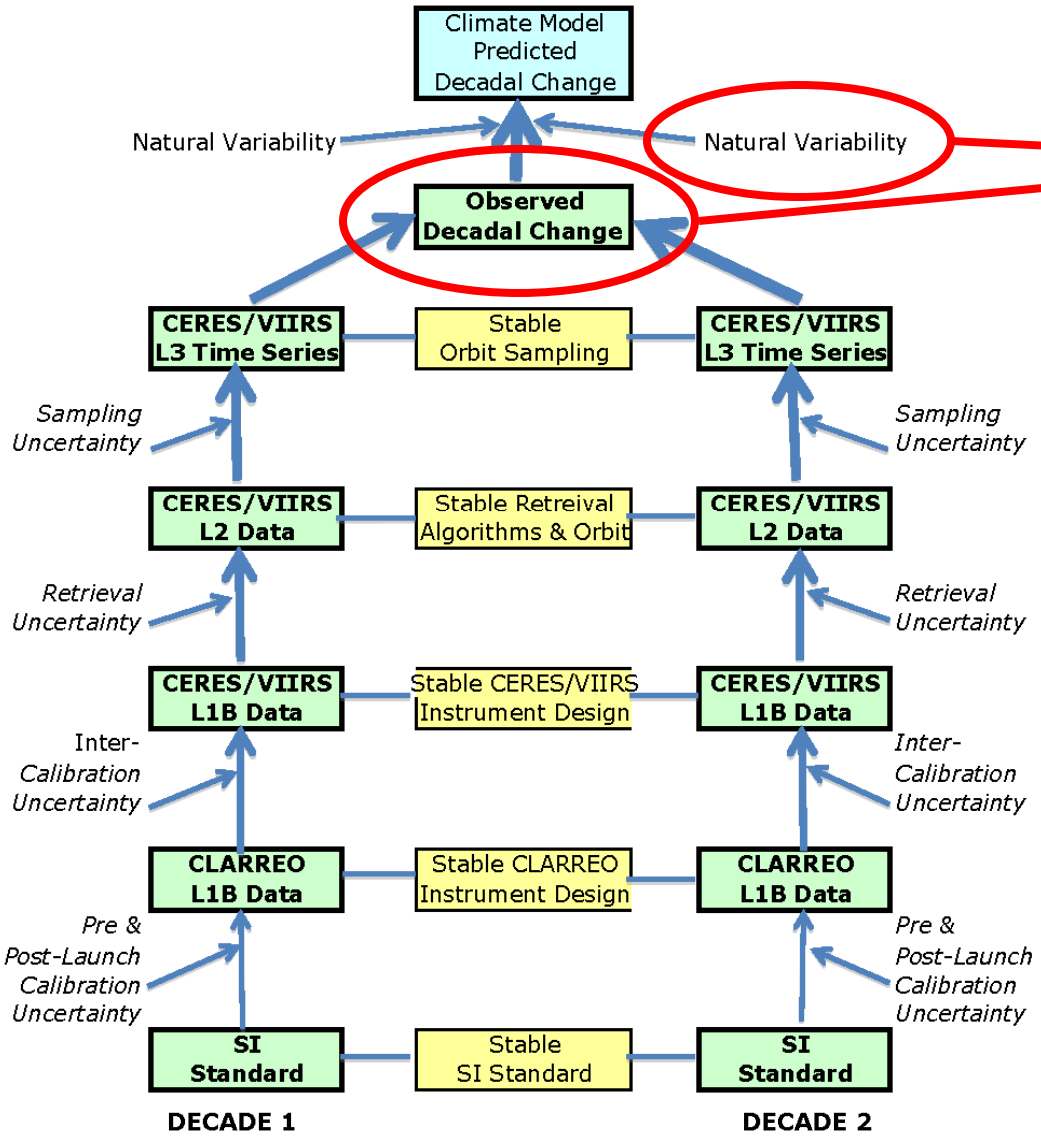
Tracing CLARREO Decadal Change Science Objectives to Mission Requirements

Example of Observing Decadal Change Through Calibration to CLARREO Reference



Decadal Change Accuracy Requirements:

Decadal change accuracy within 20% of a perfect climate observing system.

Decadal change time to detect trends within 15% of a perfect observing system.

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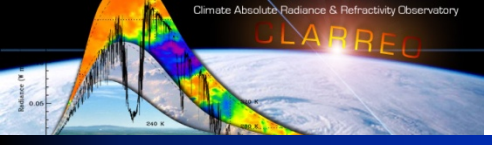

What is the Level of Natural Variability?

We consider the CLARREO climate change variables that drive the observations by IR and RS spectra and GNSS-RO

Use data sources sufficiently accurate to observe the levels of natural variability (CERES/MODIS/GEOS-4 merged data set for radiative fluxes, cloud properties, atmospheric properties). 5 year record without any major volcanic events similar to Pinatubo. Represents typical background variability including ENSO.

Table of 1 sigma natural variability for relevant time/space scales.

Requirement for trend detection is to reduce errors below 1/3 of natural variability at the relevant time/space scale for each decadal change observation.

Climate Variable	Spatial Scale	Time Scale	Natural Variability Data Source	1-sigma Variabilit	Unit
SW Reflected Flux	global	annual	Doelling Aug 2009 CLARREO Study	**0.17**	Wm^{-2}
SW Reflected Flux	global	monthly	Loeb et al. J. Climate 2007	**0.55**	Wm^{-2}
VIIRS visible band	global	annual	Scaled to SW reflected Doelling Aug 2009	**0.20%**	% mean radiance
VIIRS visible band	global	monthly	Scaled to SW reflected Loeb et al. 2007	**0.60%**	% mean radiance
LW Emitted Flux	global	annual	Doelling Aug 2009 CLARREO Study	**0.19**	Wm^{-2}
LW Emitted Flux	global	monthly	Scaled to Loeb et al. J. Climate 2007	**0.61**	Wm^{-2}
Temperature	global	annual	Doelling Aug 2009 CLARREO Study	**0.1**	K
Temperature	global	monthly	Scaled to LW flux Loeb & Doelling	**0.3**	K

Natural Variability Increases as Time/Space Scale Decreases

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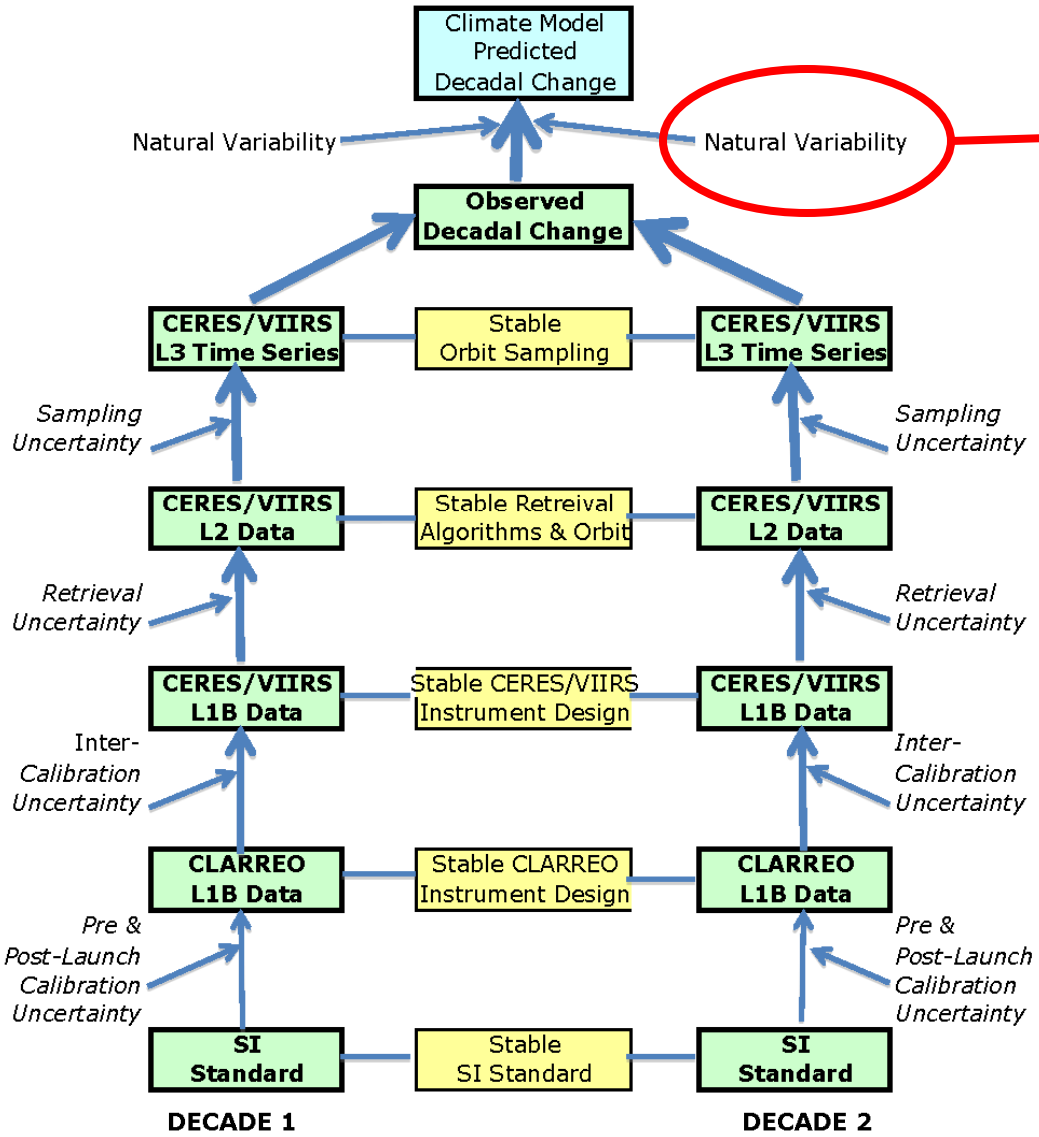

Trend Detection Above Natural Variability: Mission Duration

Mission duration minimum of 3 years and consumables for 5 years is required to overcome natural variability such as ENSO.

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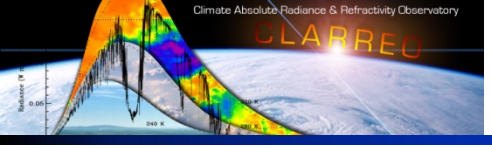
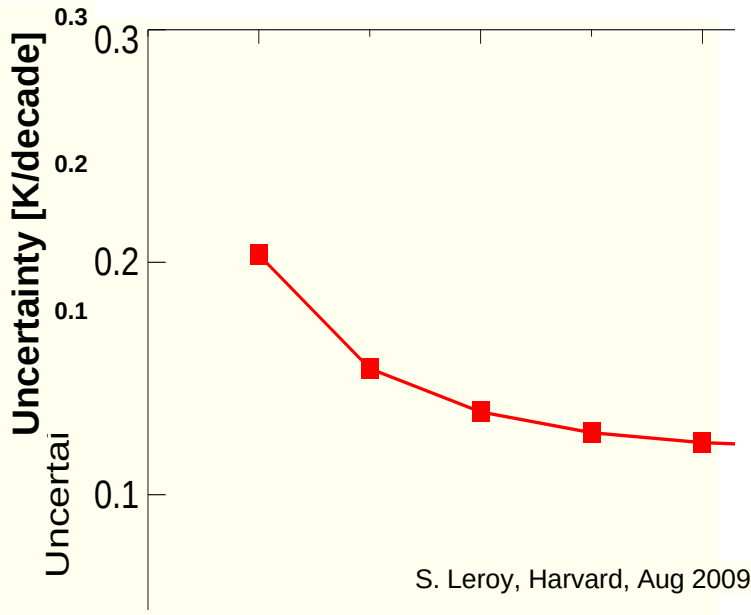


Trend Detection Above Natural Variability: Mission Duration

- Decadal climate change signals have to be rigorously detected above natural variability of the climate system (e.g. ENSO on 5-yr time scale). This is often called interannual variability and can be estimated from current observations (CERES, AIRS, SCHIAMACHY, MODIS, etc), as well as from climate models.
- Sufficient length of record is required to reduce natural variability
- Example for stratospheric temperature trends (S. Leroy, CLARREO science study) shows that natural variability places a requirement on CLARREO mission duration: **3-5 year mission duration** for two CLARREO missions over a 15 year climate record (beginning of first mission to end of the second). 15 years is a typical time for decadal change signals to exceed natural variability.



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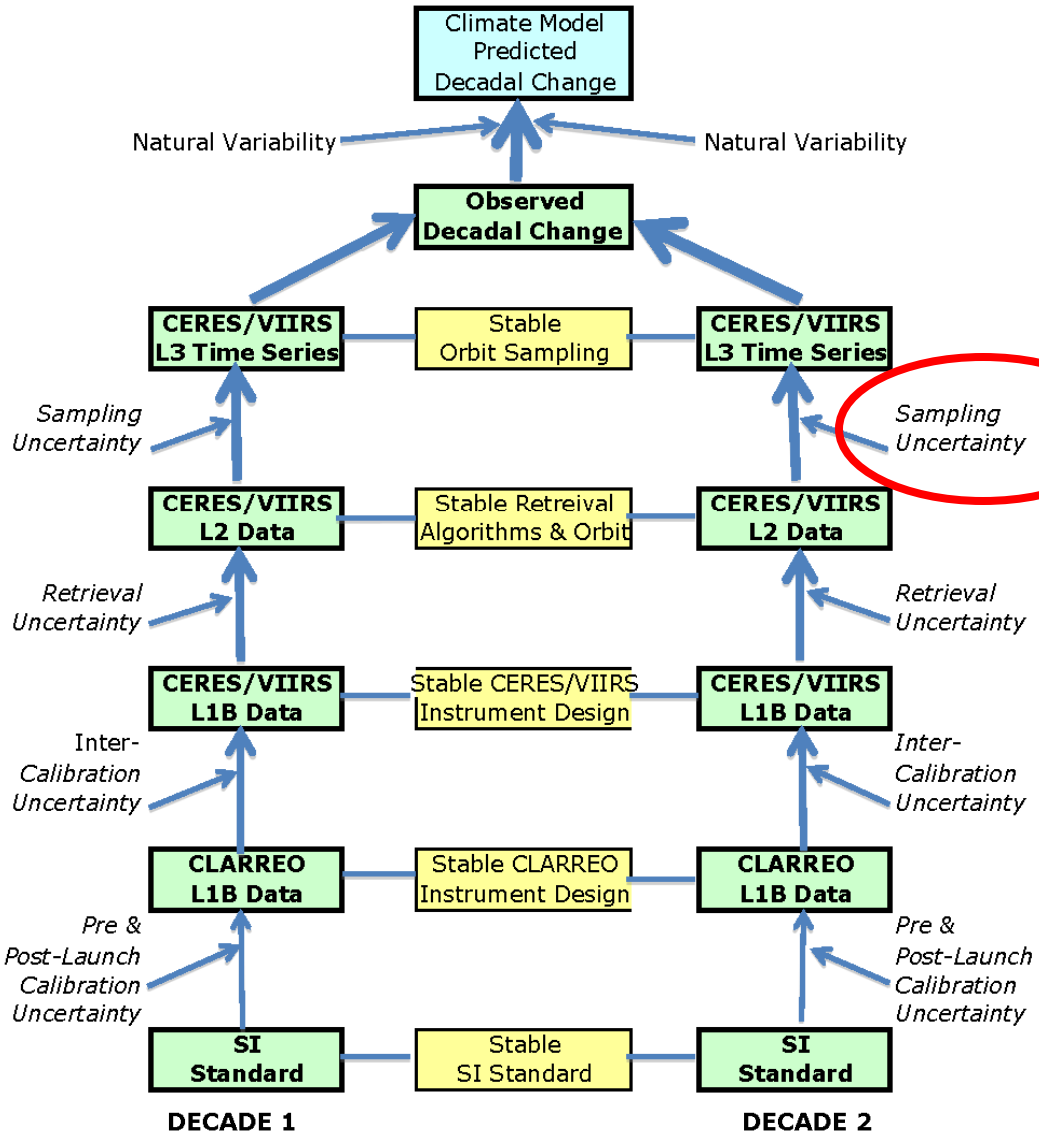

Orbit Sampling Uncertainty Vs Natural Variability

Orbital sampling studies show that 2 90 degree orbits are required to reduce sampling error to less than 1/3 of natural variability

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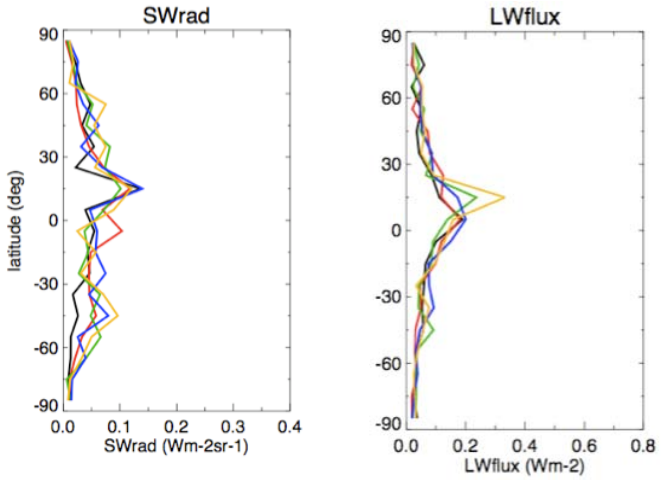
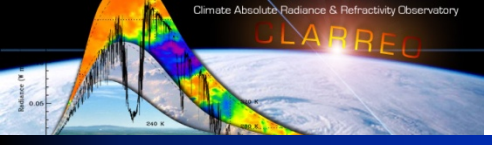
CLARREO Orbit Sampling Requirement: IR and RS spectra

- CERES data used to determine sampling errors relative to inter-annual natural variability
  - Global and zonal annual means of CLARREO orbit sampled data were compared with the complete data set (1 deg lat/lon res, hourly time res, global 5-year data set)
  - Single and multiple spacecraft tested in 98°, 90°, 83°, and 74° orbits
- Sampling from 2 spacecraft achieves CLARREO sampling accuracy goals in IR and RS
  - RS zonal sampling error is 25% of natural variability: meets requirement < 1/3
  - LW zonal sampling error is 11% of natural variability: meets requirement < 1/3
- Two 90° spacecraft provide the most robust sampling strategy for both the benchmarking and reference calibration goals



RMS error	ZONAL			GLOBAL		
	SWrad (Wm-2sr-1)	SWflux (Wm-2)	LW (Wm-2)	SWrad (Wm-2sr-1)	SWflux (Wm-2)	LW (Wm-2)
Truth 1-sigma	.192	.628	.640	.055	.173	.194
SS 13:30	.062	.196	.126			.039
13:30+10:30	.045	.138		.019	.048	
P90-1	.089	.267	.110	.029	.081	.036
P90-2	.044	.140	.068	.012	.033	.020
P90-3	.031	.096	.048	.009	.027	.012
P83-1	.087	.272	.112	.024	.076	.036
P83-2	.051	.157	.071	.016	.050	.025
P83-3	.038	.117	.048	.012	.037	.012
P74-1	.102	.322	.096	.037	.112	.033
P74-2	.062	.199	.054	.020	.064	.019
P74-3	.051	.160	.041	.013	.039	.012

Doelling, 2009



CLARREO Orbit Sampling Requirement IR and RS Spectra

- If Sunsynchronous and 90 degree orbital sampling errors are similar: why not go with sunsynchronous orbit to simplify spacecraft and instrument thermal environment?
  - 90 degree orbit precesses through all local times of day and a single clarreo surviving satellite can still provide Reference Intercalibration for all sunsychronous orbits for a full range of climate regimes (tropics to polar). Not true for a sunsynch CLARREO.
  - 90 degree samples all local times of day, allowing full diurnal cycle sampling and verification if any diurnal cycle changes have occurred on decade time scale. This eliminates any uncertainties about sunsynchronous sampling at only 2 times of day.
  - 90 degree nadir radiance is still sufficient to handle solar reflected benchmark despite anisotropy variations with scene type at nadir (similar relative % radiance & flux errors). This was a serious concern before we did the full simulation using CERES data and CERES anisotropic models for all scene types to simulate clarreo nadir benchmark sampling (previous table).

2 CLARREO 90 degree orbits meet all RS and IR science requirements

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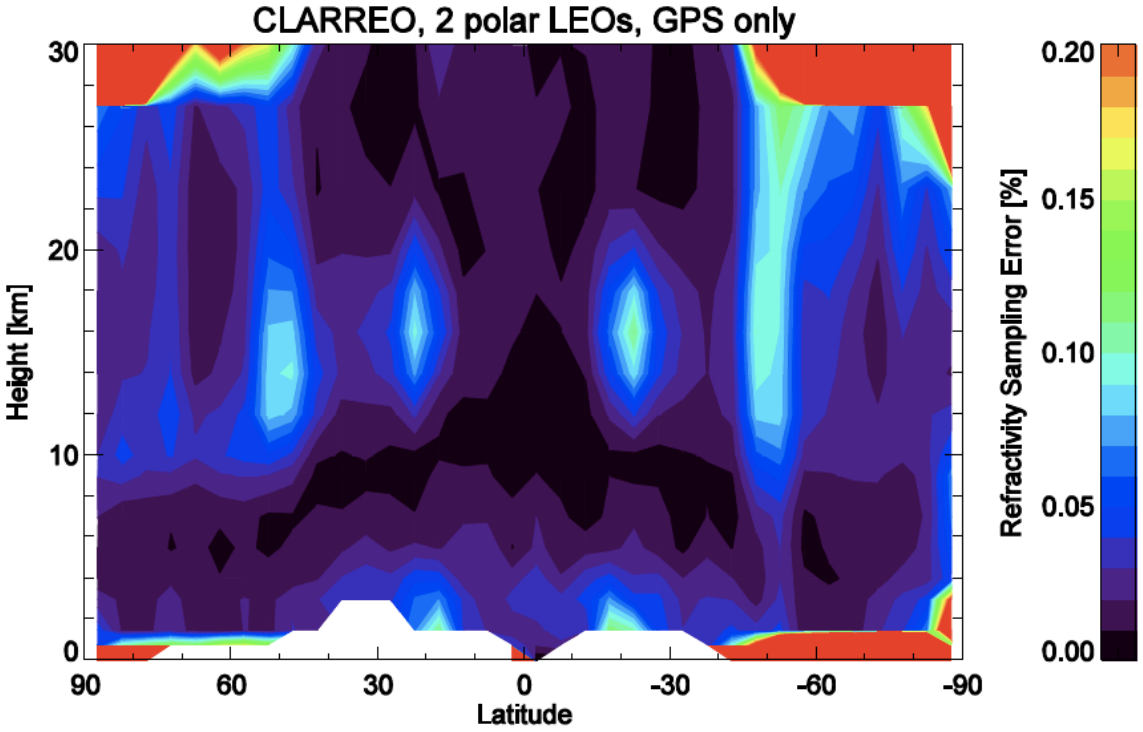
CLARREO Orbit Sampling Requirement GNSS-RO



Errors increase by 40% for GPS only

Simulated 2 CLARREO low Earth orbiters in polar orbit, spaced 90º in ascending node.

Simulated 24 GPS and 27 Galileo in nominal configuration.

Ran for 8 years, interpolated to NCEP reanalysis.

Binned by month, averaged over year, compared to NCEP reanalysis truth.

2 CLARREO 90 degree orbits meet the GNSS-RO Sampling Requirement

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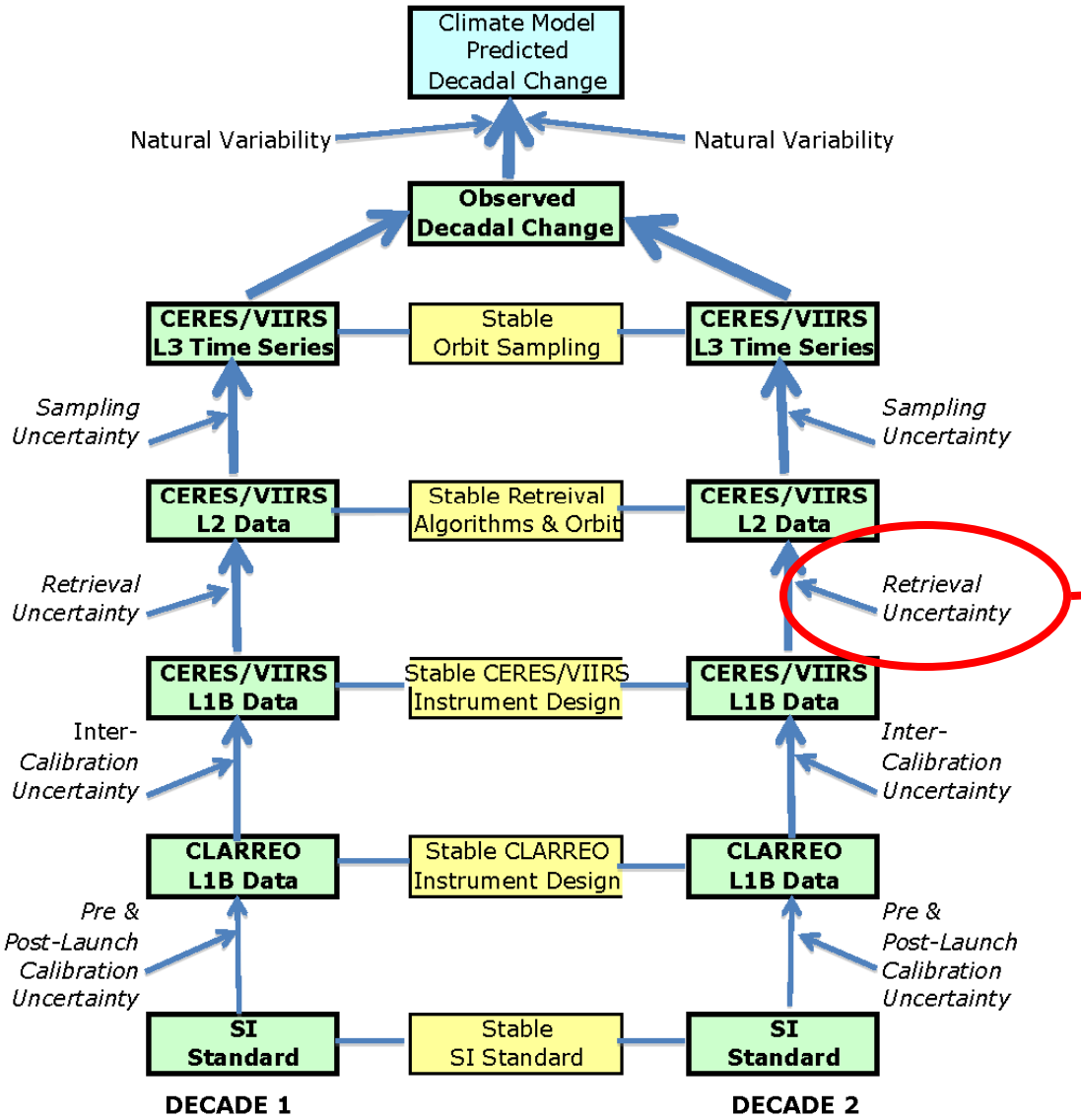

Retrieval algorithms must maintain constant algorithms over decades

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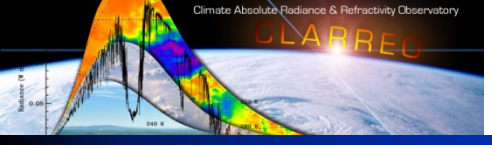

Retrieval Bias in Climate Trends

- Climate research community currently assumes stability of retrieval bias as long as the retrieval algorithm code is unchanged during processing of climate data records and calibration of the underlying data is stable (e.g. CERES, TSIS).
- CLARREO will undertake studies to demonstrate this for a wider range of decadal climate change variables relevant to CLARREO: temperature and water vapor profile, cloud properties, surface albedo.
- This uncertainty source is not relevant to CLARREO benchmark measurements used for climate change fingerprinting methods.

Constant Retrieval Algorithms at Decade Time Scales are Required

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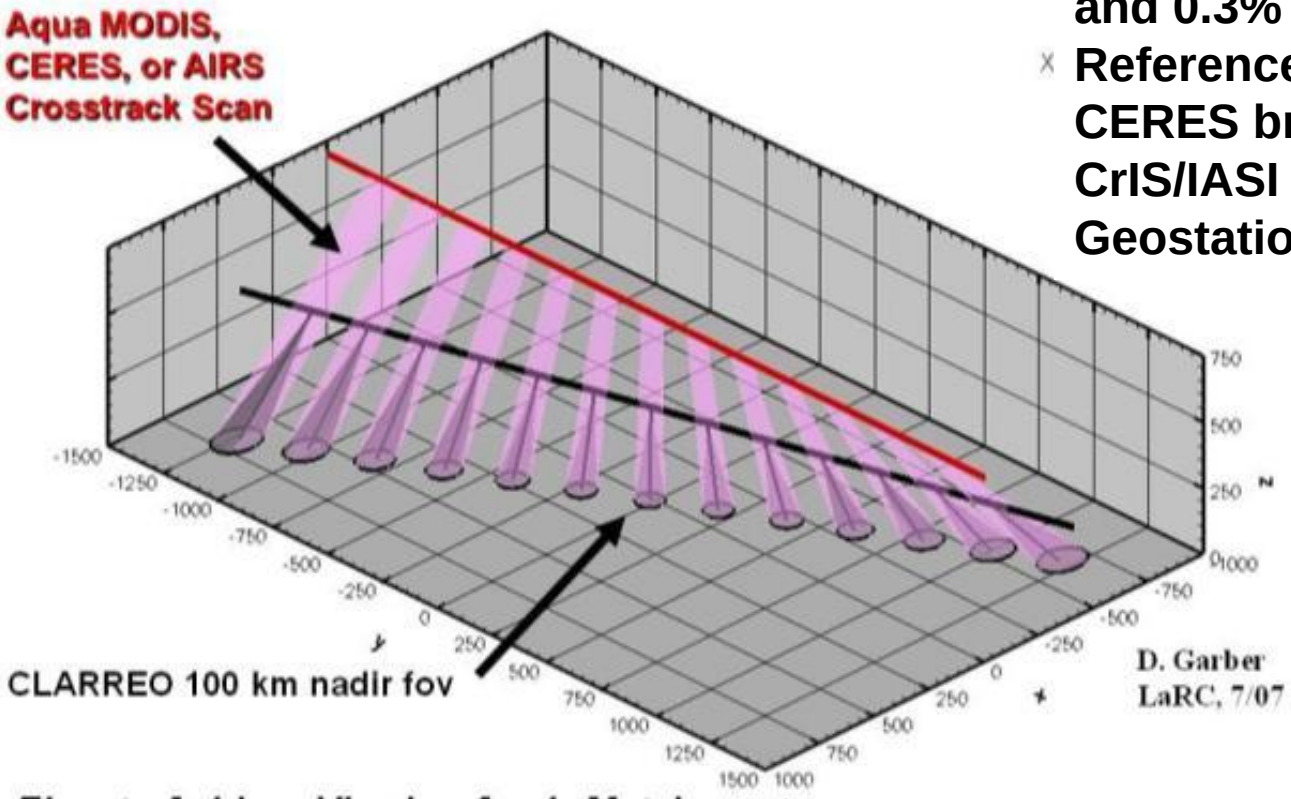
Time/Angle/Space Matched Reference Intercalibration At Decadal Climate Change Accuracy

Spatial Matching to 20km scale
Time matching to 5 minutes
Angle matching to 1 degree:
Required for 0.1K 3 sigma IR and 0.3% (2 sigma) Solar Reflected Reference Intercalibration:
CERES broadband, VIIRS imager
CrIS/IASI IR interferometers,
Geostationary imagers, sounders



Time to Achieve Viewing Angle Matches:
40 seconds per 100km orbit altitude Difference: 140 seconds above

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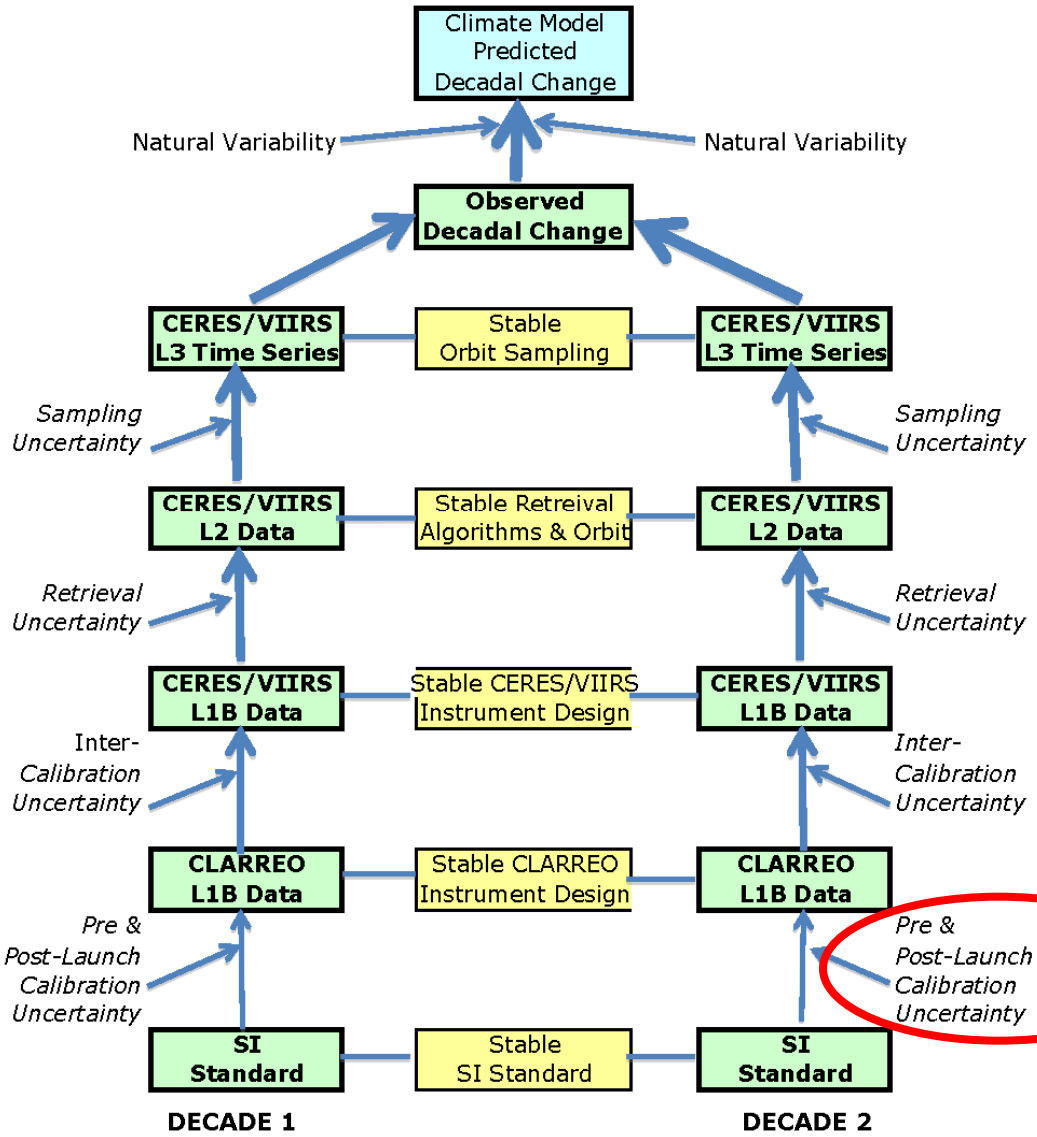

On-Orbit CLARREO Calibration Uncertainty

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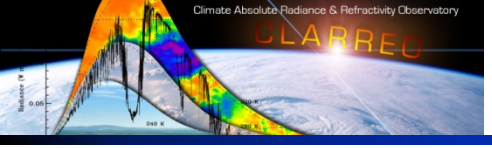

CLARREO Calibration to SI Standards

- **Calibration Characterization at climate accuracy and time scales**
  - Pre-launch characterization, testing, and calibration
    - Instrument builder site
    - Independent site calibration
    - SI traceable transfer radiometers, sources (e.g. NIST SIRCUS system)
  - Spacecraft Integration testing and calibration (vacuum chamber)
  - In orbit characterization, testing, and calibration
    - On orbit sources, verification of source accuracy
    - Earth viewing, solar, lunar & calibration operations schedules
    - Aircraft instrument under-flights
    - Future absolute calibration of the moon using high altitude balloon (30km) would provide an additional verification (5, 10, or even 20 yrs from now)
    - Engineering unit or instrument spares for ground testing anomalies.

Traceability to SI Standards is key to decadal change accuracy

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