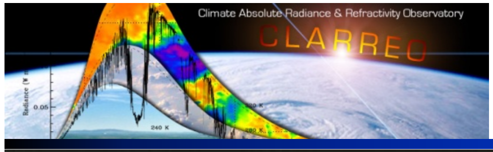
2. CLARREO: The Climate Calibration Mission

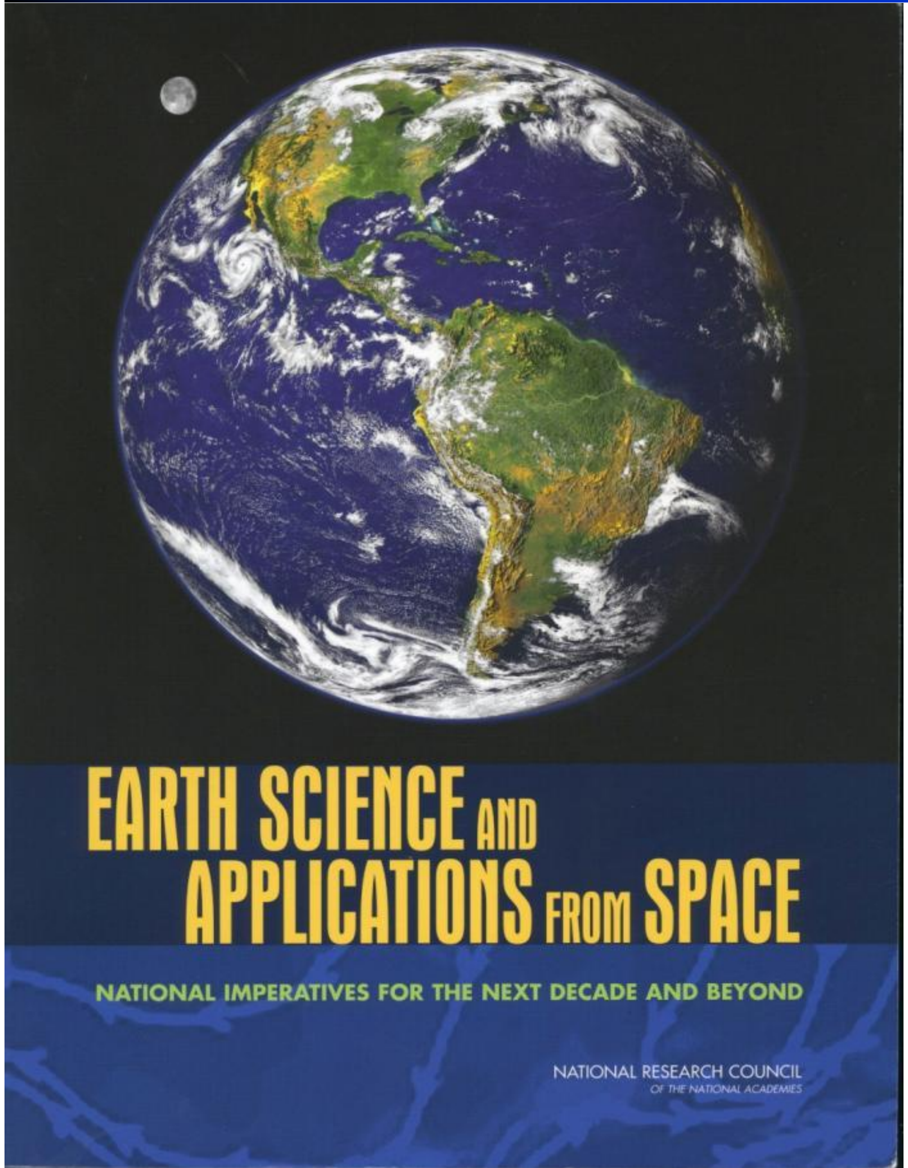
Bruce Wielicki, David Young, CLARREO Science Team

Climate Absolute Radiance & Refractivity Observatory

CEOS Working Group on Calibration and Validation
March 2-5, 2010



Decadal Survey defines CLARREO



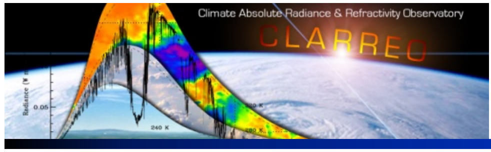
NOAA CLARREO

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

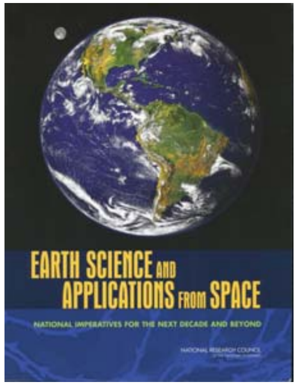
NASA CLARREO

- **Solar reflected spectra (SI traceable accuracy of 0.3% 2σ)**
- **Infrared emitted spectra (SI traceable accuracy of 0.1K 3σ)**
- **Global Navigational Satellite System Radio Occultation (SI traceable accuracy of 0.1K 3σ)**
- **Three 90-degree polar orbits with IR/GPS on all 3, solar on 1.**

CLARREO is a Cornerstone of the Climate Observing System



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)

A Mission with Decadal Change Accuracy Traceable to SI Standards

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 NPL/Imp Coll.	International	TRUTHS RS SI traceability/GERB/IR interferometers

A diverse "best in class" science team to set requirements

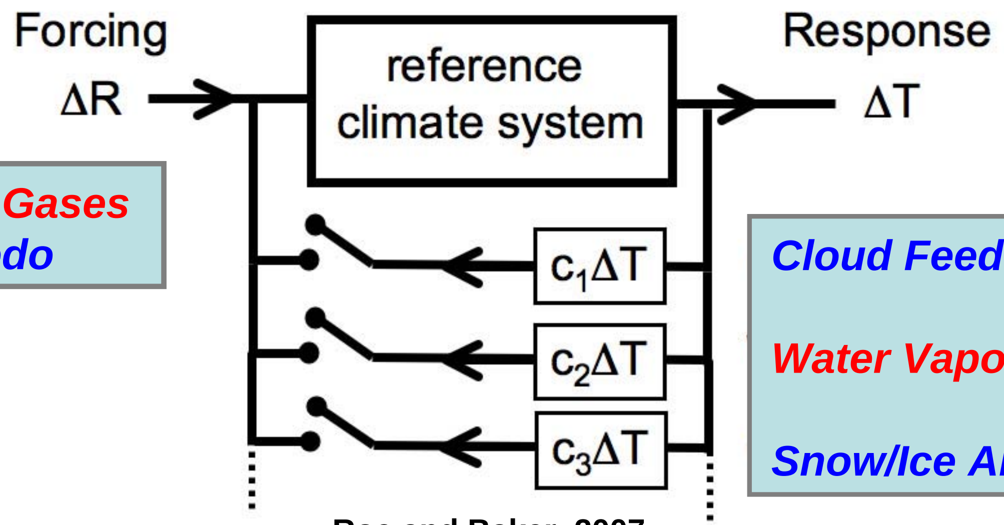
CLARREO Science Value
ClimateForcing, Response, Feedback

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

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

Earth's Climate

-Greenhouse Gases
-Surface Albedo



Roe and Baker, 2007

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

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

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:

  $F_a = (1 + \Sigma f^2_i)^{1/2} - 1$, 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 variabilityso that in total, CLARREO degrades climate trend accuracy less than 20%.*

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

Accuracy of Decadal Change Trends Time to Detect Trends

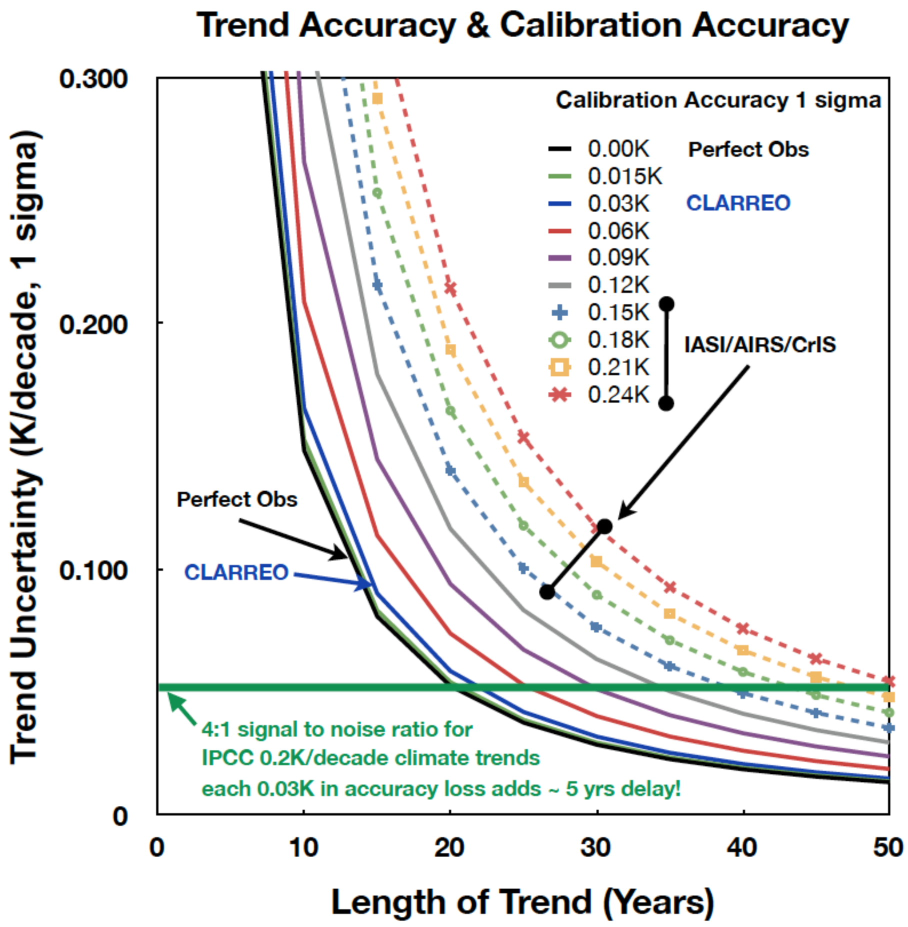
- The CLARREO requirement is for climate change trend accuracy to be within 20% of a perfect observing system, and time to detect trends to be within 15%. To reach this goal, individual error sources must provide accuracy within 10 to 15% of a perfect observing system (e.g. orbit sampling, calibration).

- 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%

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

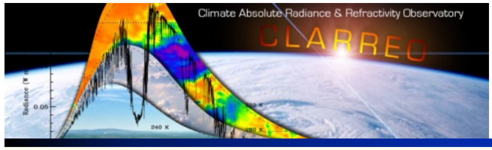


Global average temperature trend results include all major error sources: natural variability, calibration error, orbit sampling (2 satellites), instrument noise. Results for Reflected Solar trends are similar.

- 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.*

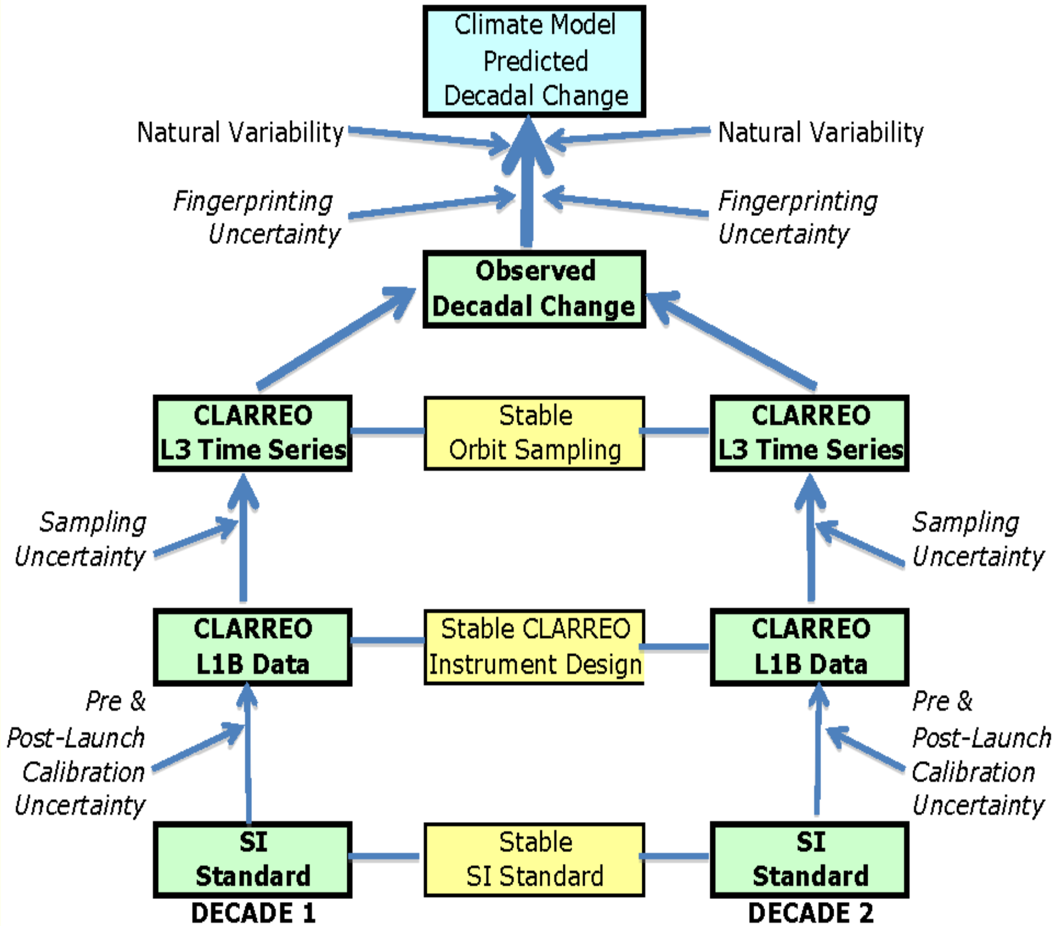
Climate Change Accuracy is Critical to Making Difficult Policy Decisions



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

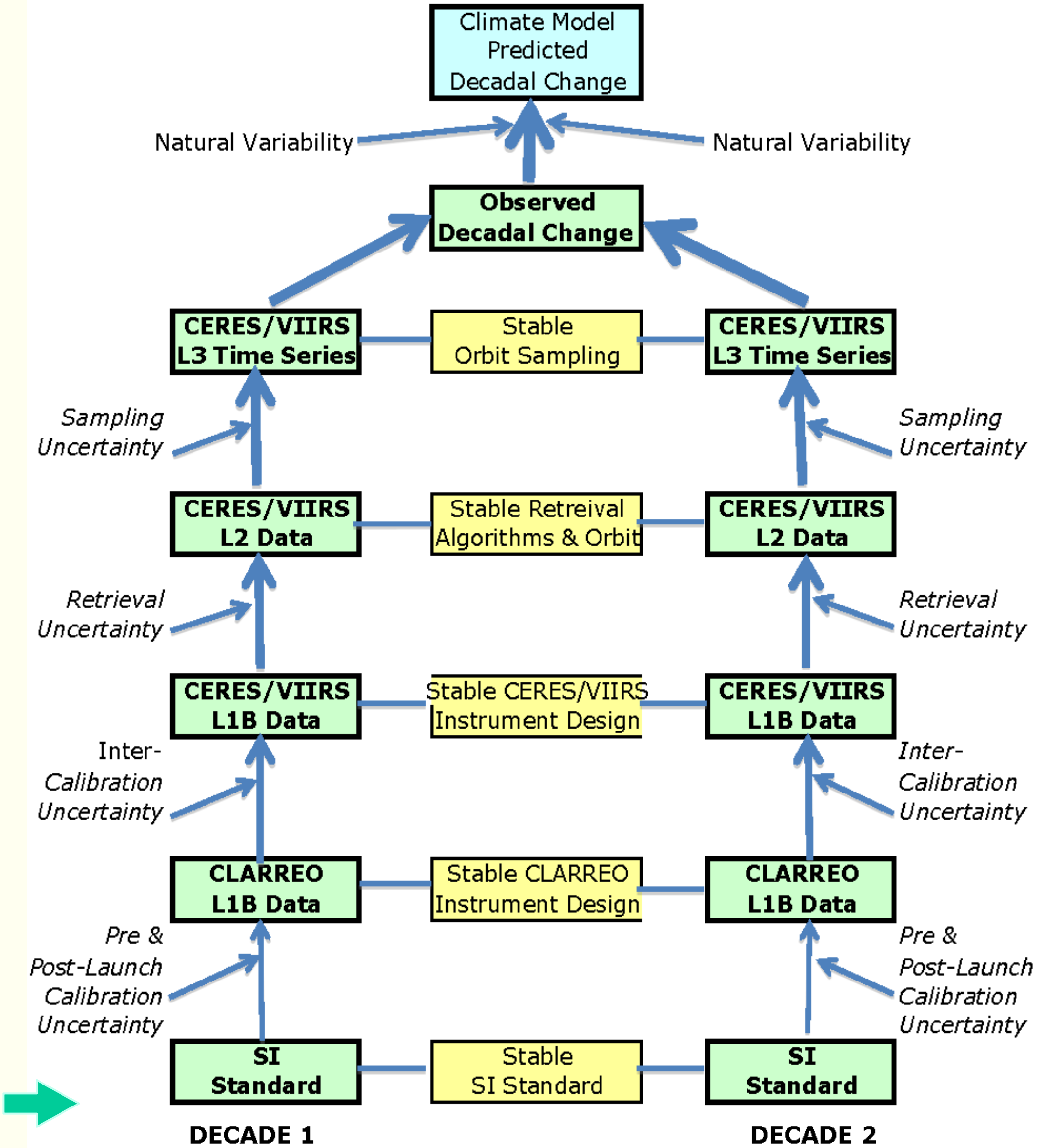


Traceable uncertainties from decadal change observations to SI standards, *at decadal change accuracy*

Tracing CLARREO Decadal Change Science Objectives to Mission Requirements

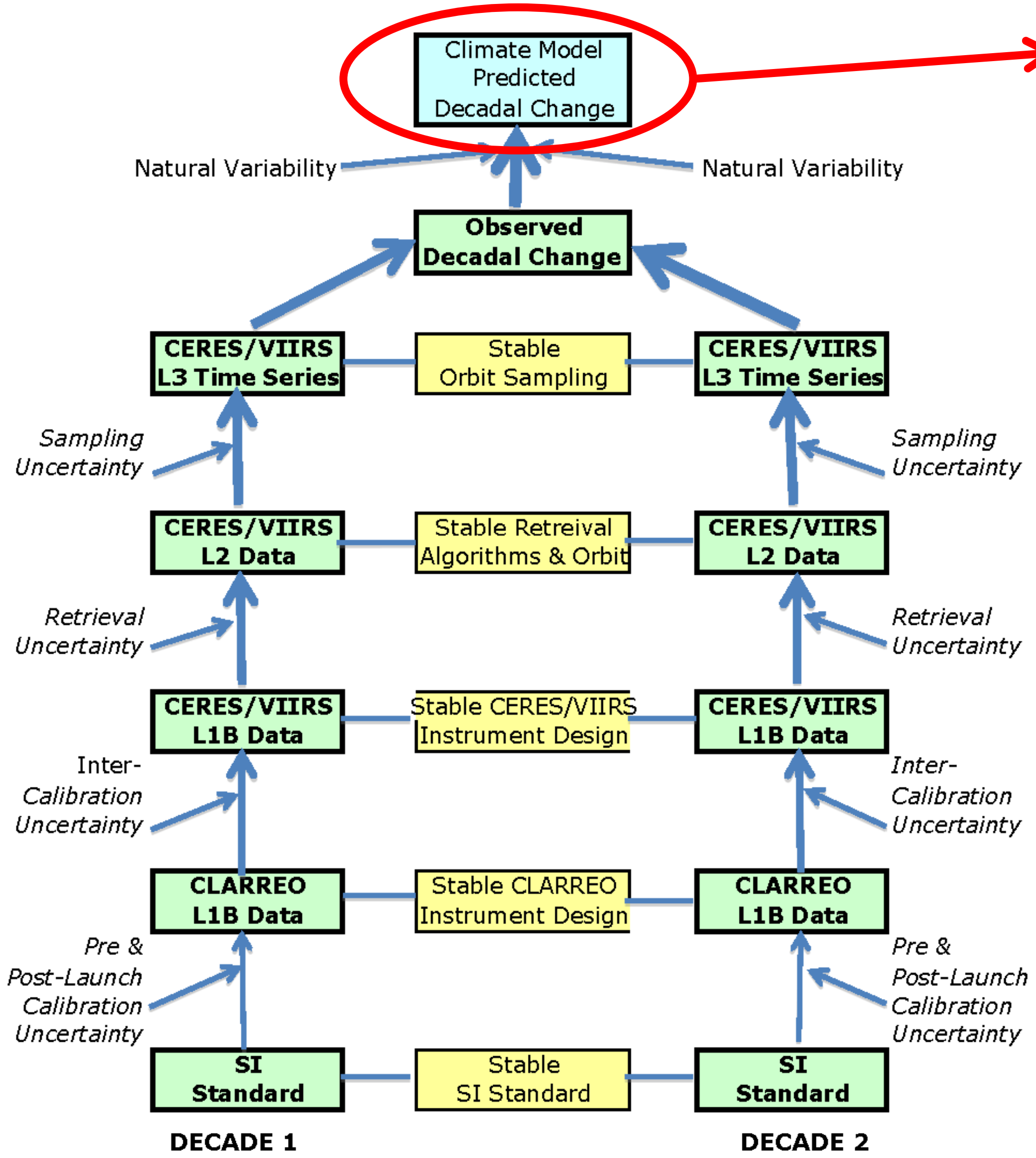
- Climate Model Decadal Prediction
- Tested against CLARREO decadal change observations
- CLARREO record length set to overcome noise from natural variability
- CLARREO sampling set to reduce error to < 1/3 natural variability
- Verify stability of retrieval algorithms for climate variables and for fingerprinting 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

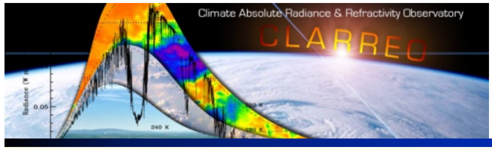
Example of Observing Decadal Change Through Calibration to CLARREO Reference



Climate Model Observing System Simulation Experiments (OSSEs):

- Information Content, Spectral Coverage, Spectral Resolution

- Accuracy of Spectral Fingerprinting Methods



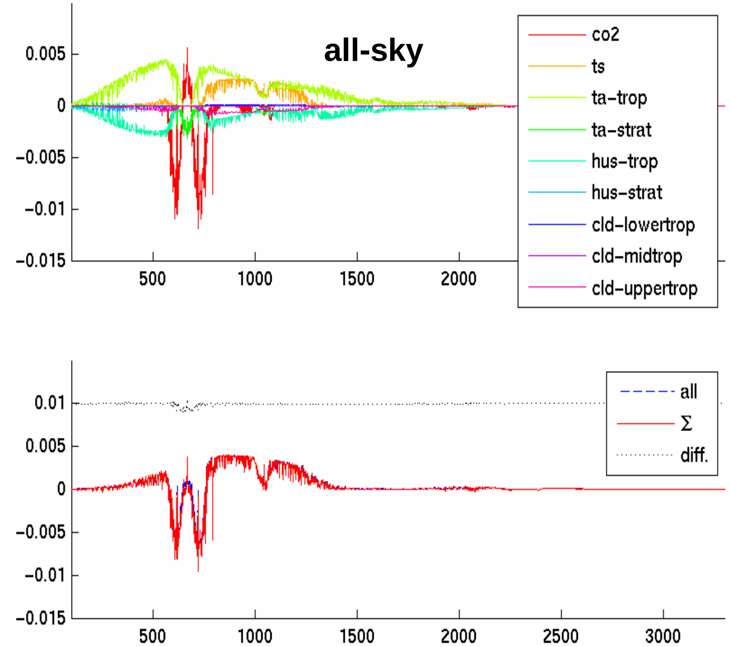
Climate OSSEs-
Observing System Simulation Experiments

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

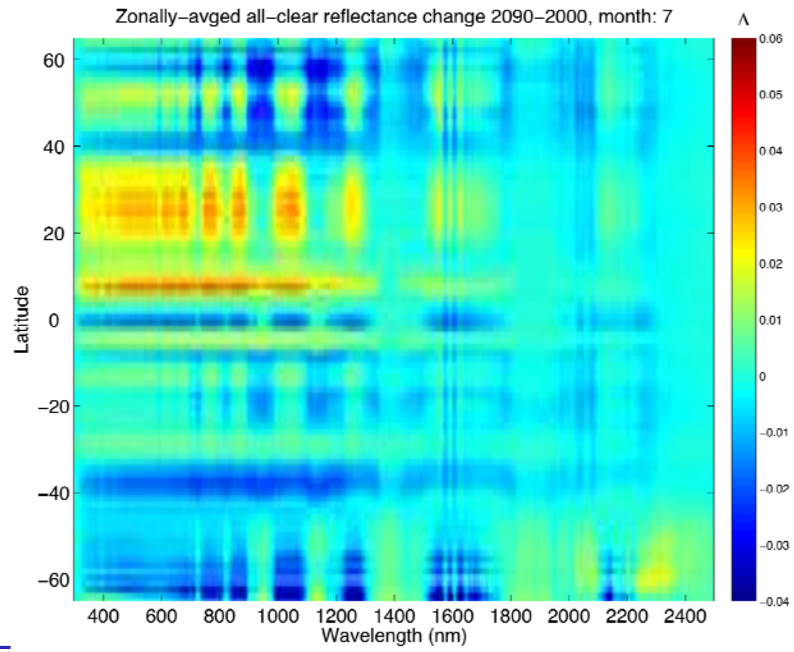
OSSEs were begun with 3 modeling groups (GISS, GFDL, U-Cal Berkeley) to determine measurement requirements

Studies include climate change fingerprinting methods using time/space averaged spectral data to define spectral resolution (IR 1 cm^{-1}, RS 10 nm) and spectral coverage (IR 200 to 2000 cm^{-1}, RS 320 to 2300 nm).

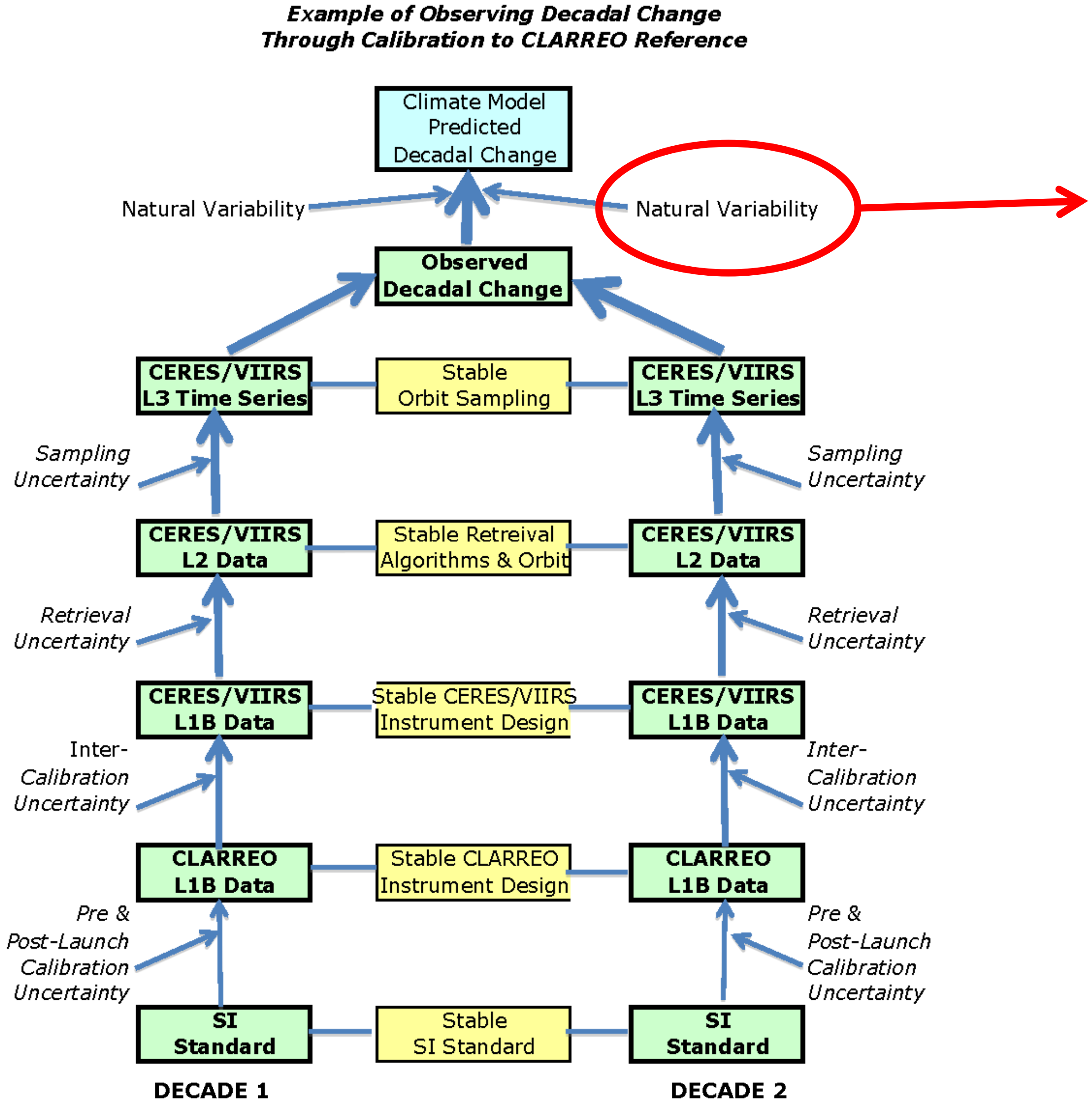
- Studies by GFDL/ Harvard demonstrate the linearity of all-sky decadal change IR signals
- Eliminates the requirement for global clear-sky observations (Huang and Leroy, 2009)



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)



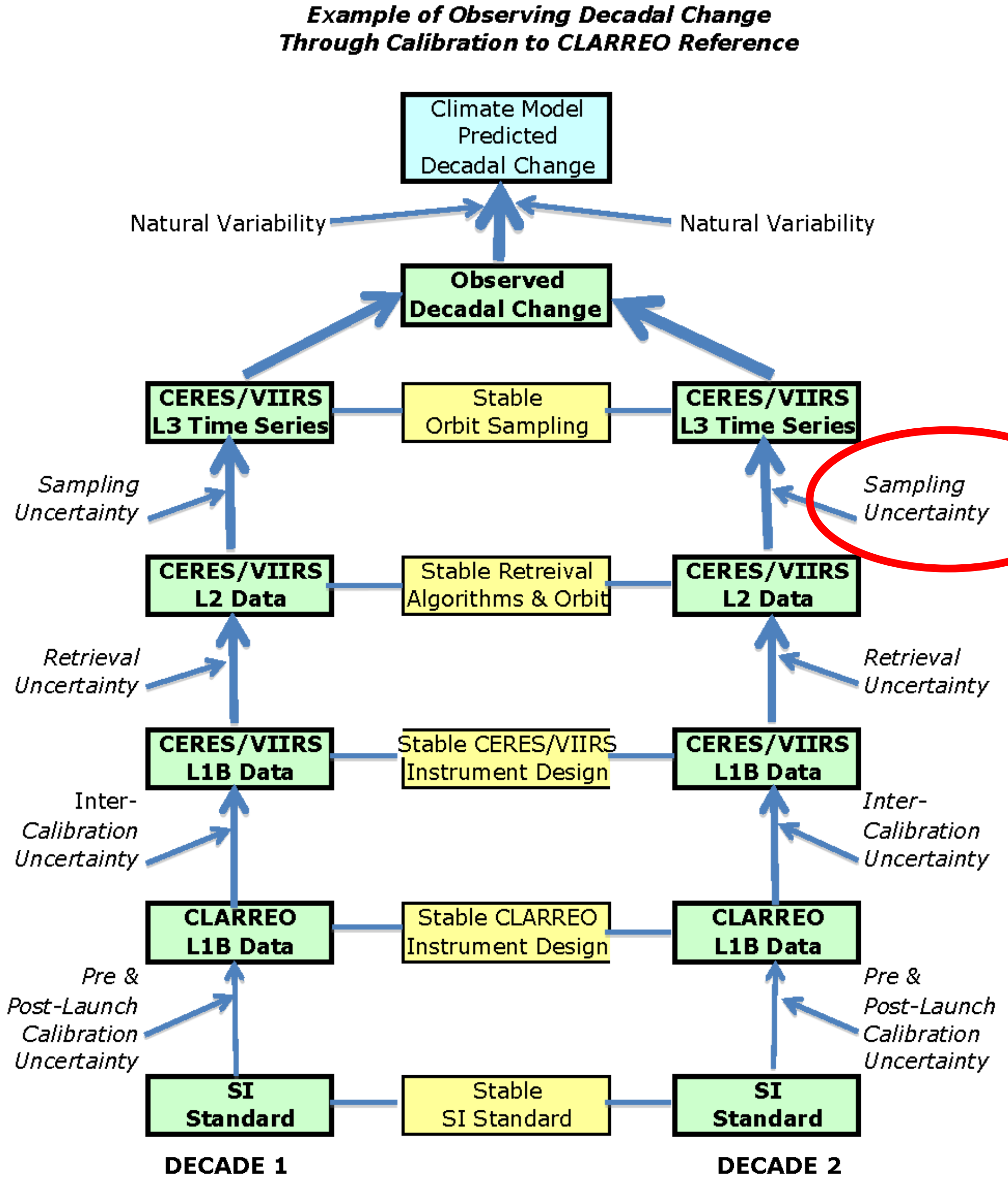
Tracing CLARREO Decadal Change Science Objectives to Mission Requirements



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.

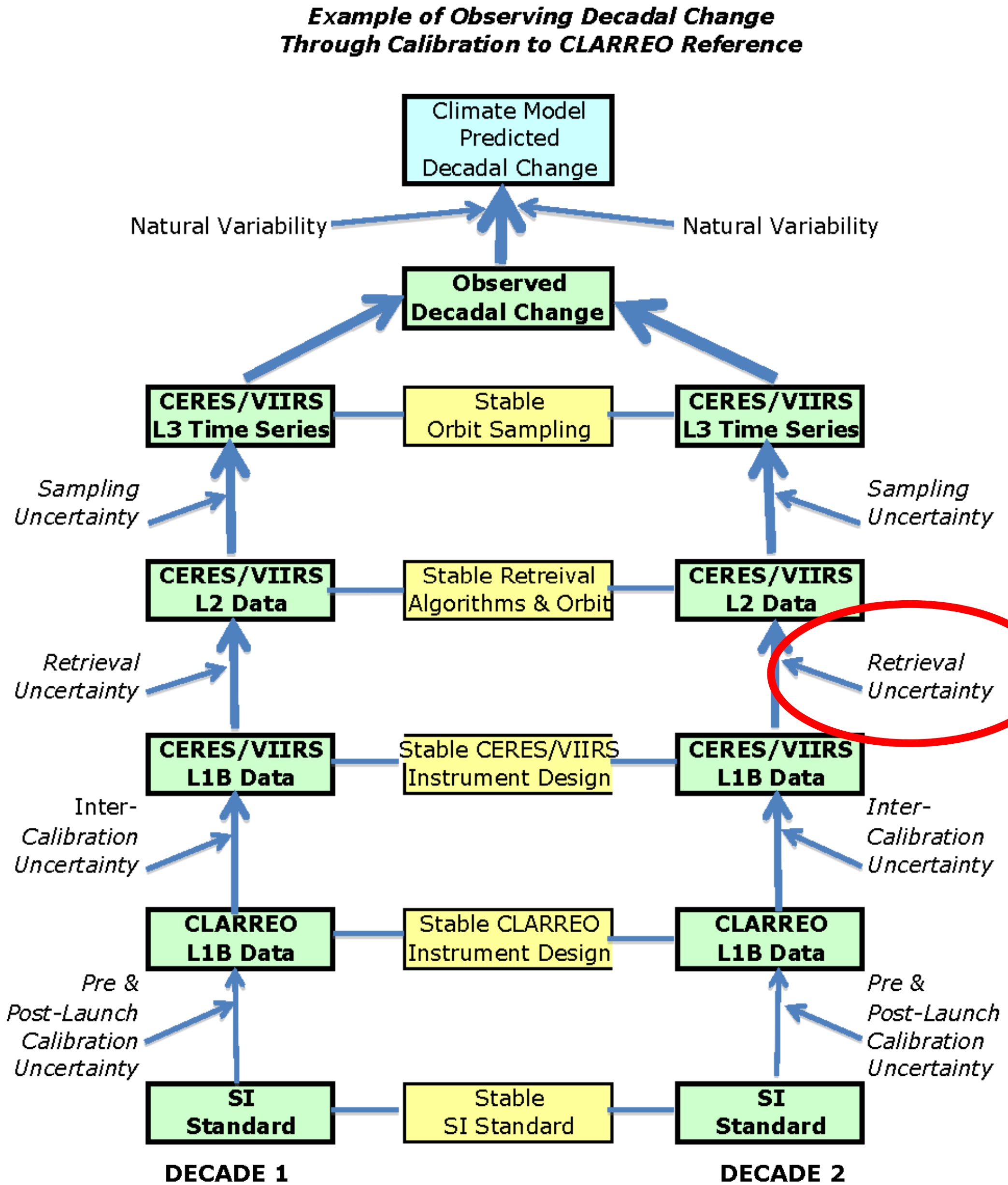
Tracing CLARREO Decadal Change Science Objectives to Mission Requirements



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

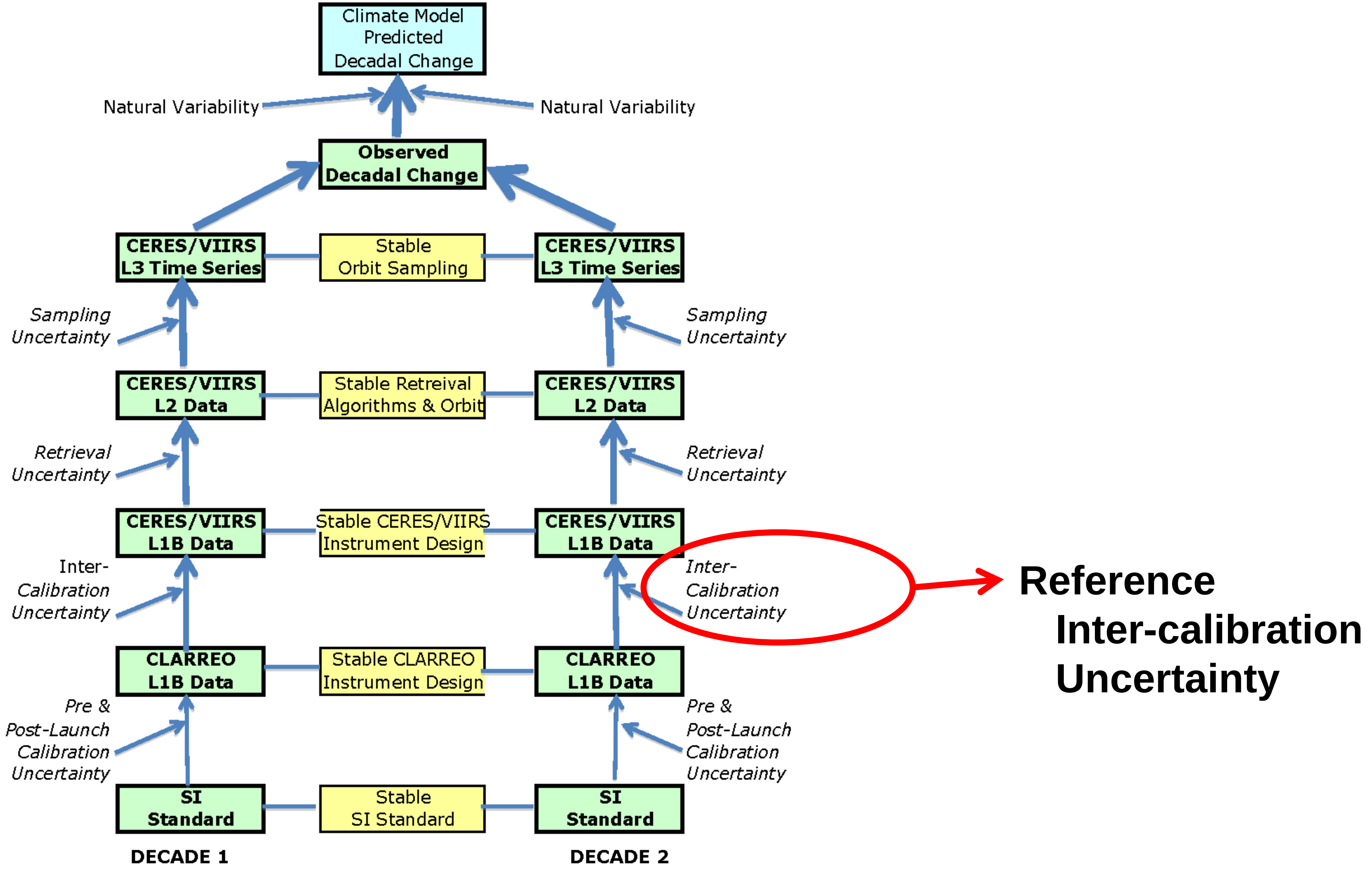
Tracing CLARREO Decadal Change Science Objectives to Mission Requirements



Retrieval algorithms must maintain constant algorithms over decades

Tracing CLARREO Decadal Change Science Objectives to Mission Requirements

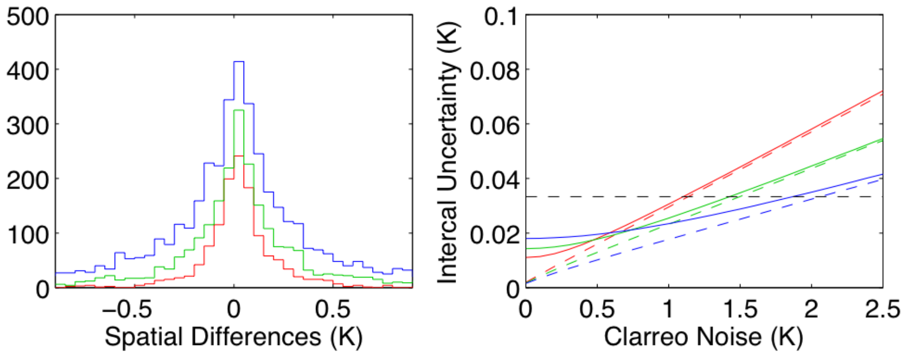
Example of Observing Decadal Change Through Calibration to CLARREO Reference



CLARREO Reference Inter-calibration Uncertainty: IR spectra

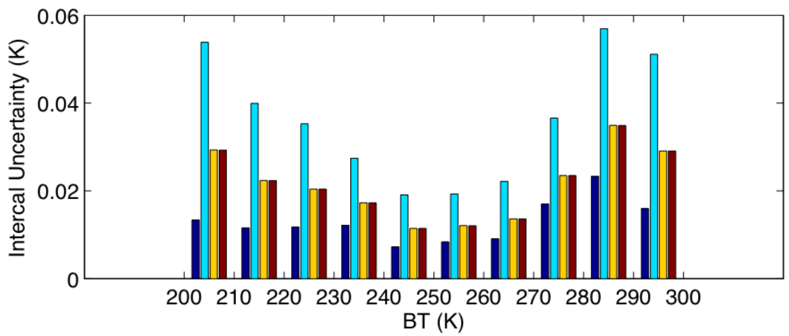
- Studies have answered outstanding questions concerning the accuracy of using CLARREO as a reference calibrator of operational IR sensors
- Nadir-only viewing provides sufficient sampling for IR intercalibration of gain, offset, and response nonlinearities.
- Sampling time and FOV will determine integration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



Holz et al., 2009

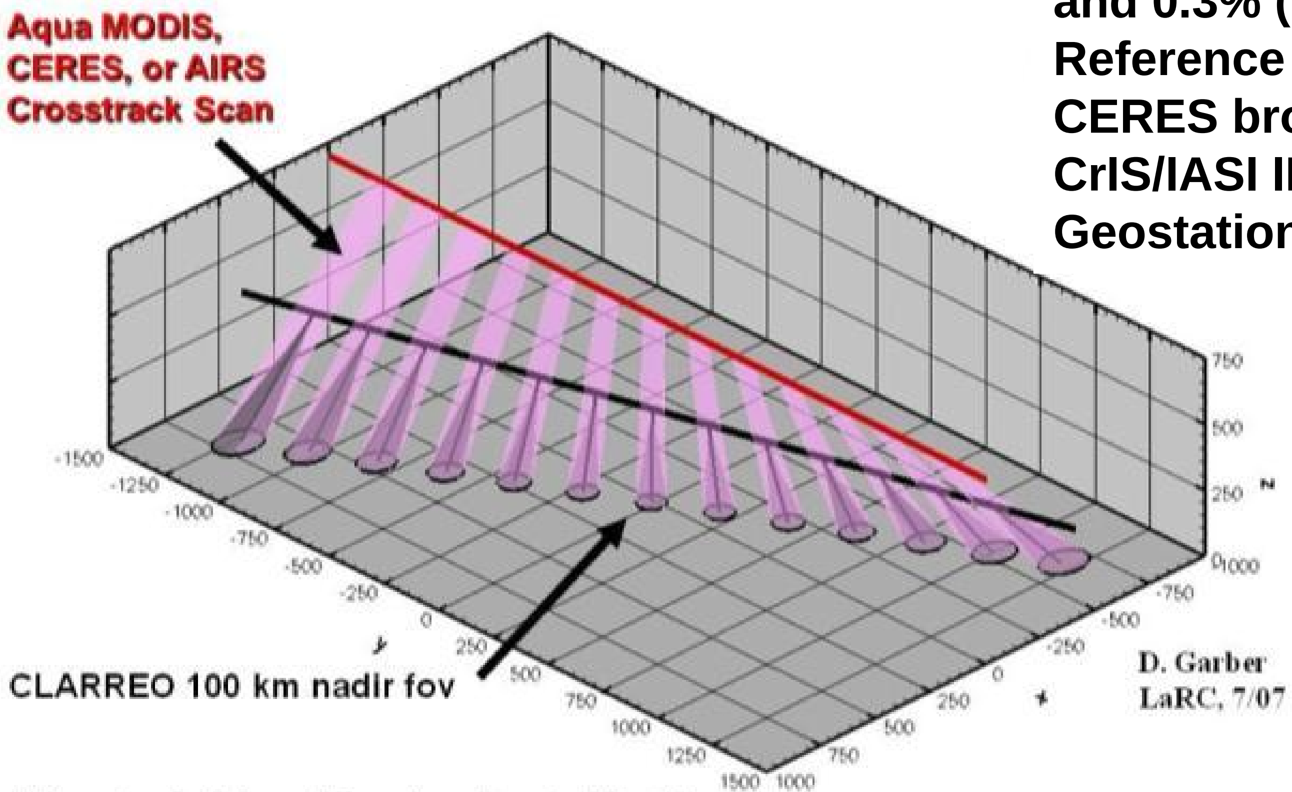
CLARREO Reference Inter-calibration Uncertainty: RS spectra

- Studies conducted by LaRC and GSFC have determined the ability 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% (2 sigma)
- 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

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

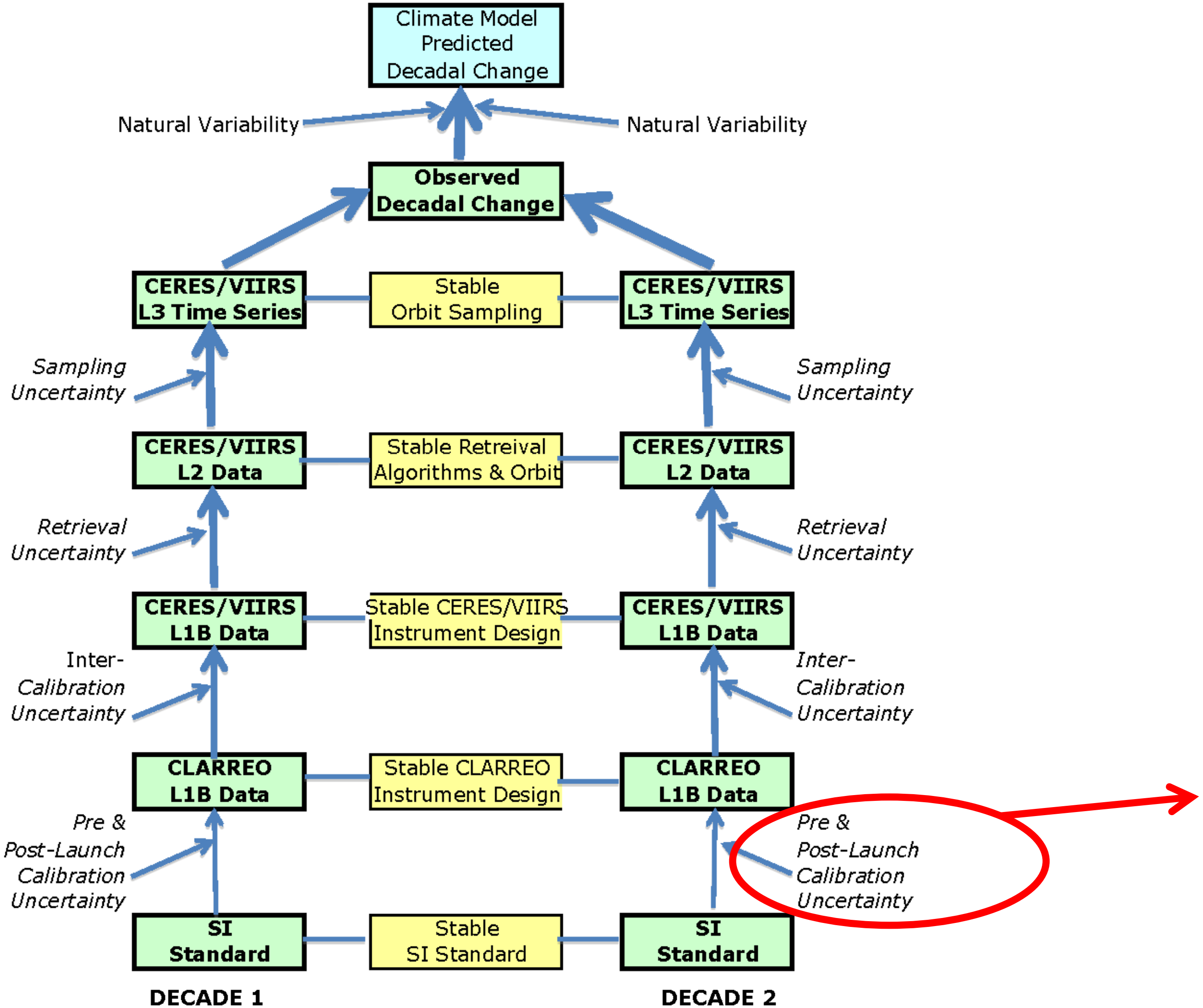
Spatial Matching to 20km scale
Time matching to 5 minutes
Angle matching to 1 degree:
Required for 0.1K 3 sigma IR
and 0.3% (2 sigma) Solar Reflected
Reference Intercalibration:
CERES broadband, VIIRS imager
CrIS/IASI IR interferometers,
Geostationary imagers, sounders



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

Tracing CLARREO Decadal Change Science Objectives to Mission Requirements

Example of Observing Decadal Change Through Calibration to CLARREO Reference



On-Orbit CLARREO Calibration Uncertainty

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 (3-sigma) for the IR spectra absolute accuracy required. Driven by natural variability of IR spectra.*
- *0.3% (2-sigma) 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% (2-sigma) refractivity, consistent with an accuracy of 0.1K (3-sigma) 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

CLARREO Calibration to SI Standards

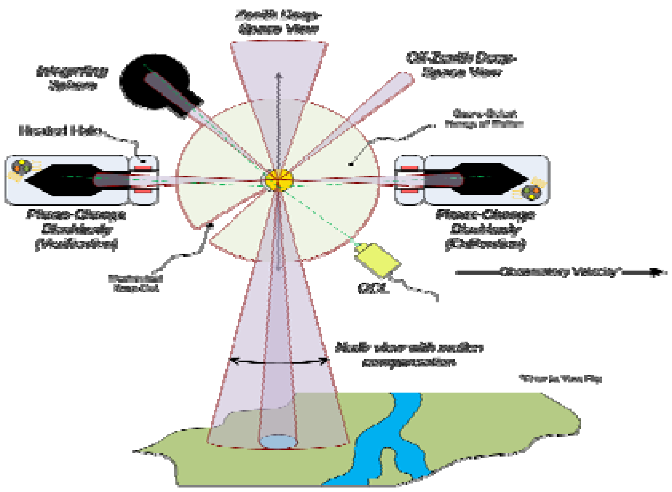
- Challenge
  - Rigorous determination of the time-dependent bias (i.e., stability of the observational record) is critical to creating trusted climate records. (Ref. ASIC[3] report)
  - On-orbit sensors generally degrade over time. Independent of a very stable calibration source, this bias is difficult to detect and correct for.
- Solution – SI traceable on-orbit at climate change accuracy level

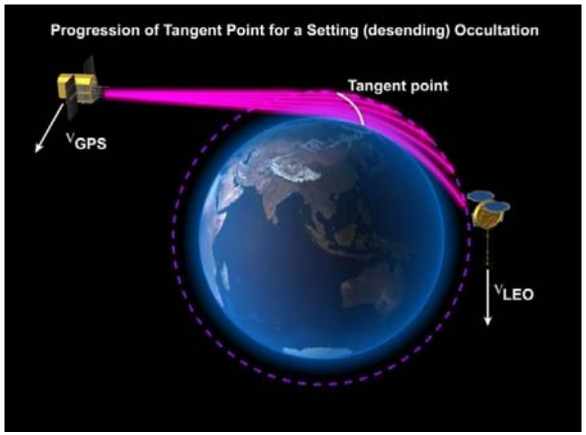
Infrared Interferometer

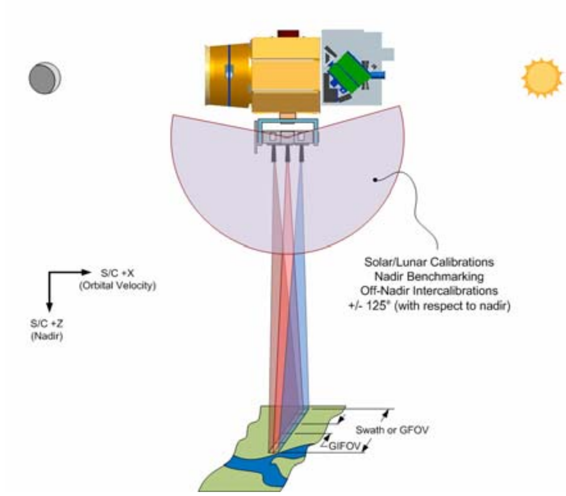
Source Based (Kelvin)

Reflected Solar Spectrometer

Solar, Lunar, TSIS based (Sun, SI Watt)

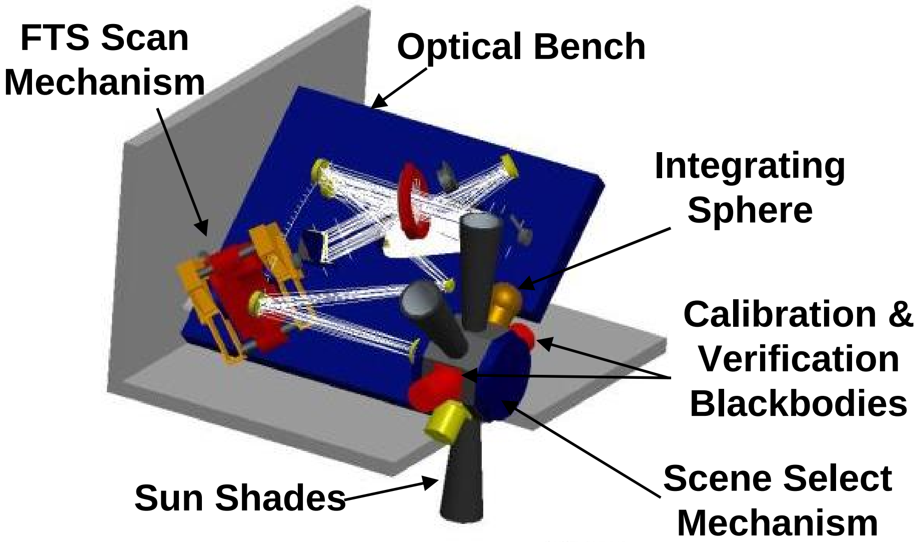


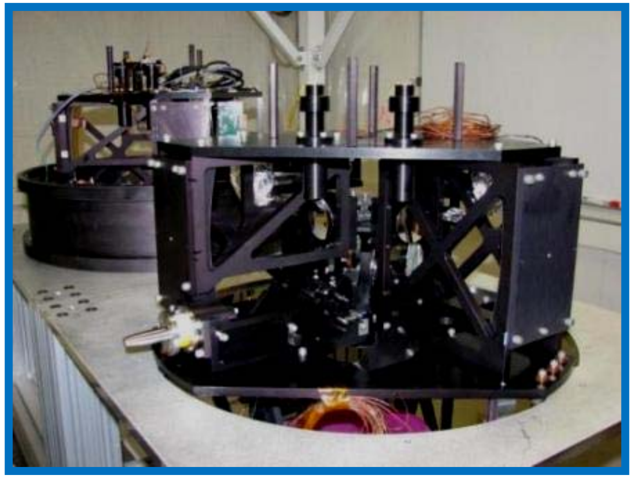


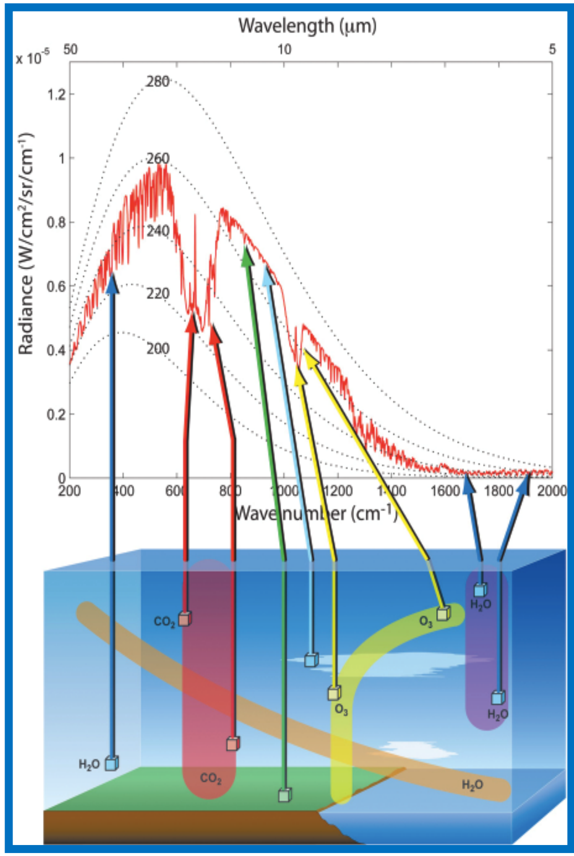


GNSS-RO: Refractivity (SI second)

Infrared Instrument Suite





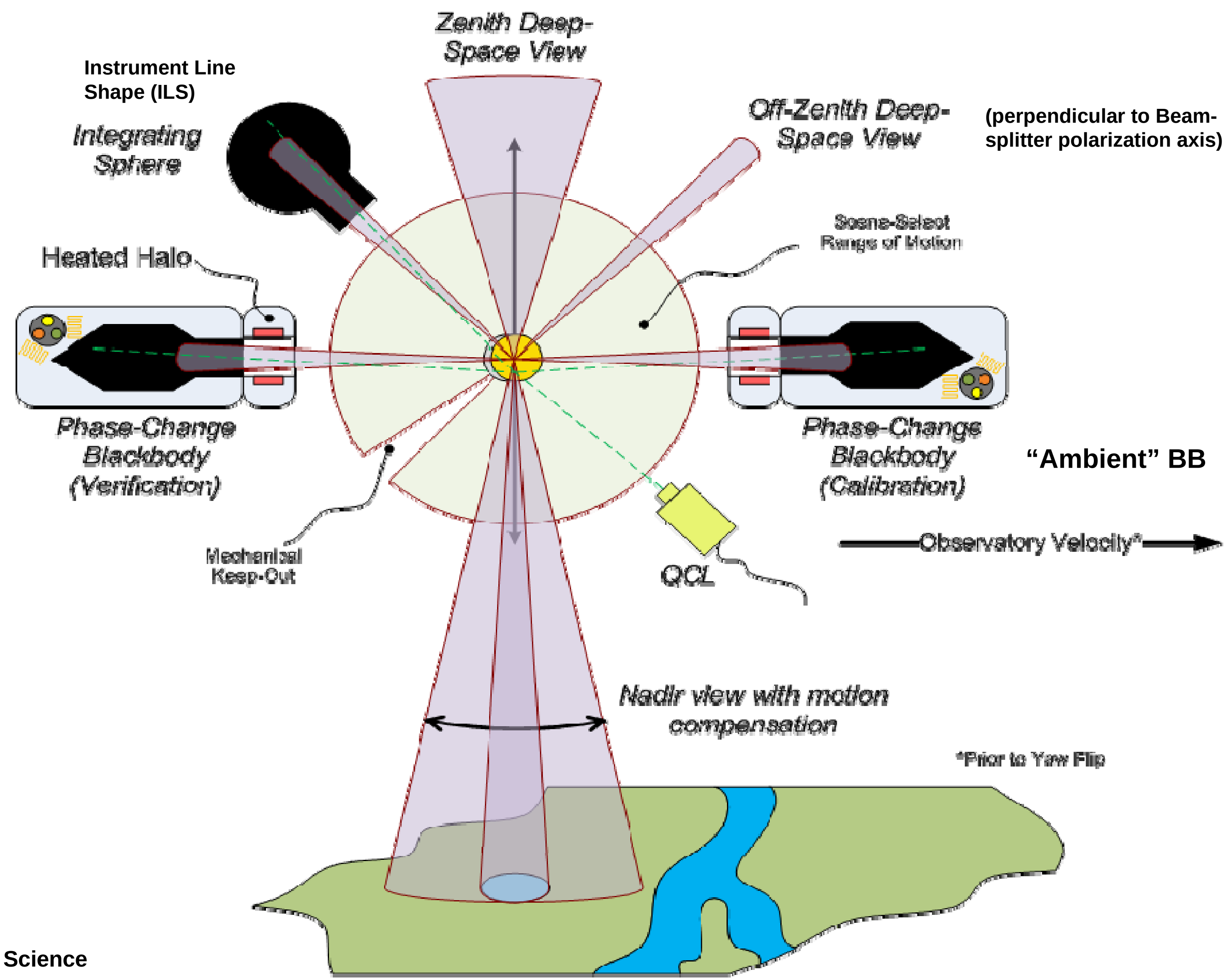


Courtesy of J. Anderson Harvard University

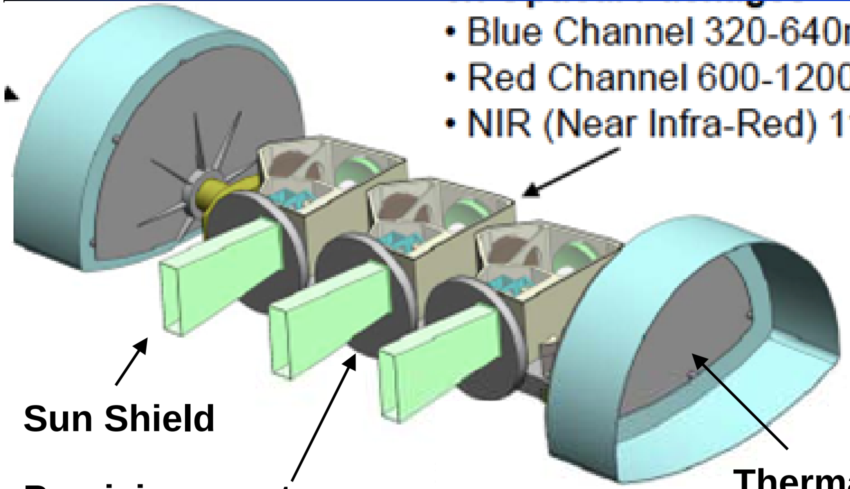
- 200-2000 cm^{-1}, 0.5 cm^{-1}unapodized resolution
- Mass: 87 kg, Power: 210 W
- Dimension: 42x65x70 cm^3
- Data Rate: 220 kb/sec
- IFOV: 25 km footprint (nadir only)

SI Traceable Accuracy 0.1K (3σ) all Earth Scene Temps (200 to 300K)

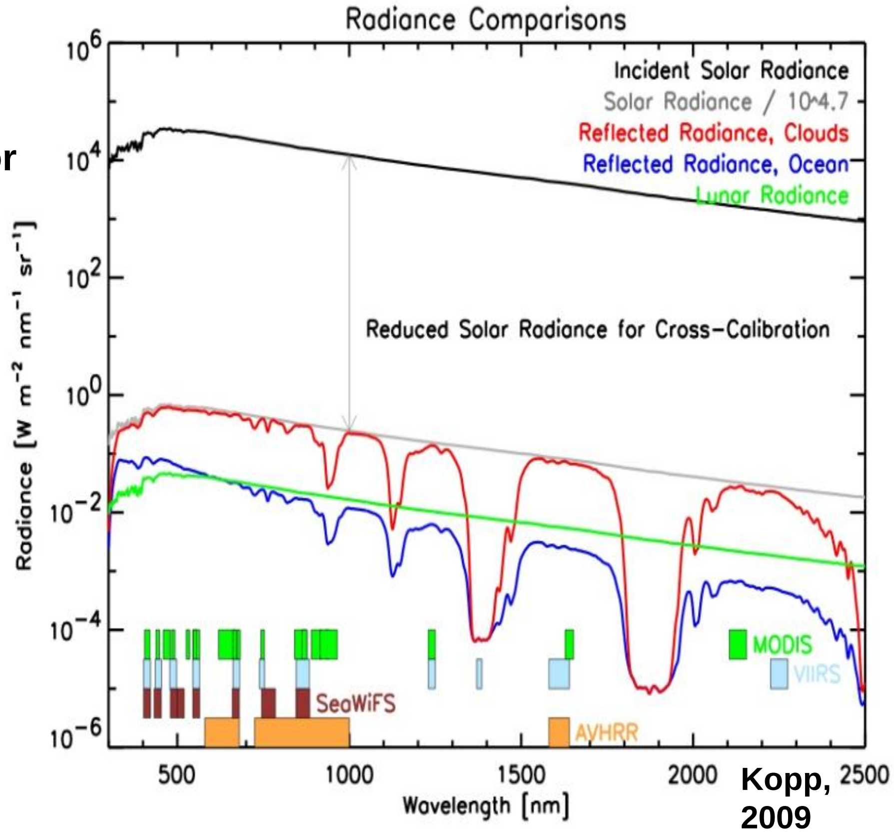
Calibration is the foundation of CLARREO



Reflected Solar Instrument Suite



Polarization sensitivity less than 0.25%
Spectral Resolution 8nm, Sampling 4nm below 1000nm, 16nm resolution > 1000 nm

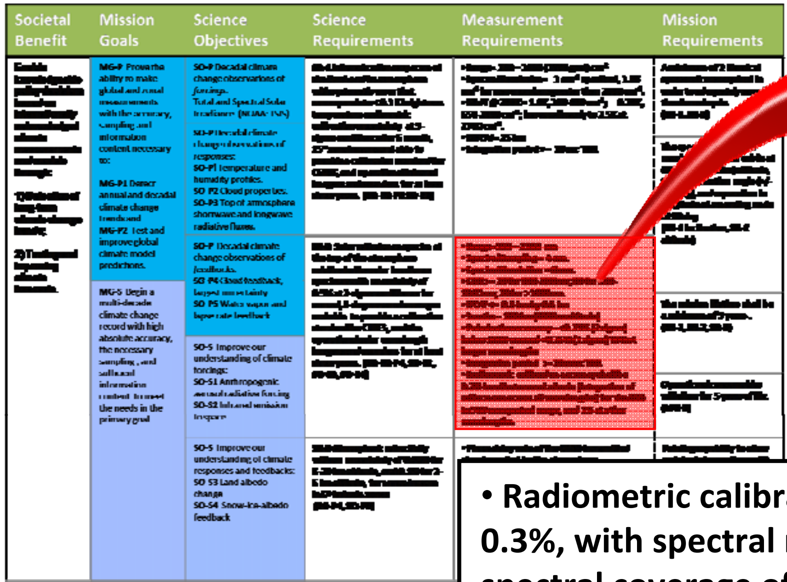


Kopp, 2009

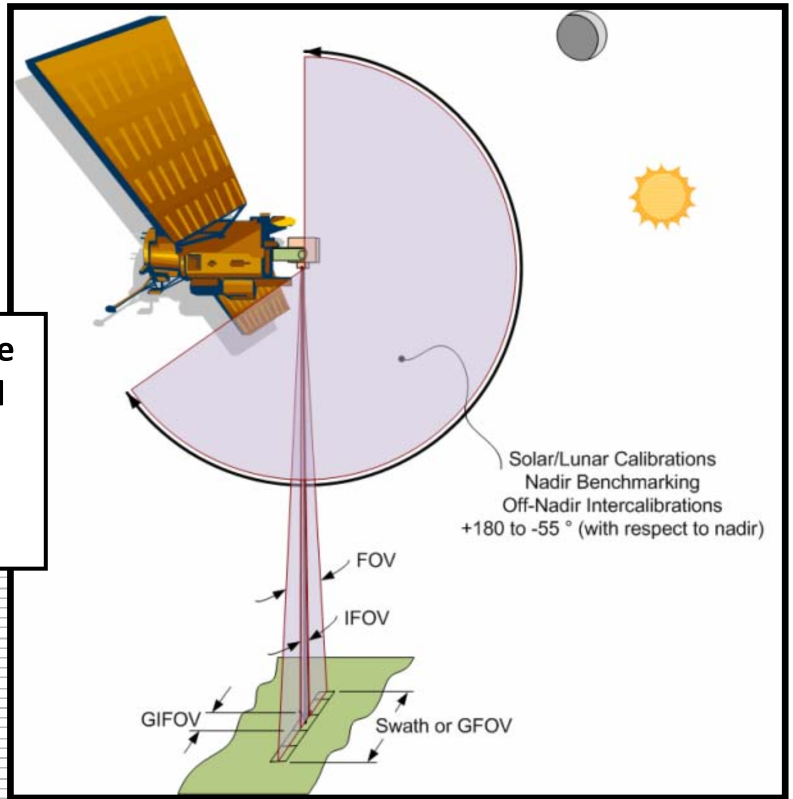
- **Mass** — **64 kg CBE**
- **Power** — **94 W CBE**
- **Data Rate** — **11 Mbps**
- **Spatial swath** — **0.5km IFOV, 100km**
- **Nadir for spectral benchmarking**
- **Gimbal pointing for lunar/solar calibration & Reference Intercalibration**

SI Traceable Accuracy 0.3% (2σ) in Earth Spectral Reflectance

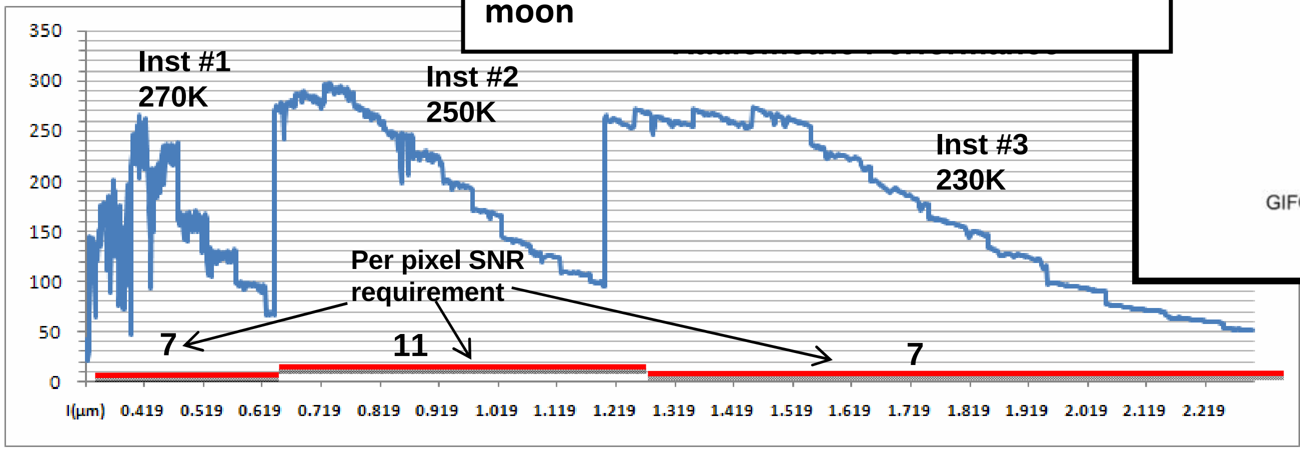
Measurement Requirements: Reflected Solar



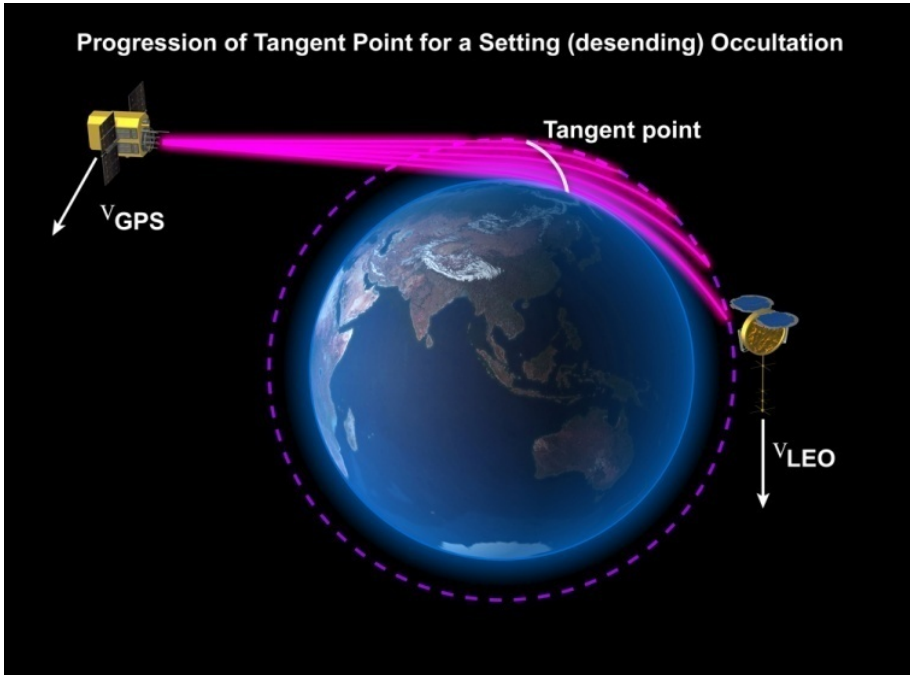
Reflected Solar



- Radiometric calibration accuracy shall be 0.3%, with spectral resolution of 8nm and spectral coverage of 320 to 2300 nm
- Calibration in orbit against the sun and moon



GNSS Radio Occultation Measurements

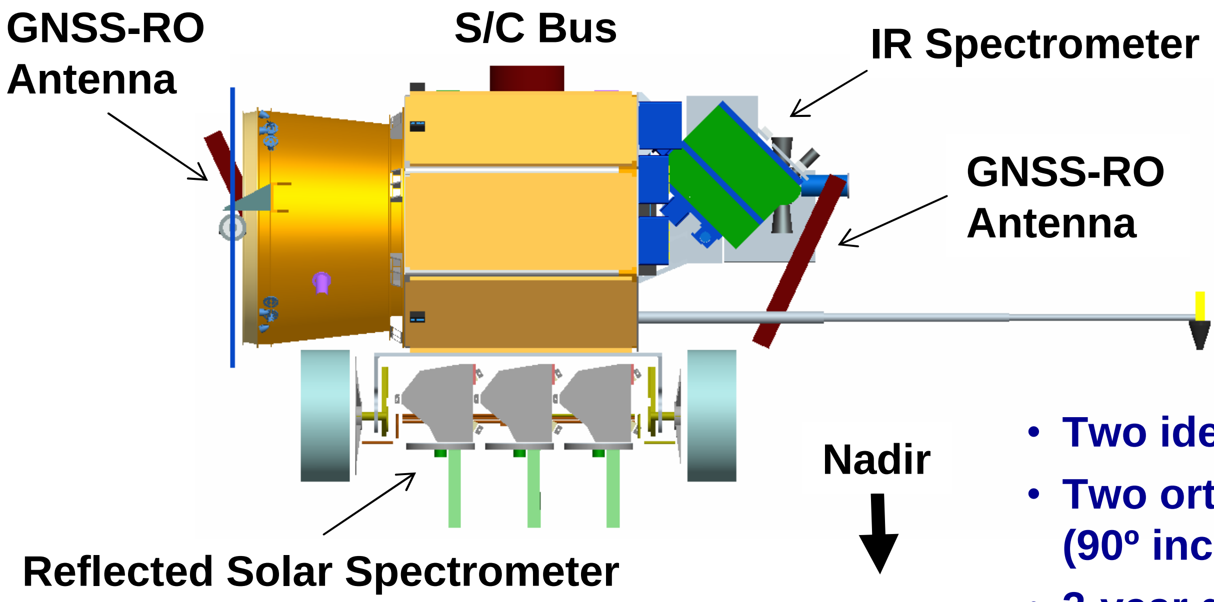


- **Mass 17 kg**
- **Power 32 W**
- **Data Rate: 117 kbps**
- **Volume:**
  - **Receiver: 19x12x23 cm^3**
  - **RO Antenna: 48x87x2 cm^3**
  - **POD Antenna: 30 cm dia. x 4 cm**

- **Radio occultation of GNSS signals used to derive atmospheric refractivity**
- **Accuracy is attained through a direct link to the SI standard of time**
- **Provides critical information on temperature, pressure, and humidity profiles to address temperature lapse rate feedbacks, temperature response, and remove ambiguities in IR all-sky spectra optimal fingerprinting**

SI Traceable Accuracy in Refractivity Equivalent to 0.1K (3σ)

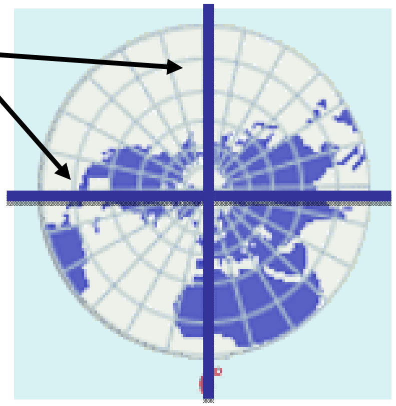
CLARREO Mission Concept



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.



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 “NIST in Orbit”.
- 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.

Backups: CLARREO IMR Science 1/29/10

CLARREO's Unique Role in Testing Climate Models

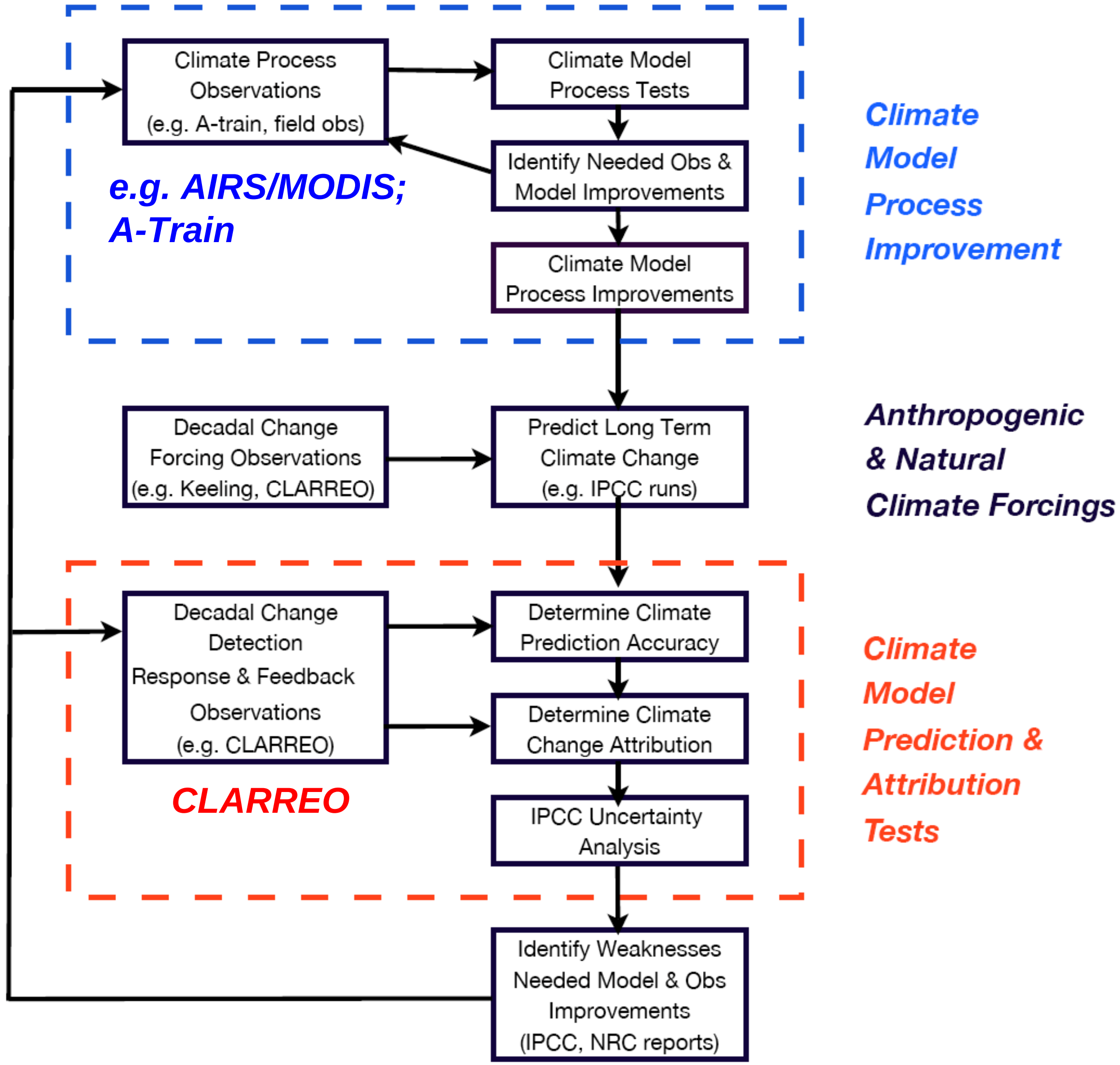
Climate Models are the scientific hypothesis for how the world works.

Most satellite missions attack individual processes in a climate model: Aerosols, Ice, CO_2, Clouds…. Divide and conquer.

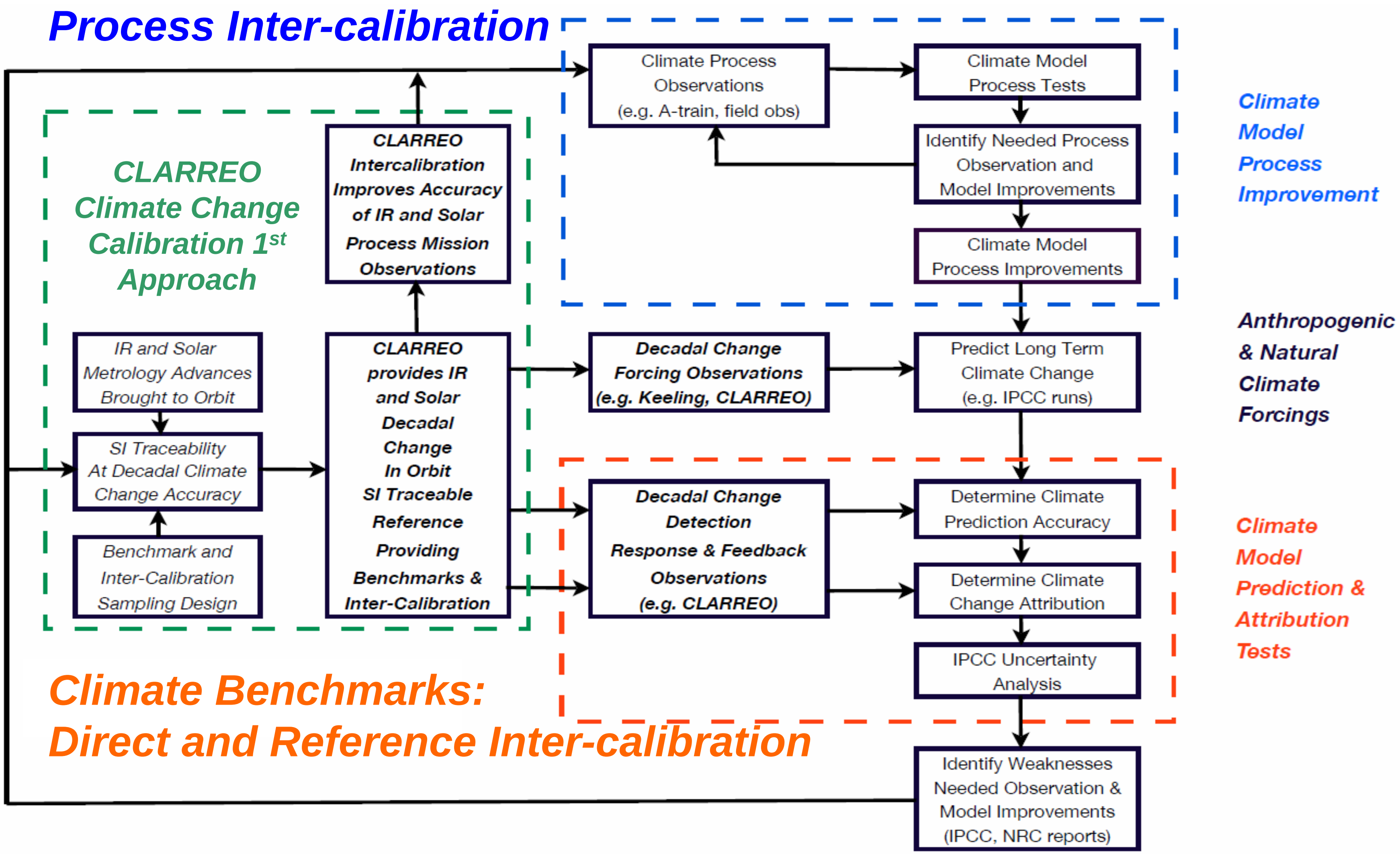
CLARREO verifies the integrated climate model decadal change prediction with crosscutting S.I traceable calibration, IR spectra, solar reflected spectra, GPS… Integrate and test.

From CLARREO Science Questions Document, October 9, 2008

The Role of Observations in Testing and Improving Climate Models, Climate Change Detection, and Attribution



CLARREO and Climate Science



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

CLARREO Threshold Mission

- Reduce from 2 spacecraft to 1.

- Orbit remains 90 degree inclination polar orbit

- Reductions in mission science value:
  - Reduced decadal trend accuracy: larger sampling errors.
  - Eliminates seasonal cycle benchmarks (6 month mean required to sample full diurnal cycle with only 1 satellite).
  - Eliminates verification of consistent trends from CLARREO instruments on two different platforms: reduced confidence
  - Reduces mission reliability and likelihood to reach 3 to 5yr lifetime.
  - Overall science value reduced by ~ 35%, versus cost reduction of ~ 15%.

- Maintain additional instrument copies to allow future flights of opportunity.

Science Next Steps: Phase A

- IR climate model OSSEs: further improvements of IR fingerprinting accuracy for cloud feedback, further orbit sampling studies.
- RS climate model OSSEs: further examination of RS fingerprinting accuracy for cloud feedback and surface albedo feedback, further orbit sampling studies.
- Extend polarization dependence models using more extensive PARASOL data set.
- Examine potential for improved accuracy of radio occultation below 5 km altitude and above 20km altitude.
- Verify stability of retrieval algorithm biases for decadal change
- Continue increasing the accuracy of reference intercalibration simulations using current observations.

CLARREO Level 1 Requirements
Science goals and objectives

- **2.1 Mission Goals and Science Objectives**

  The CLARREO mission addresses the need to rigorously observe climate change over decadal time scales and to use decadal change observations as the most critical method to determine the accuracy of climate change projections such as those in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Climate predictions verified against decadal change observations with rigorously known accuracy are critical in order to enable sound policy decisions.

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

3.1.1 Baseline Science Requirements

[CL.PRJ.1.REQ.3000] **Accurate and Traceable** Observations shall be made with verifiable on-orbit accuracy sufficient to resolve decadal change and to survive gaps in data sets of similar types of observations, and traceable to SI standards for knowledge of uncertainty and comparison with future measurements.

CLARREO Level 1 Requirements
Infrared Baseline Science Measurement

[CL.PRJ.1.REQ.3001] **Infrared Baseline Science Measurement** CLARREO shall obtain infrared radiance spectra of the Earth and its atmosphere using nadir views from orbiting satellites. The benchmark and reference intercalibration measurements require:

a Broad spectral coverage of the earth emitted spectrum, including the Far-Infrared, that captures climate trend information about atmospheric structure, composition, clouds, and surface properties;

b Spectral resolution chosen for greenhouse gas species separation and for vertical structure information;

c Radiance measurement systematic error that corresponds to < 0.1 K brightness temperature radiometric calibration uncertainty (3-σ confidence, excluding random noise) for the range of expected earth scene temperatures and wavelengths relevant to climate;

d Spatial and temporal sampling sufficient to provide global coverage and reduce sampling errors to levels that degrade the measured climate trend accuracy by less than 15%, and that degrade the time to detect climate trends less than 10%. The degradation of trend accuracy is relative to the limits of accuracy caused by climate natural variability.

CLARREO Level 1 Requirements
Reflected Solar Baseline Science Measurement

[CL.PRJ.1.REQ.3002] **Reflected Solar Baseline Science Measurement** CLARREO shall obtain the solar spectral nadir reflectance of the Earth and its atmosphere relative to the solar irradiance spectrum. The benchmark and reference intercalibration measurements require:

a Broad spectral coverage of the earth shortwave reflected spectrum, that captures climate trend information about atmospheric structure, composition, clouds, and surface properties;

b Spectral resolution chosen to resolve atmospheric structure, composition, clouds, surface properties and to allow reference intercalibration of the solar reflected spectral bands of climate relevant operational sensors (VIIRS and CERES are currently identified. Final sensors TBR);

c Reflectance measurement with an absolute uncertainty of 0.3% relative to global mean reflected solar energy (2σ confidence excluding random noise) for the range of earth reflected solar energy at the wavelengths relevant to decadal climate change.

d Spatial and temporal sampling sufficient to provide global coverage and reduce sampling errors to levels that degrade the measured climate trend accuracy by less than 15%, and that degrade the time to detect climate trends less than 10%. The degradation of trend accuracy is relative to the limits of accuracy caused by climate natural variability.

Accurate, High Spectral Resolution RS Spectra Provide Critical Climate Change

CLARREO Level 1 Requirements Radio Occultation Science Measurement

[CL.PRJ.1.REQ.3003] **Atmospheric Refractivity Baseline Science Measurement** CLARREO shall obtain atmospheric refractivity from which can be determined climate trend information about atmospheric structure, composition, and clouds. The benchmark and reference intercalibration measurements require:

a Refractivity with an SI-traceable uncertainty of 0.03% for 5-20 km altitude

b Spatial and temporal sampling sufficient to provide global coverage and to reduce sampling biases for climatologically significant spatial and temporal averages: annual means in 10º latitude zones over all longitudes.

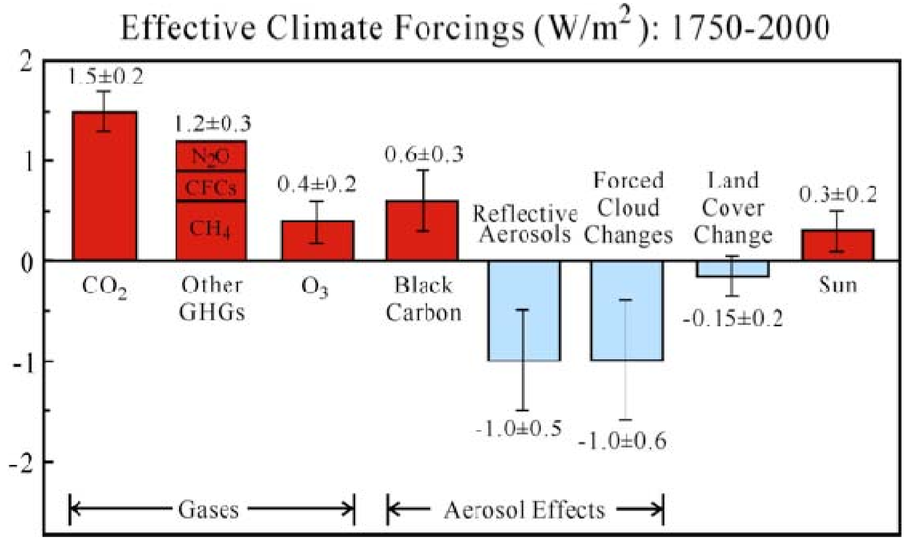
Accurate Radio Occultation Refractivity Provides Critical Climate Change

CLARREO Science and Aerosol Radiative Forcing

- CLARREO assumes that aerosol radiative forcing will be provided by other missions (GLORY APS instrument starting 2010, ACE Decadal Survey mission ~2020, future combinations of surface and satellite aerosol data and 4-D assimilation chemical transport models.

- CLARREO considered adding APS to observe aerosols after GLORY mission and before ACE in 2020. Recommended to NASA HQ that CLARREO feedback science would be enhanced by this more accurate aerosol radiative forcing.

  Recommended to NASA HQ that APS be flown on a free-flyer continuity mission as part of recovery of lost NPOESS climate sensors, but not as part of CLARREO.

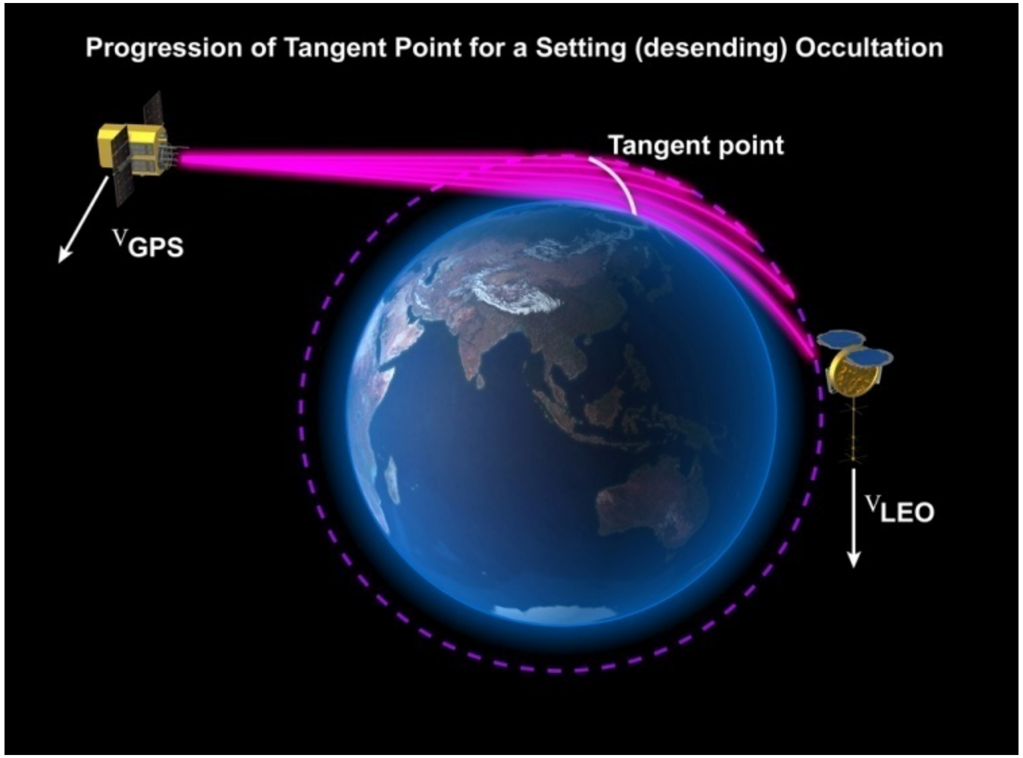


Climate forcing agents in the industrial era.

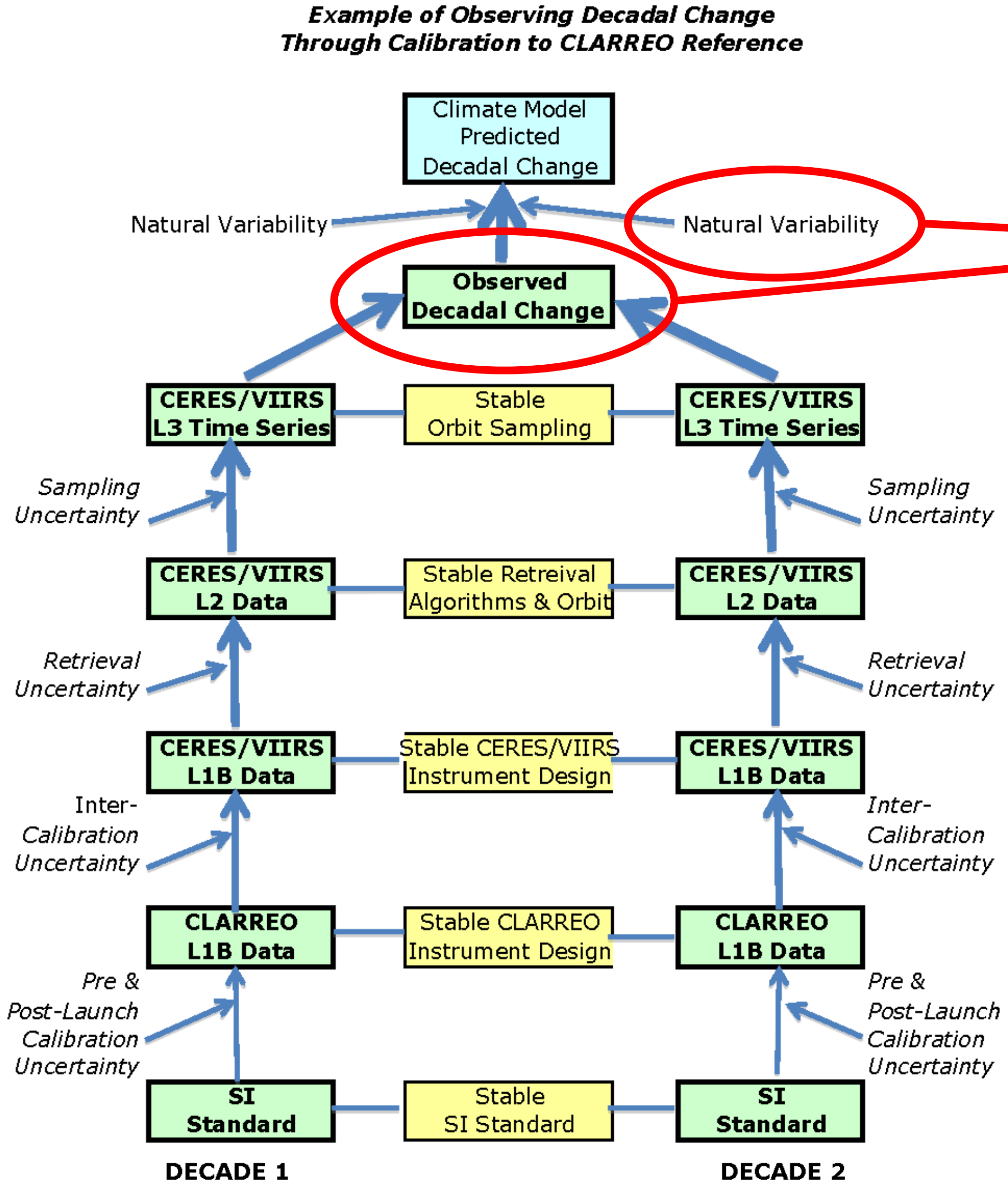
Hansen et al., JGR, 110, D18104, 2005 Stated uncertainties are modeling uncertainties
These uncertainties should be re-cast as observation imposed constraints

How RO Works and What It Measures

- CLARREO RO receiver observes the GNSS S/C signal set or rise behind Earth's limb as it moves through atmosphere.
- Receiver observes change of delay of the signal between the two satellites and is a function to the slowing and bending of signal.
- Change of delay, measured as a Doppler frequency shift, is translated to a bending angle, α. A vertical refractivity profile, N_i, is created at the tangent points.
- N_i allows for reconstruction of the temperature, pressure, and humidity in the neutral atmosphere.



Tracing CLARREO Decadal Change Science Objectives to Mission Requirements



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.

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.

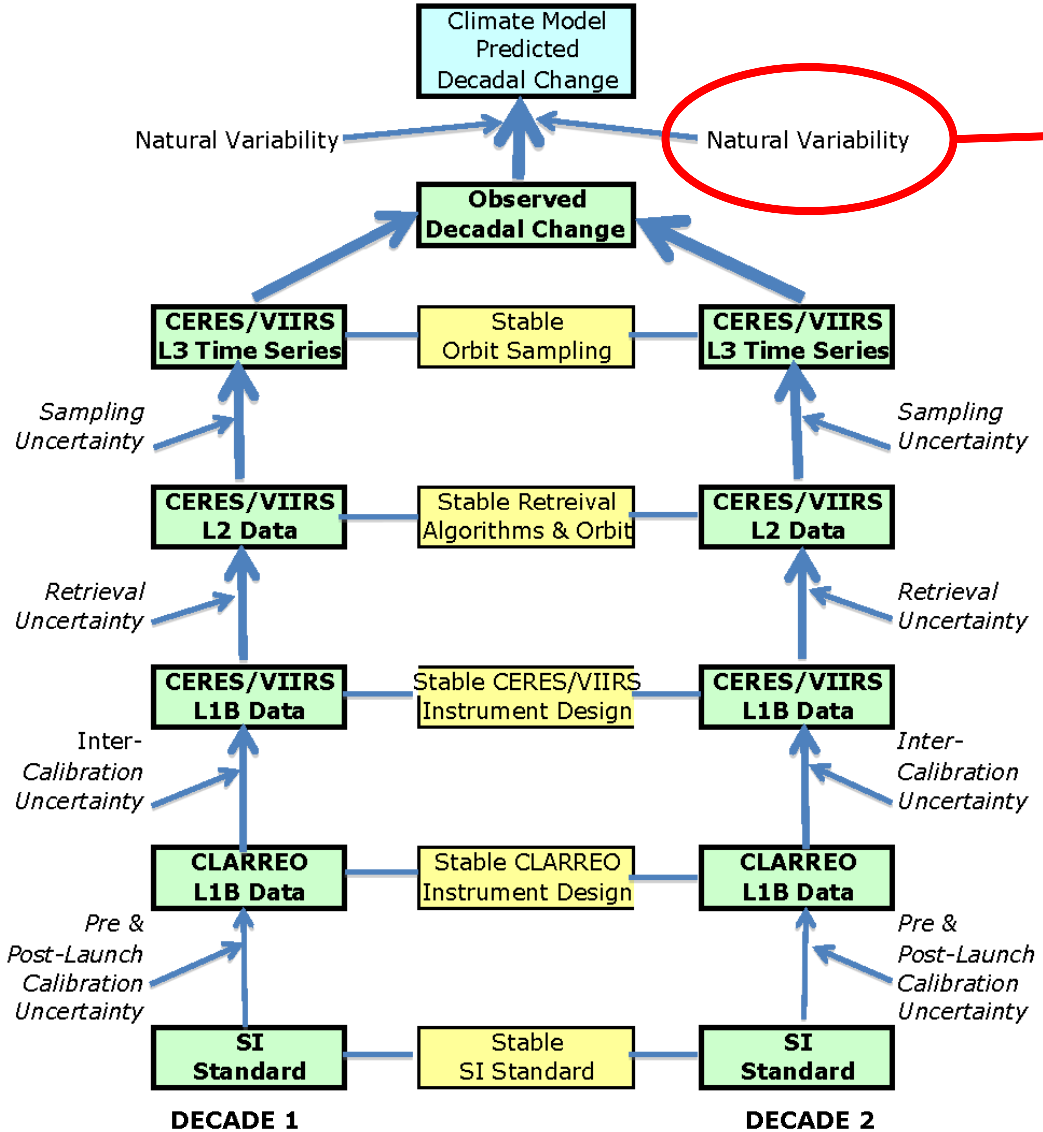
Requirement for trend detection is to reduce errors below 1/3 of natural variability at the relevant time/space scale for each decadal change observation.

Clmate 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

Tracing CLARREO Decadal Change Science Objectives to Mission Requirements

Example of Observing Decadal Change
Through Calibration to CLARREO Reference

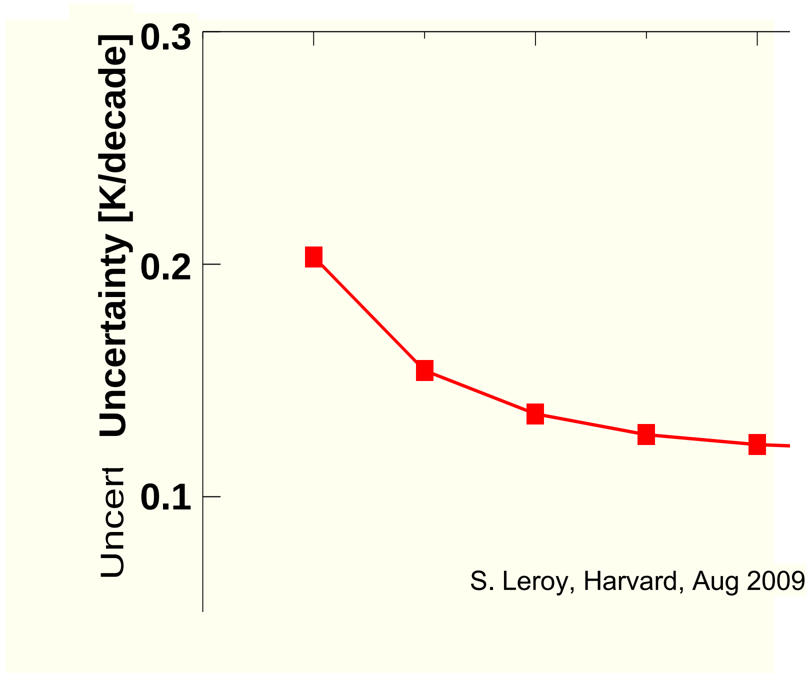


Trend Detection Above Natural Variability: Mission Duration

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

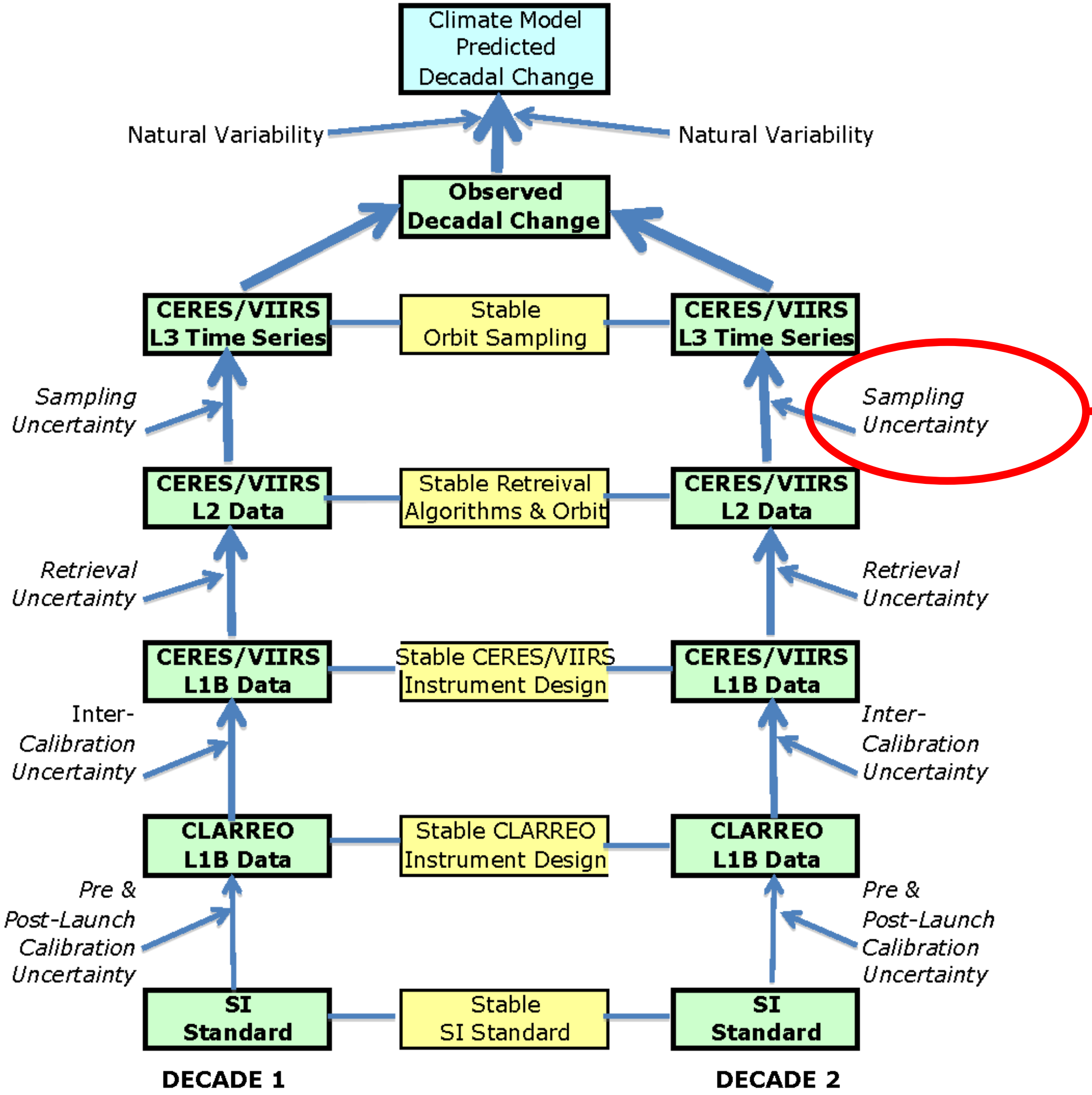
Trend Detection Above Natural Variability: Mission Duration

- 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) showsthat 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.



Tracing CLARREO Decadal Change Science Objectives to Mission Requirements

Example of Observing Decadal Change
Through Calibration to CLARREO Reference

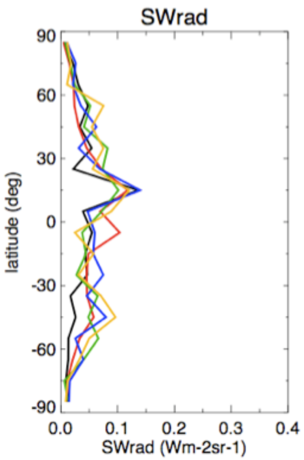


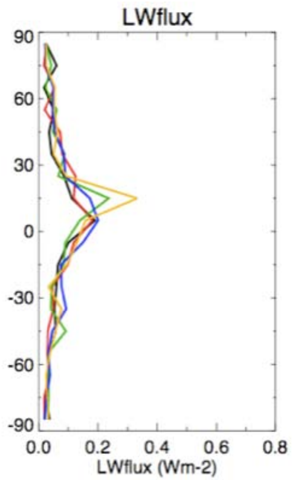
Orbit Sampling Uncertainty Vs Natural Variability

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

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

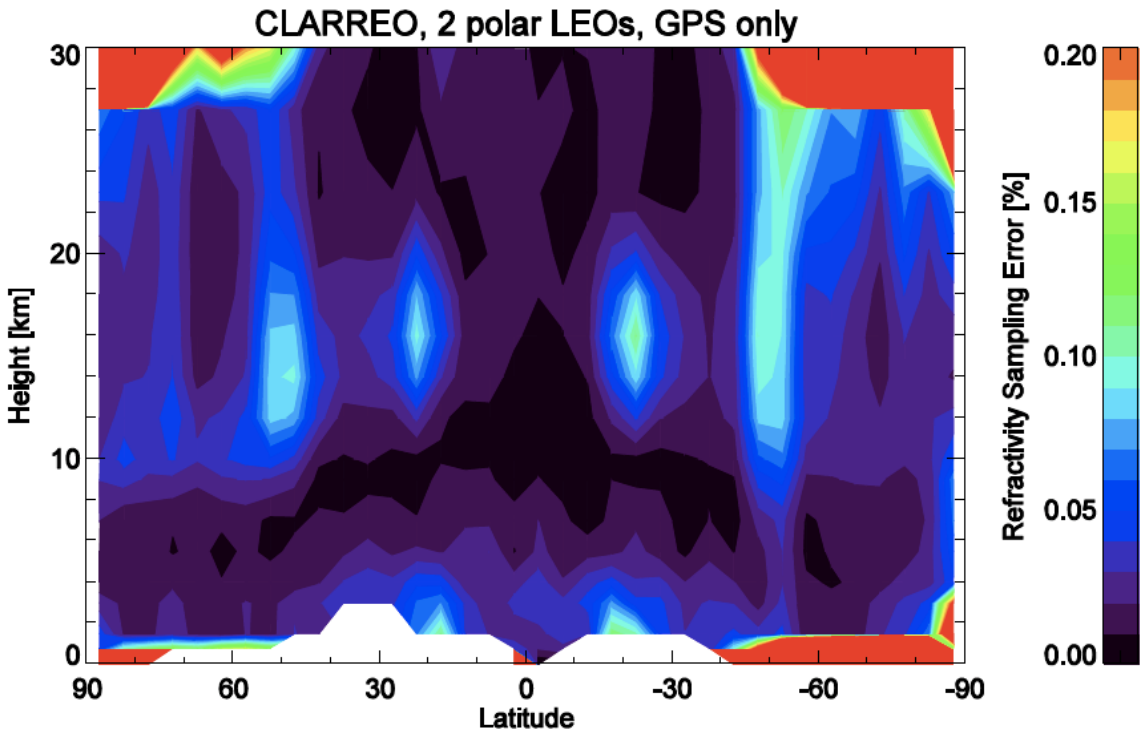
Doelling, 2009

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

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.

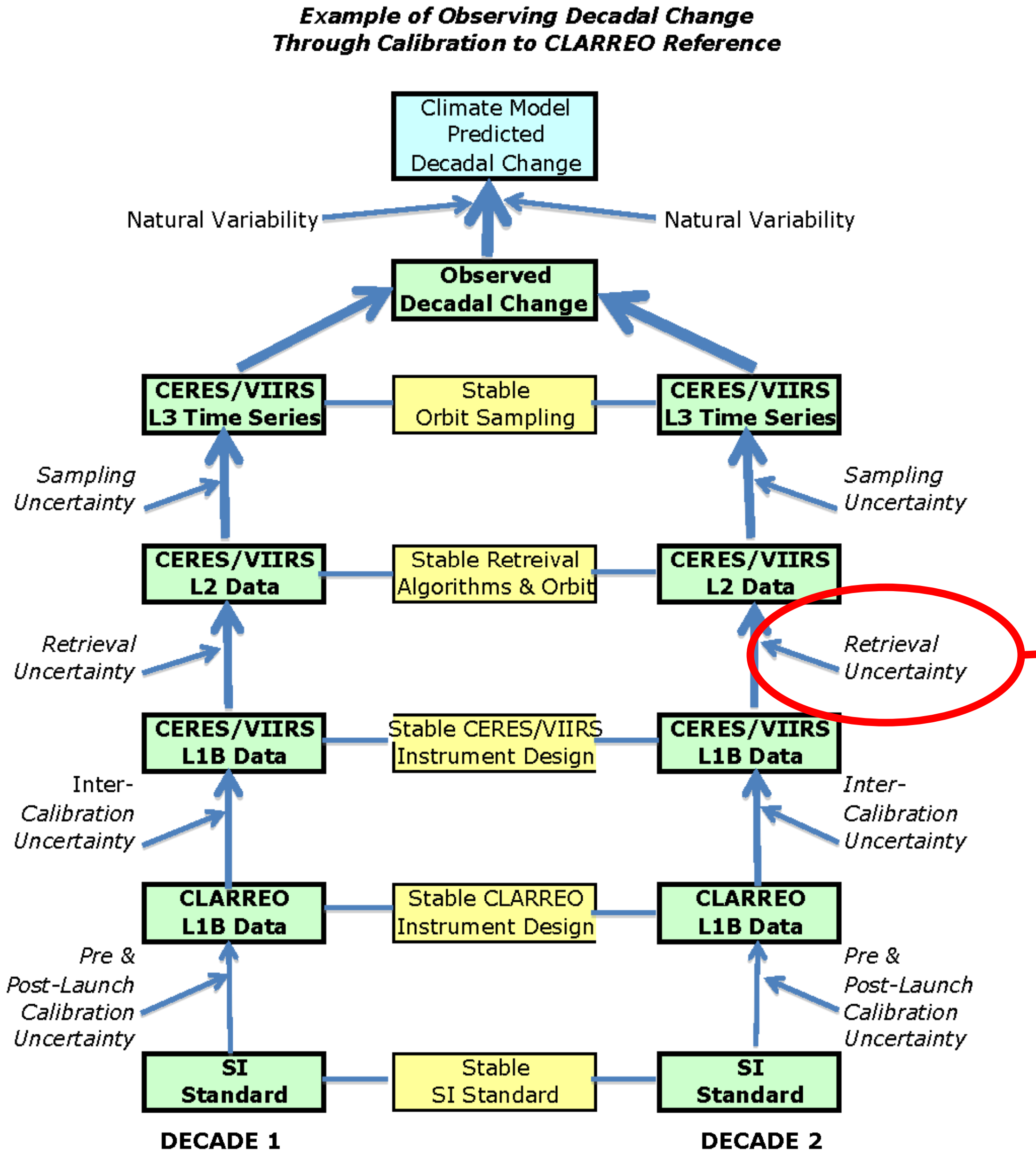
Simulated 24 GPS and 27 Galileo in nominal configuration.

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

Tracing CLARREO Decadal Change Science Objectives to Mission Requirements



Retrieval algorithms must maintain constant algorithms over decades

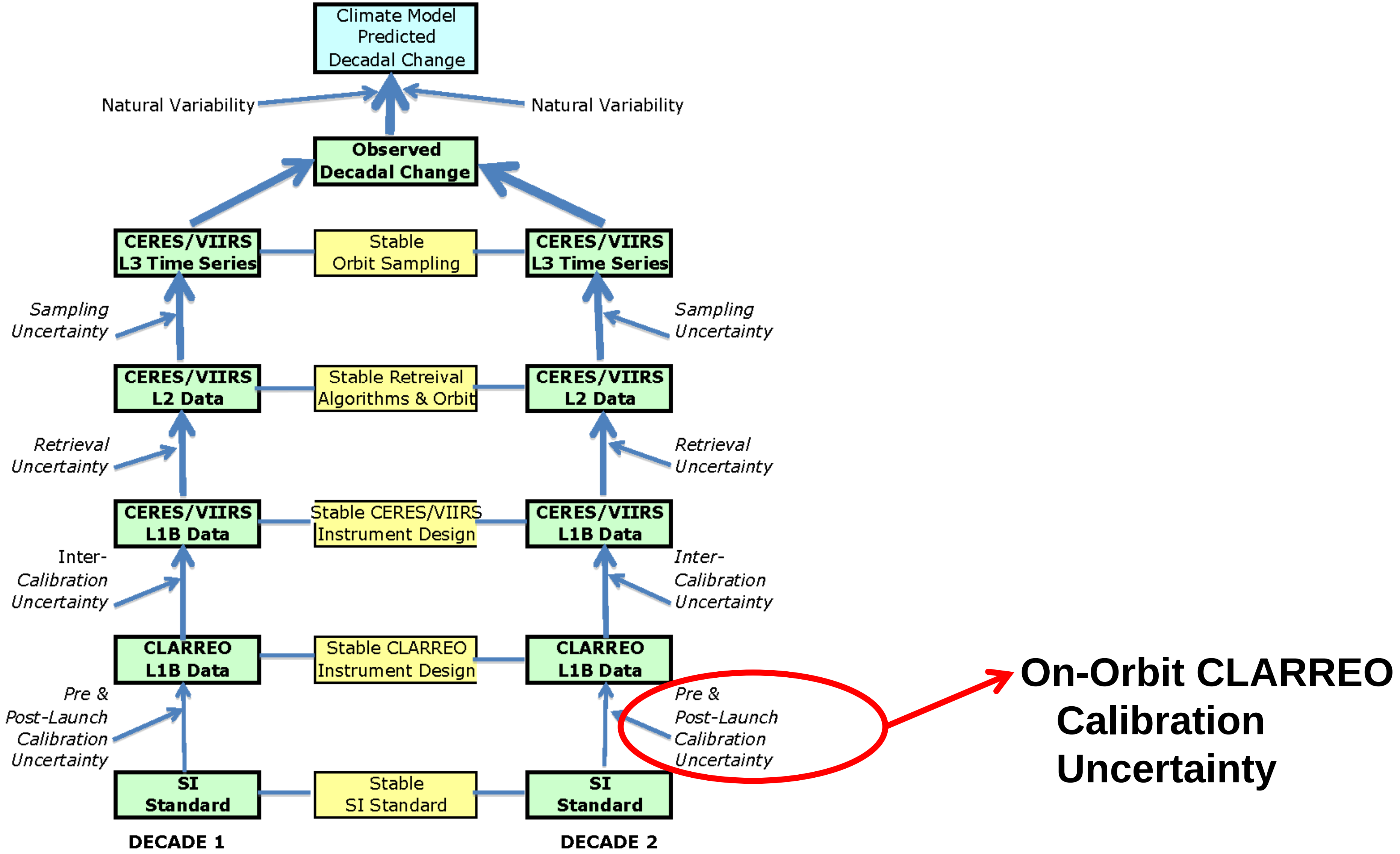
Retrieval Bias in Climate Trends

- 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

Tracing CLARREO Decadal Change Science Objectives to Mission Requirements

Example of Observing Decadal Change Through Calibration to CLARREO Reference



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

Summary of CLARREO Requirements

- Science Objective: Highly accurate and SI-traceable decadal change observations sensitive to the most critical but least understood climate radiative forcings, responses, and feedbacks. Accuracy within 20% of a perfect climate observing system for decadal change time/space scales.
- Infrared Spectrally Resolved Radiance Emitted from Earth to Space determined with an SI traceable accuracy of 0.1K (3 σ), 200 – 2000 cm^{-1}, at 0.5 cm^{-1} unapodized resolution. Nadir fov (25 to 100km diameter) for fingerprinting and reference intercalibration.
- Spectrally Resolved Solar Reflectance from Earth to Space determined with an SI traceable relative accuracy of 0.3% (2 σ), 320 – 2300 nm, 8 nm spectral resolution (<1000 nm), 16 nm resolution (>1000 nm) 0.5 km nadir pixels, 100 km swath for fingerprinting and reference intercalibration. Gimball to support solar and lunar calibration, reference intercalibration.
- GNSS-Radio Occultation determined with SI traceable refractivity accuracy of 0.03% for altitudes from 5 to 20km.
- Two 90 degree orbits to reduce sampling errors to less than 1/3 natural variability, achieve reference intercalibration sampling, diurnal sampling.
- 3 year mission duration with consumables for 5 years.