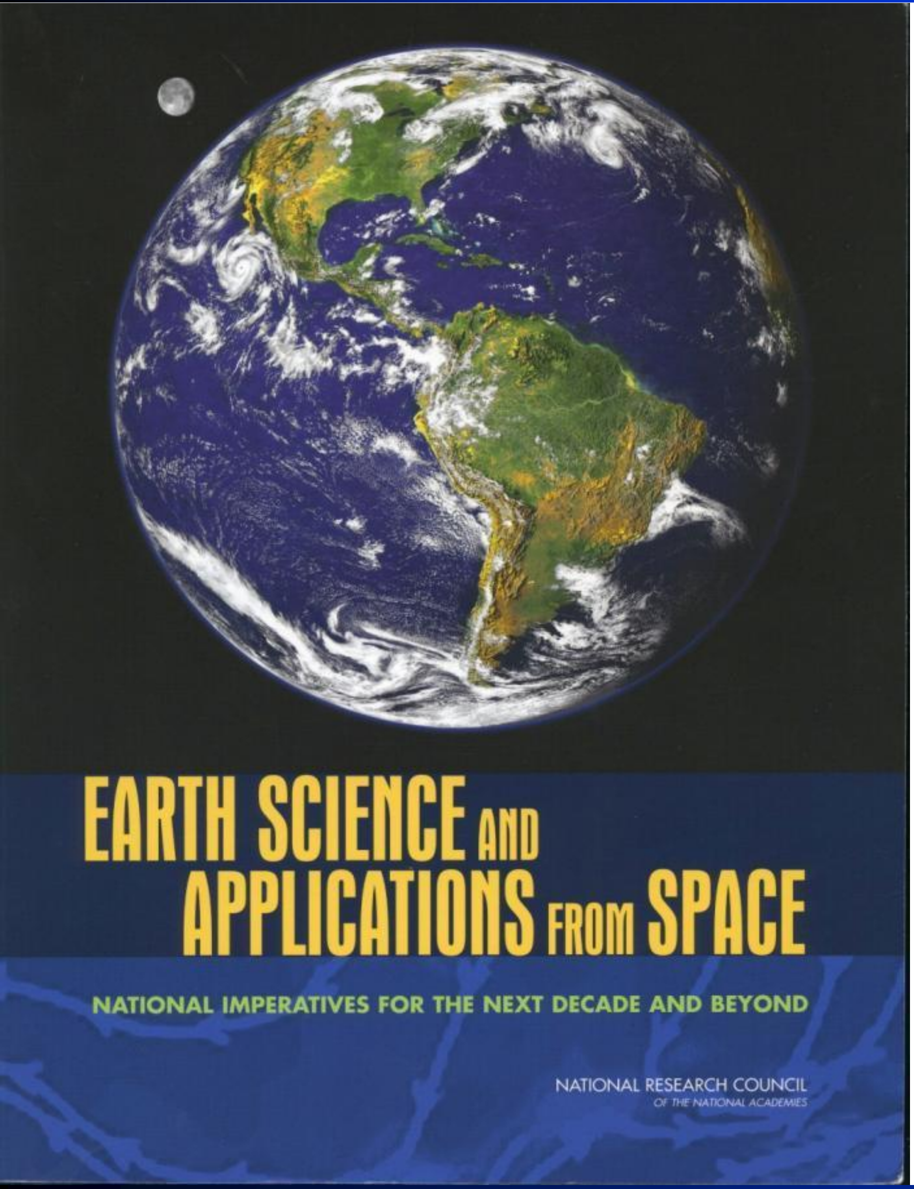
CLARREO Summary for New SDT Members

Climate Absolute Radiance & Refractivity Observatory

January 31, 2011

Decadal Survey defines CLARREO



NOAA CLARREO

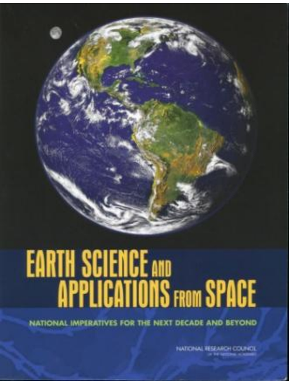
- CERES (Clouds and Earth’s Radiative Energy System)
- TSIS (Total Solar Irradiance Sensor)

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).
- Three 90 degree orbits for diurnal cycle sampling

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), imagers such as VIIRS, AVHRR, geostationary

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 3 years 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 IR Inst Lead Climate Obs	FIRST/CERES/CALIPSO/SAGE, RS/IR intercalibration RS/IR orbit sampling, RS fingerprinting, Radxfer Models IIP for IR instrument
Harvard Univ.	IR Science/Inst GNSS-RO	INTESSA/IR Spectra fingerprinting, dec. change accuracy 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

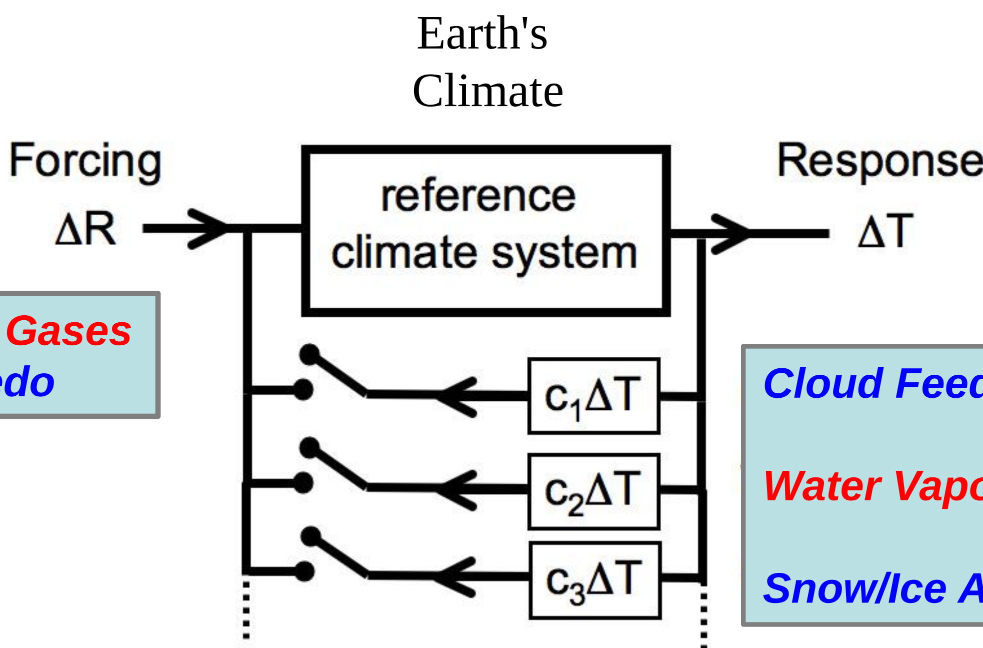
A diverse expertise science team to set requirements

CLARREO Science Value
Climate Forcing, Response, Feedback

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

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

- ***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

Science Impact

Climate Sensitivity uncertainty is driven by uncertain **Feedbacks**:

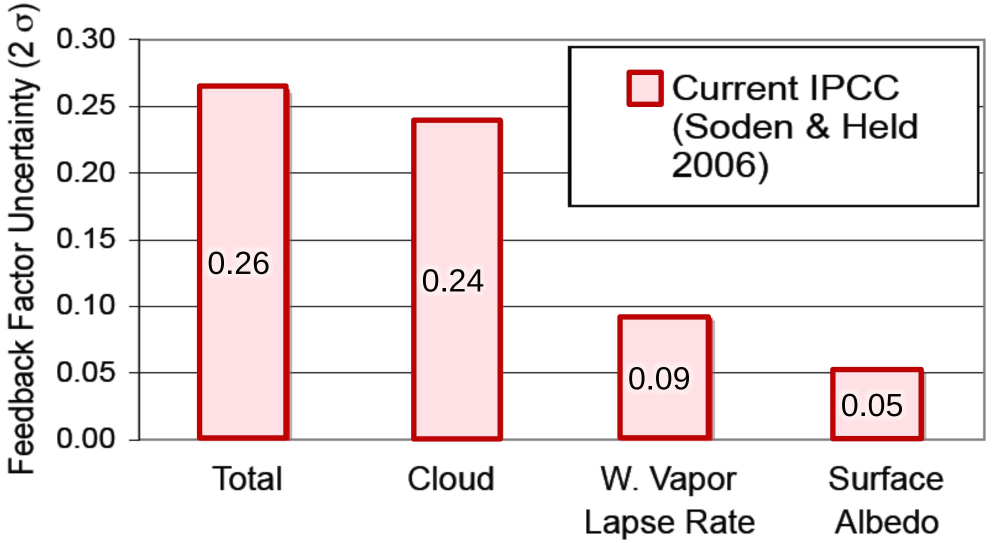
- Factor of 3 uncertainty in response to doubled CO_2
- Relative uncertainty known

Climate Change **Response**:

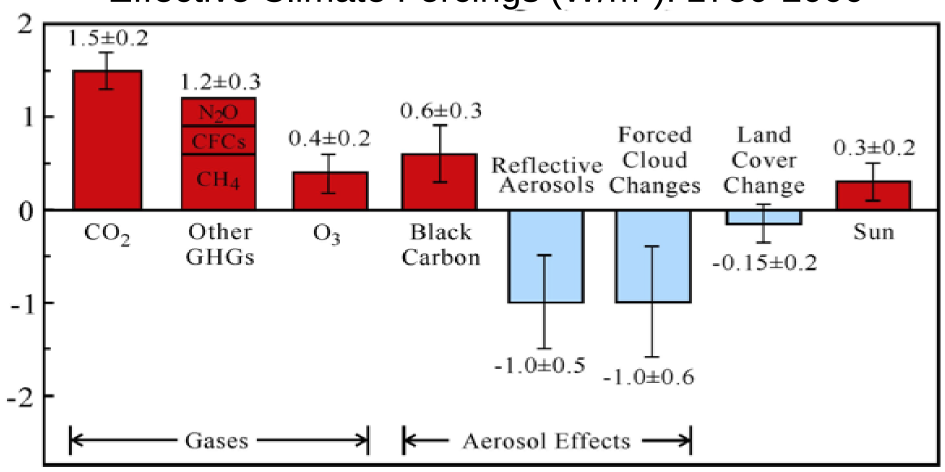
- Temperature Profile,
- Water Vapor Profile,
- Cloud Properties,
- Surface albedo (snow, sea-ice, land cover)

Radiative **Forcings**:

- Verify greenhouse gas infrared radiation effects
- Aerosols advances by GLORY APS and NRC ACE missions.



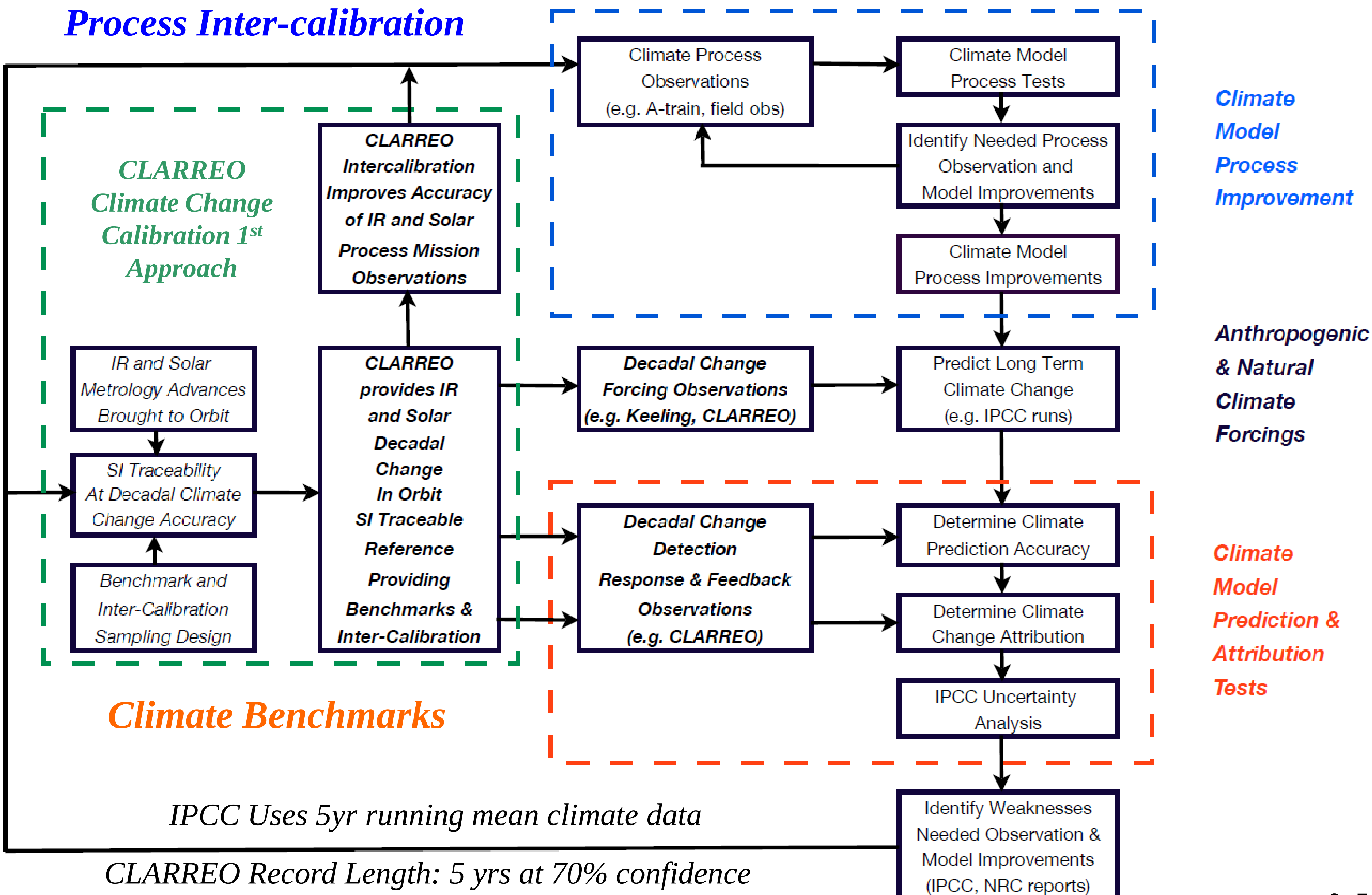
Effective Climate Forcings (W/m²): 1750-2000



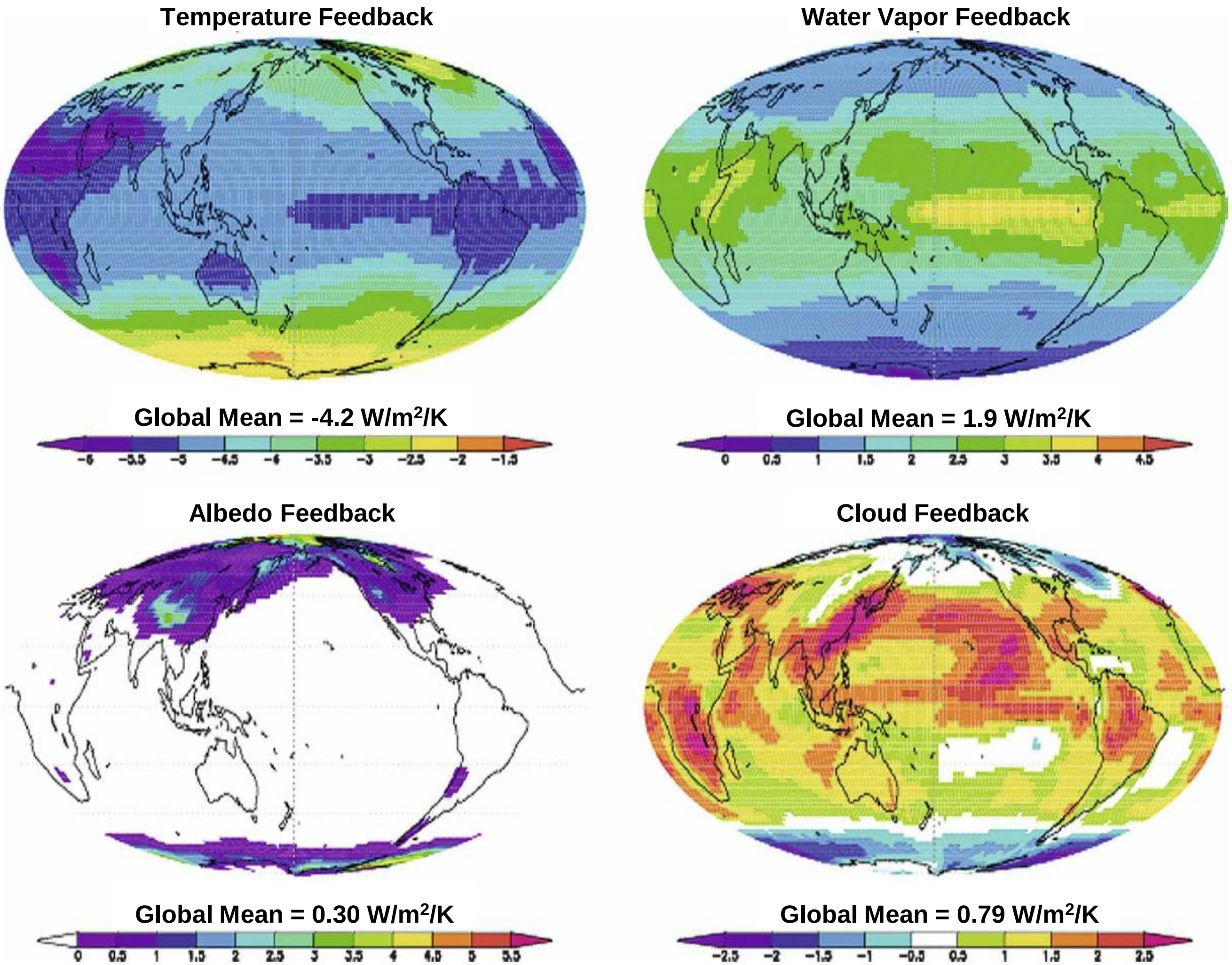
Climate forcing agents in the industrial era.

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

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

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:

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

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:

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

Degradation in time to detect trends is only ⅔ of degradation in accuracy.

Provides an integrated error budget across all decadal change error sources

Decadal Change Trends

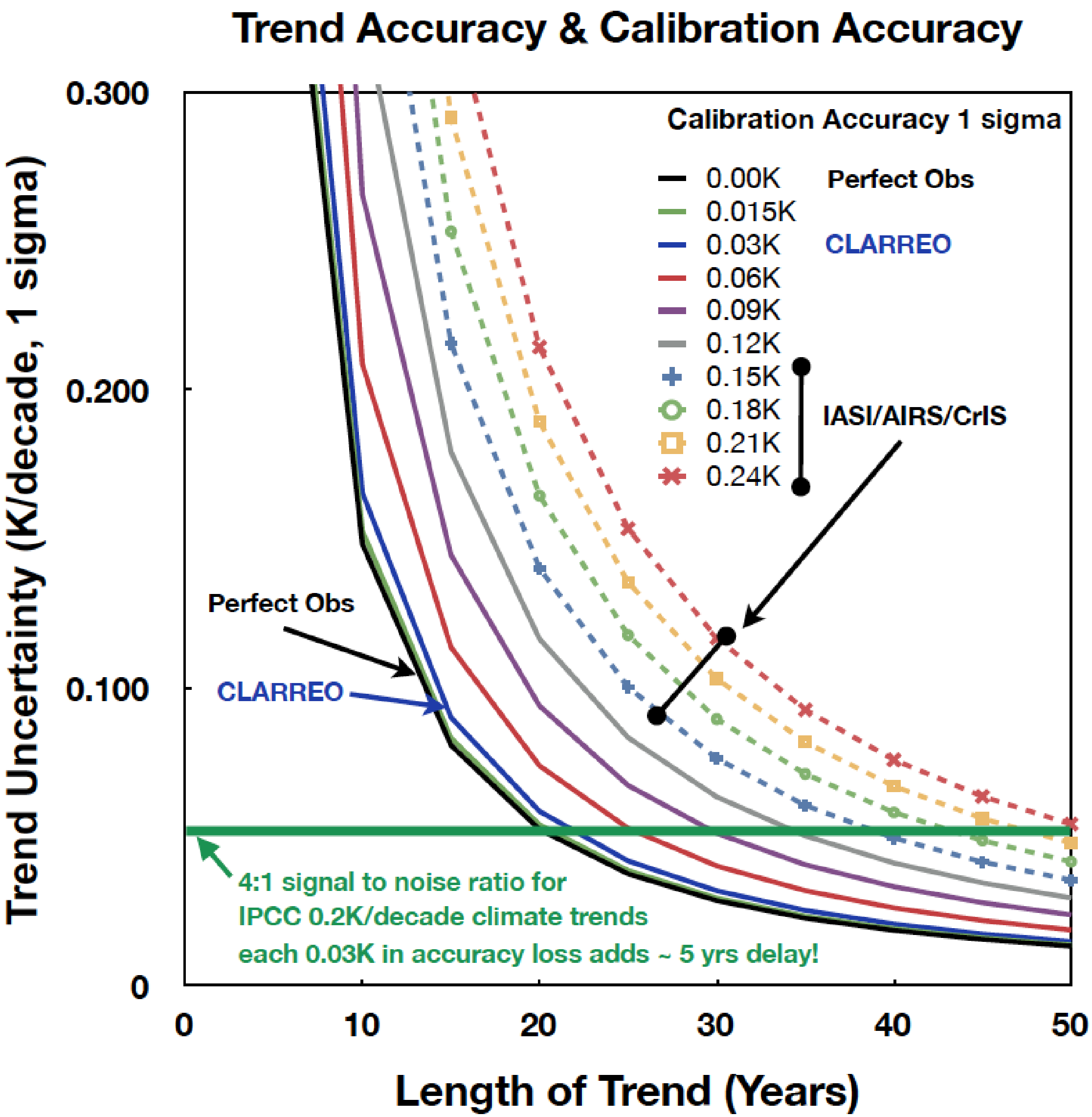
- The accuracy of CLARREO observations is required *only at large time and space scales such as zonal annual, not at instantaneous field of view. Therefore all errors in the CLARREO error budgets are determined over many 1000s of CLARREO observations: never 1, or even a few.*

- 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.

- *So what accuracy relative to a perfect observing system is needed?*

CLARREO is an unusual mission: requirements focus on long term change

Requirement is to be within 20% accuracy of an ideal climate observing system: IR

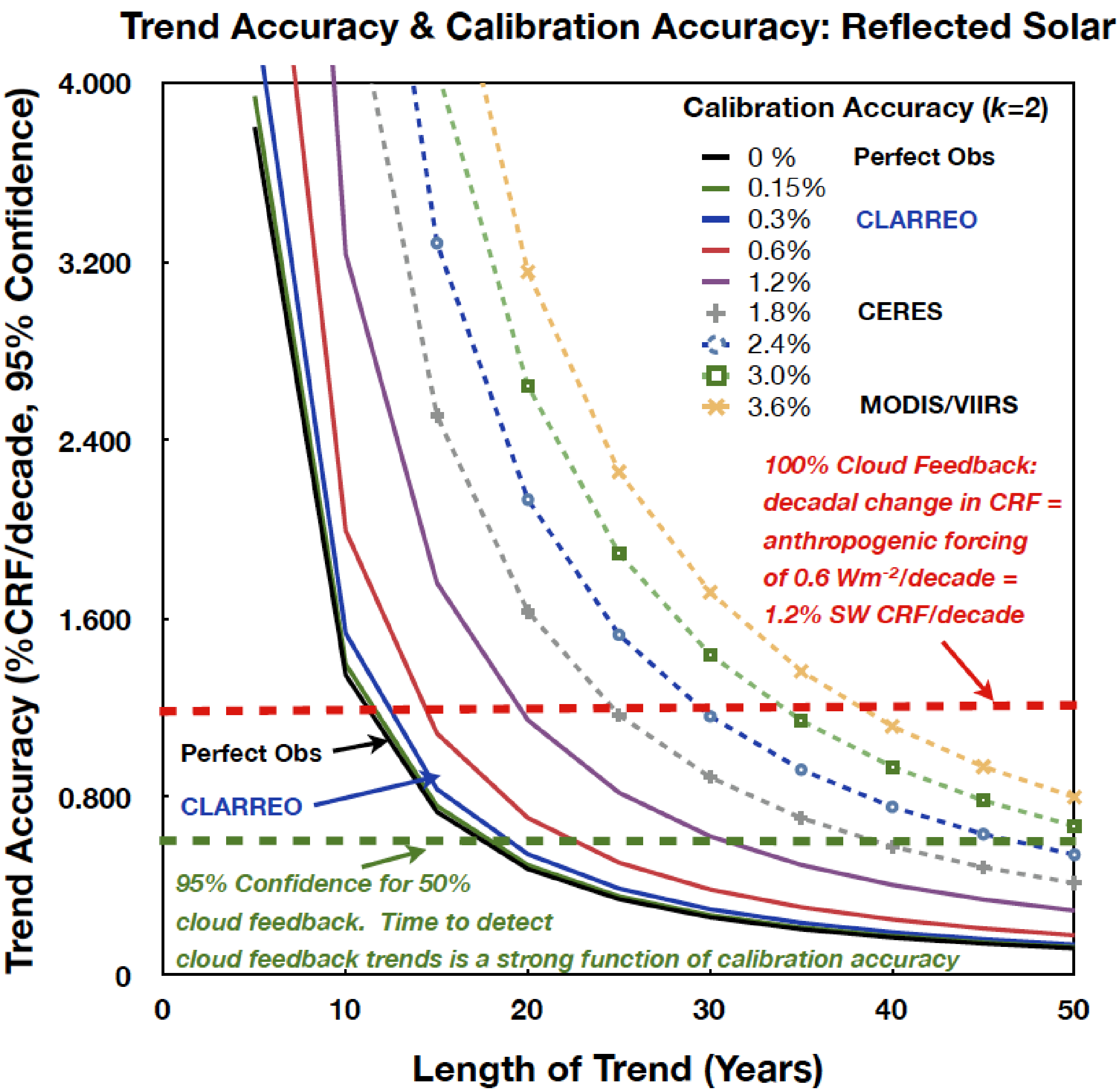


Example for Temperature Trends

- *CLARREO accuracy goals are optimal cost/value*
- *High confidence critical for policy decisions*
- *CLARREO accuracy designed to provide that confidence.*

Climate Change Accuracy is Critical to Making Difficult Policy Decisions

Requirement is to be within 20% accuracy of an ideal climate observing system: RS



Example for Decadal Change in SW Cloud Radiative Forcing

- *All major error sources included:*
  absolute accuracy
  assumes gaps occur
  orbit sampling (90 deg)
  instrument noise
  reference intercalibration uncertainty (CERES).

Climate Change Accuracy is Critical to Making Difficult Policy Decisions

CLARREO Accuracy Requirements

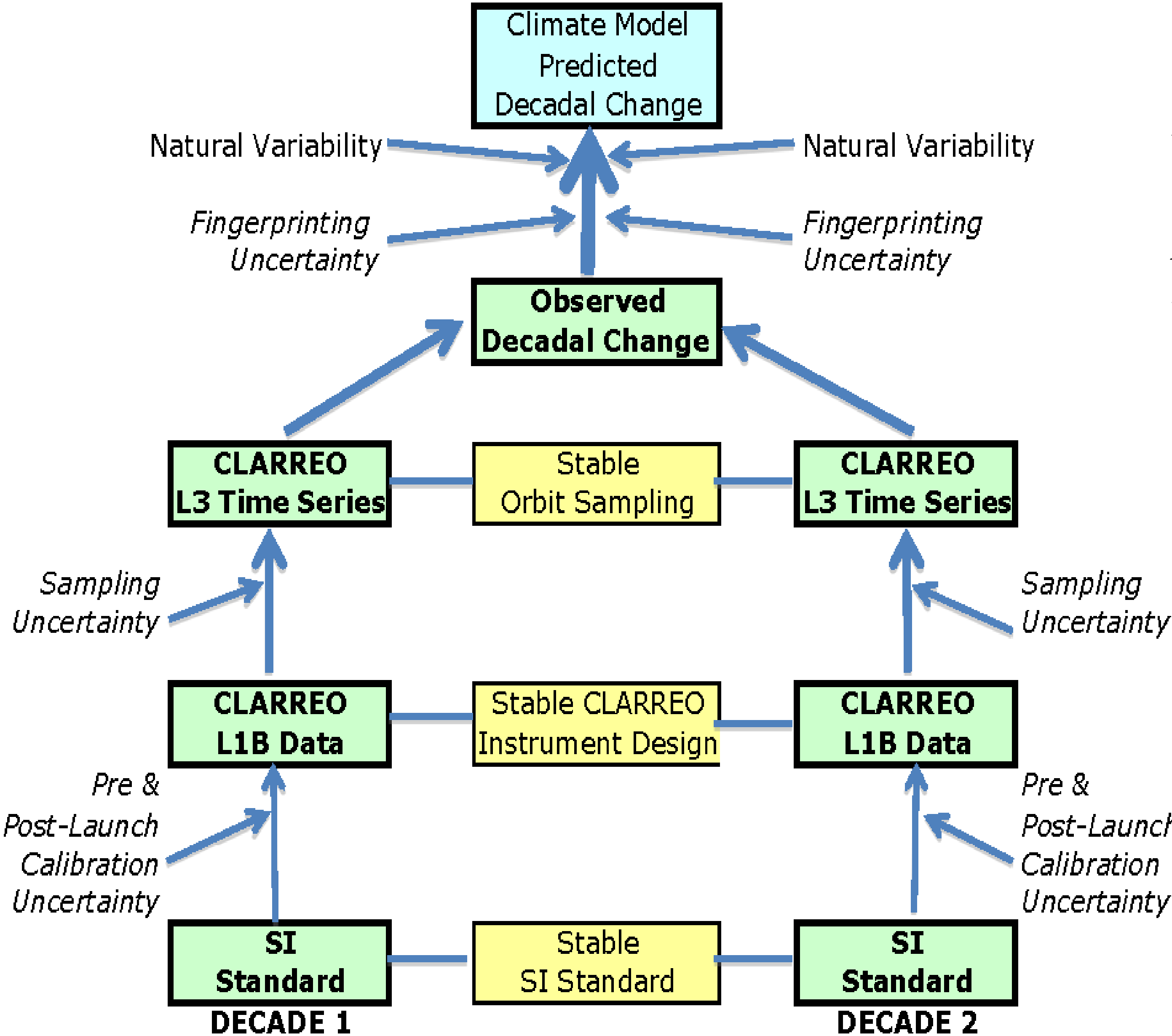
- CLARREO instrument absolute accuracy requirements are derived consistent with the goal of achieving accuracy within 20% of a perfect climate observing system, and time to detect trends within 15% of a perfect observing system.

- 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*=1) 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

Decadal Change Spectral Fingerprinting Benchmarks: Tracing Mission Requirements



Data, models

Climate OSSEs;
A-train observation + RTM simulations

Orbit Sampling Simulations

Instrument Design Studies
IIPs, NIST

Climate OSSEs- Observing System Simulation Experiments

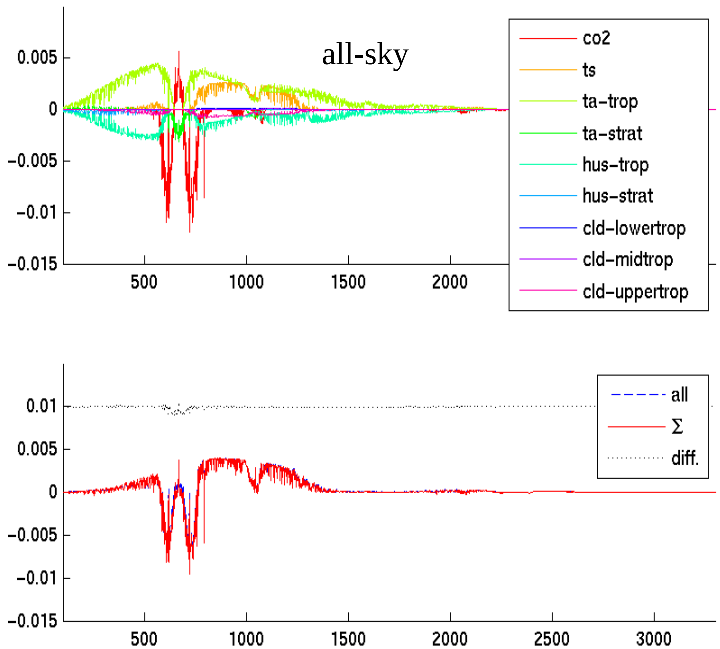
Climate modelers were identified by the Decadal Survey as primary data users

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

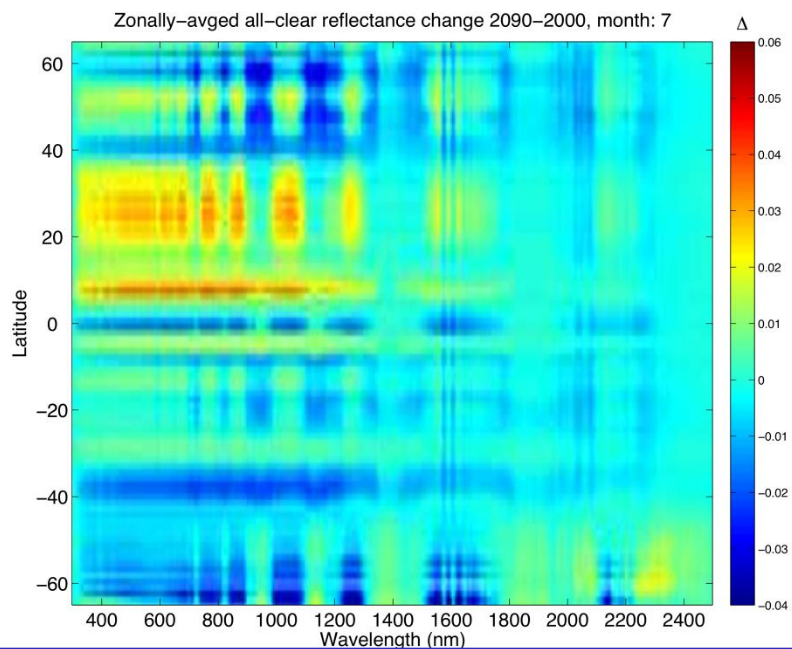
Studies include climate change fingerprinting methods using time/space averaged spectral data to define spectral resolution (IR 0.5 cm^{-1} unapodized, RS 15 nm) & spectral coverage (IR 200 to 2000 cm^{-1}, RS 300 to 2500 nm).

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

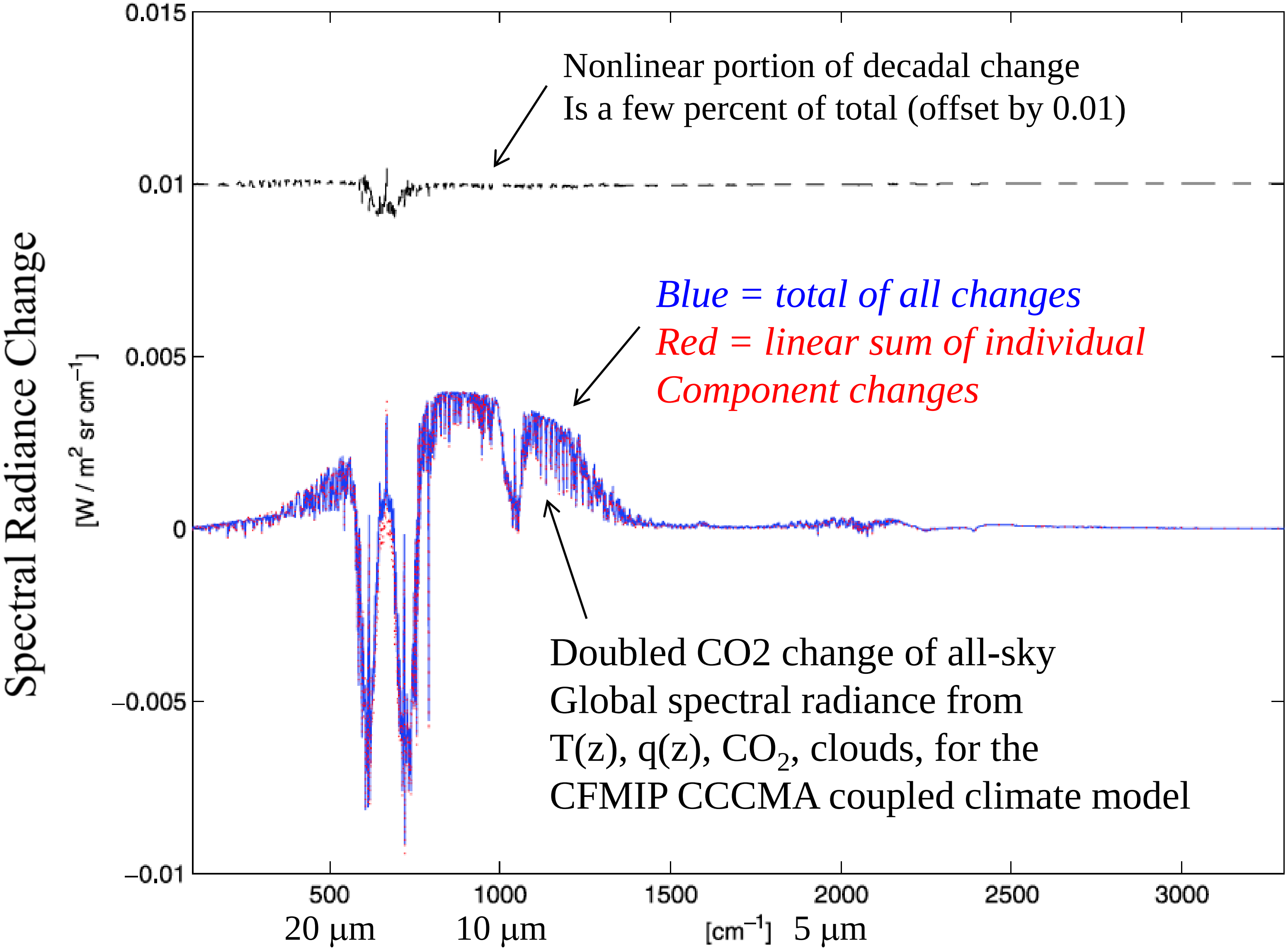
- Eliminates the requirement for global clear-sky observations (Huang and Leroy, 2009)



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)



Spectral Decadal Change is Linear



Huang et al.
2010

similar linearity found for decadal change of reflected solar spectra Jin et al., 2010

Instantaneous changes are nonlinear: decadal change is highly linear

Orbit Sampling Uncertainty

- Simulate 74, 83, 90 degree and sunsynch orbits, 1, 2, or 3 of each
- Truth data is 6 years of CERES hourly 1 degree grid global data for reflected SW flux and nadir reflectance, infrared window, and LW flux. Subsample with orbits.
- Results: sampling errors increase at smaller time/space scales, but so does natural variability, so that accuracy in trends can be met at our large time/space scales
- Given CLARREO trend accuracy/time to detect trend goals: one satellite is sufficient. Example below is for Annual zonal: but global, regional, seasonal similar

Annual	ZONAL					
	SWrad (Wm-2sr-1)		Swflux (Wm-2)		LW (Wm-2)	
	σ_s/σ_{var} (%)	F_t	σ_s/σ_{var} (%)	F_t	σ_s/σ_{var} (%)	F_t
σ_{var} [SS]	.197		.657		.637	
SS 13:30	59	1.07	58	1.07	26	1.01
SS 13:30+10:30	42	1.04	41	1.04	16	1.01
σ_{var} [P90]	.192		.628		.640*	
P90-1	70	1.10	65	1.09	25	1.01
P90-2	35	1.03	33	1.02	16	1.01
P90-3	26	1.01	23	1.01	12	1.00

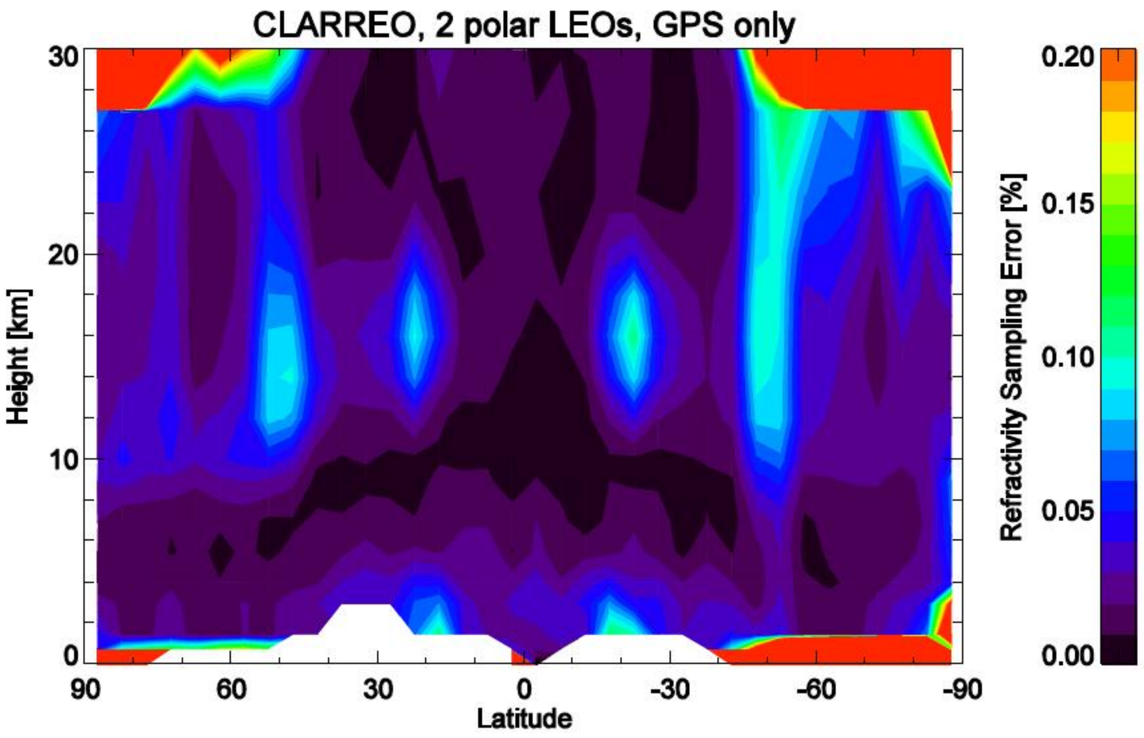
* For LW 0.640Wm^{-2} = 0.194°K

Table Definitions:
σ_{var} = natural variability
σ_s = orbit sampling error
F_t = ratio of time to detect climate trends to a perfect observing system limited only by natural variability
P90 = 90 deg inclined orbit
SS = sun-synchronous orbit
SW = shortwave reflected solar radiation (SWrad = nadir radiance, SWflux = angle integrated flux)
LW = longwave emitted infrared radiation

Doelling, Fall AGU, 2009

Single 90 degree orbit meets annual global/zonal/regional diurnal sampling

CLARREO Orbit Sampling Requirement GNSS-RO



Errors increase by 40% for GPS only

Simulated 1 or 2 CLARREO low Earth orbiters in polar orbit, spaced 90º in ascending node.

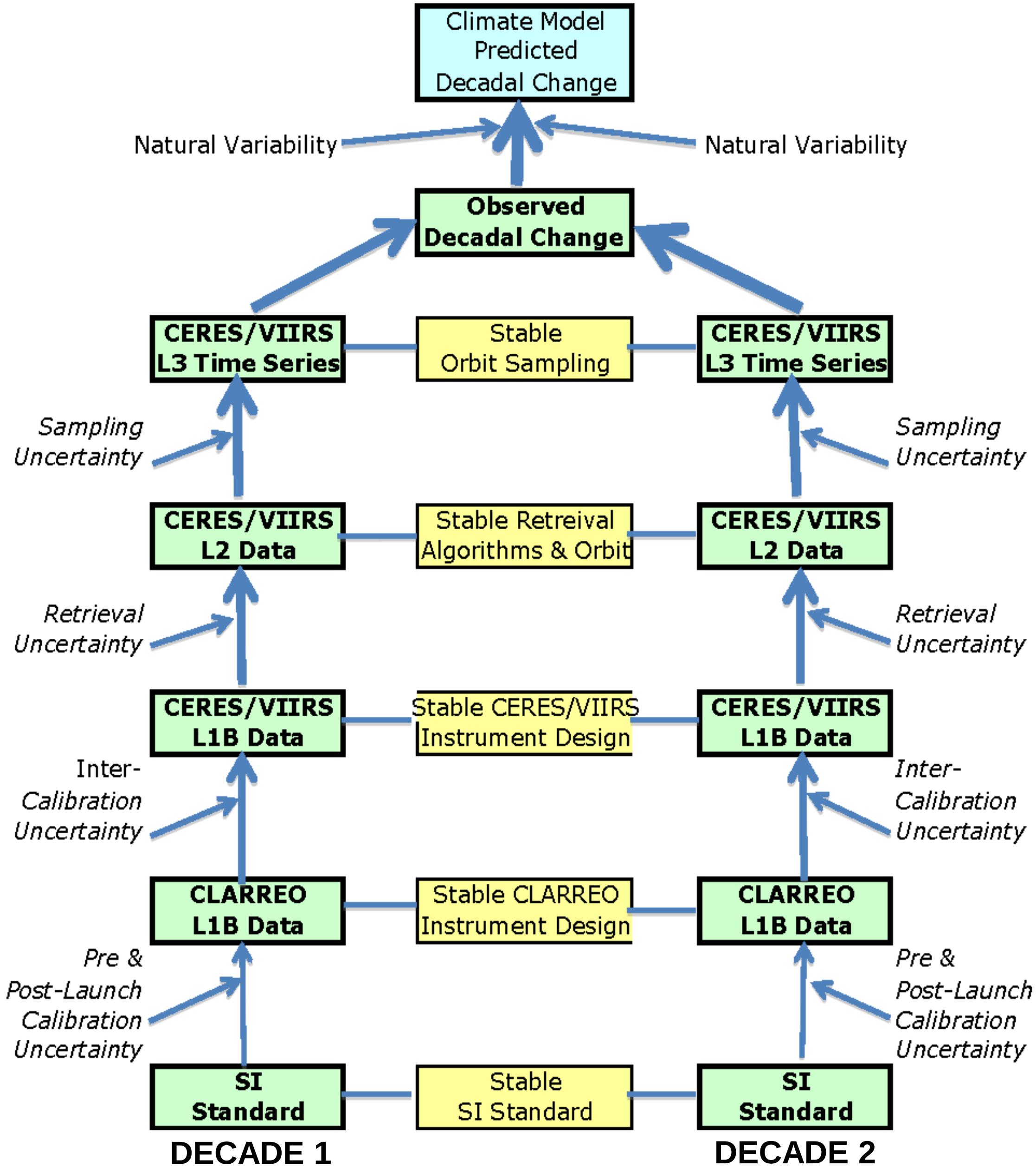
Simulated 24 GPS and 27 Galileo in nominal configuration.

Ran for 8 years, interpolated to NCEP reanalysis.

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

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

Decadal Change Reference Intercalibration Benchmarks: Tracing Mission Requirements



Climate OSSEs

Data, models

Orbit Sampling Simulations

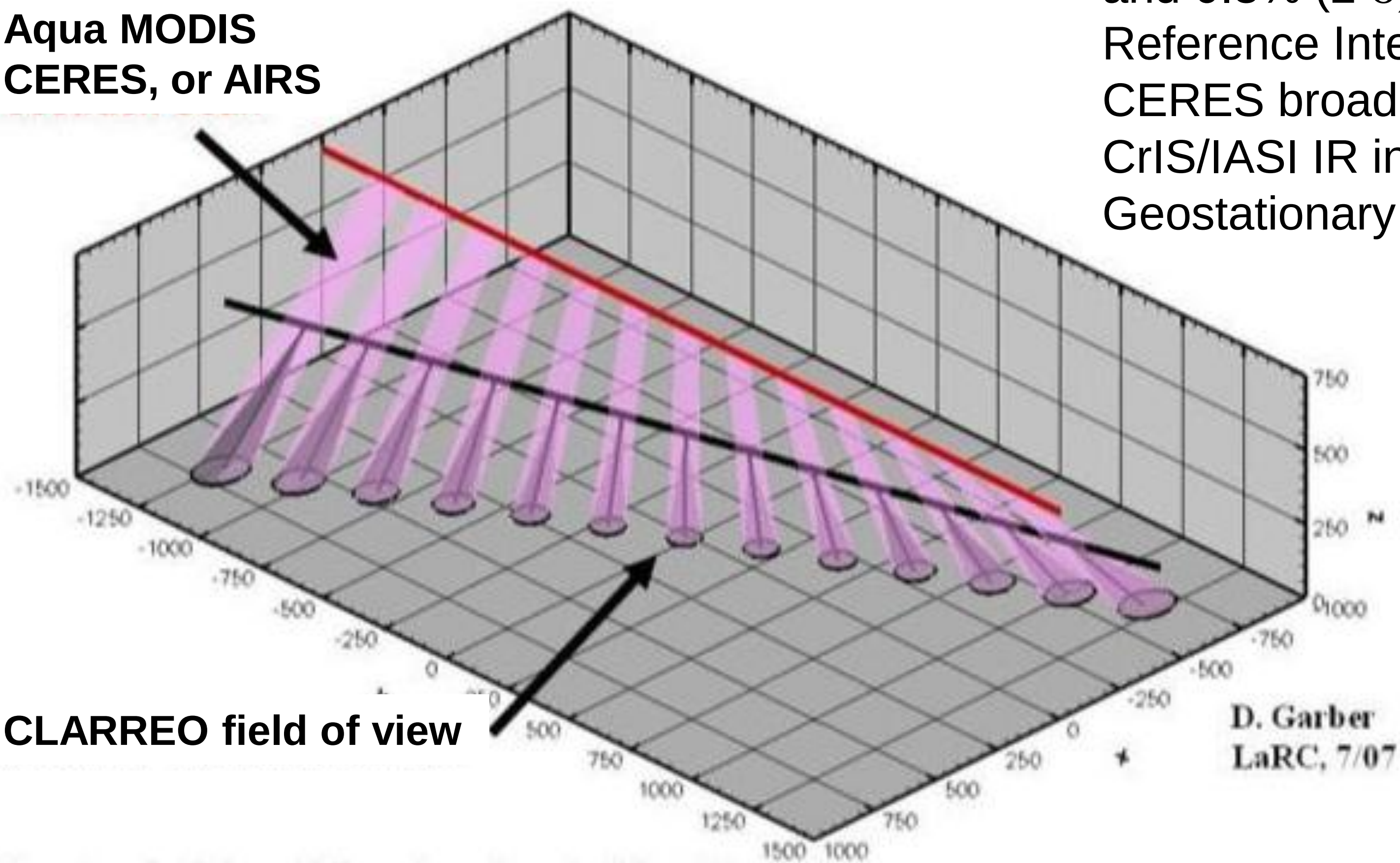
Retrieval Bias Simulations

Intercalibration Simulations

Instrument Design Studies IIPs, NIST

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 σ) IR
and 0.3% (2 σ) Solar Reflected
Reference Intercalibration:
CERES broadband, VIIRS imager
CrIS/IASI IR interferometers,
Geostationary imagers, sounders



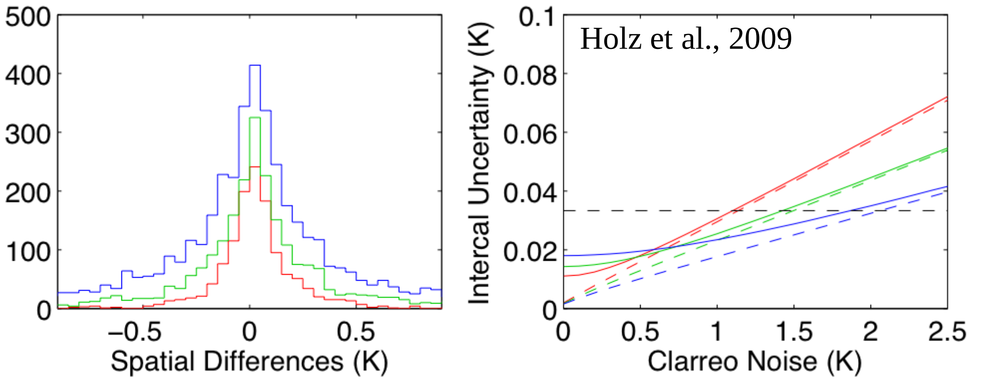
Studies using current satellite data show matching is feasible

CLARREO Reference Inter-calibration Uncertainty: IR spectra

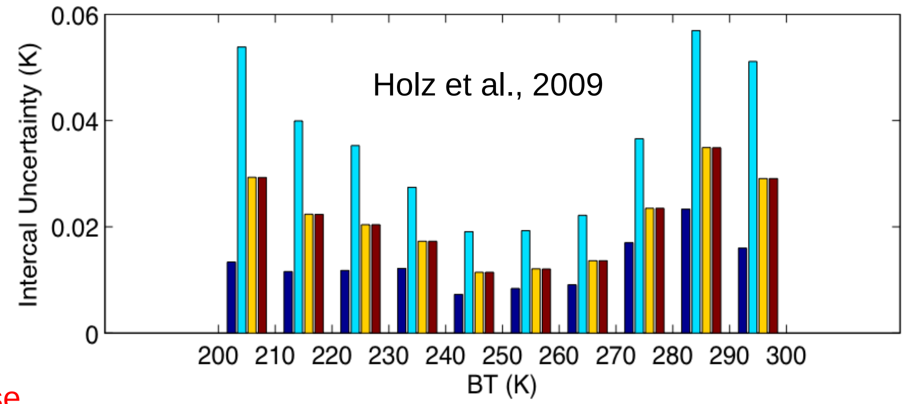
- Studies have answered outstanding questions concerning the accuracy of using CLARREO as a reference calibrator of operational IR sensors
- Nadir-only viewing provides sufficient sampling for IR intercalibration of gain, offset, and response nonlinearities.
- Sampling time and FOV will determine integration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

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



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



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

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 0.5% (*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 gimbal 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

CLARREO Draft Level 1 Requirements
Science Requirements

Baseline Accurate and Traceable
- Observations shall have their accuracy uncertainty traceable to SI standards
- There shall be a 60% or greater probability of at least 1 year (TBR) overlap of each measurement type with itself

Baseline Accuracy in Climate Trends vs a Perfect Climate Observing System
- Benchmark observations shall achieve an accuracy in decadal trends of within 20% of a perfect observing system for the combined uncertainty sources of SI traceable calibration, orbit sampling, and instrument noise, at annual global and annual zonal time/space scales.

Baseline Record Length CLARREO shall obtain each observation type with a record length of at least 5 years with likelihood of 70% (TBR) or greater.

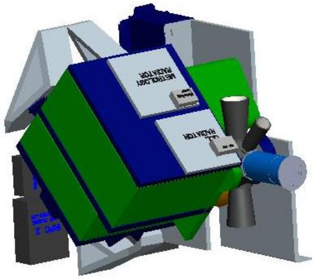
Reference Inter-Calibration Operations CLARREO shall provide data to climate relevant operational sensors (similar to VIIRS, CERES, CrIS, and IASI) that will be used to improve the accuracy of their measurements. Final sensors TBR.

Infrared Science Measurement
- Broad spectral coverage of the earth emitted spectrum (200 to 2000 cm^{-1})
- Spectral resolution (0.5 cm^{-1} unapodized)
- Measurement systematic error that corresponds to < 0.1 K brightness temperature radiometric calibration uncertainty (k=3)

Reflected Solar Baseline Science Measurement
- Broad spectral coverage (320 to 2300 nm) of the earth shortwave reflected spectrum
- Spectral resolution of 8 nm
- Reflectance measurement with an absolute uncertainty of 0.3% relative to global mean reflected solar energy (k=2)

Atmospheric Refractivity Baseline Science Measurement
- Spatial and temporal sampling sufficient to provide global coverage and to reduce sampling biases for zonal annual means
- Changes in annual means of refractivity with an uncertainty of 0.03% (k=1), over 90% TBR of the zones) for 5-20 km altitude

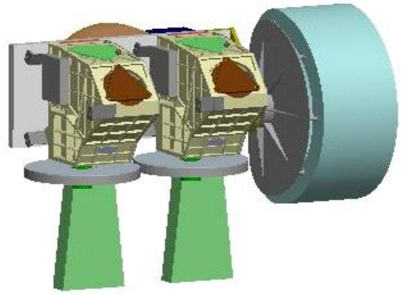
Science Instruments: L2 Requirements



Infrared (IR) Instrument Suite

Fourier Transform Spectrometer

- Systematic error less than 0.1K (*k=3)*
- 200 – 2000 cm^{-1} contiguous spectral coverage
- 0.5 cm^{-1} unapodized spectral resolution
- Nadir pointing, systematic within 0.2°
- GIFOV: 25 km – 100 km
- Consecutive earth view orbit samples ≤ 200 km
- NeDT < 10 K (1 σ)



Reflected Solar (RS) Instrument Suite

Two Grating Spectrometers with Gimbal-mounted (1-axis)

- Systematic error less than 0.3% (*k*=2) of earth mean reflectance
- 320 – 2300 nm contiguous spectral coverage
- 4 nm sampling, 8 nm resolution
- GIFOV < 0.5 km by 0.5 km
- Swath width ≥ 100km @600 km
- Nadir viewing > 90% of the time
- S/N ratio > 33 for λ < 900 nm, S/N ratio > 25 for λ > 900 nm
- Polarization sensitivity < 0.5% (*k*=2) for λ < 1000 nm, < 0.75% (*k*=2) for λ > 1000 nm

GNSS Radio Occultation Receiver

GNSS Receiver, POD Antenna, RO Antennae

- Refractivity uncertainty 0.03% (*k*=1) for 5 to 20 km altitude range
- Sampling for annual mean 10 degree latitude zones (1000 occultations/day)

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.REQ.1000 - 1005 •Verifiable on-orbit accuracy •Traceable to SI standards •Decadal trends < 20% of perfect observing system •5 yr record, likely overlap 1 yr	CL.SYS.REQ.2000 Accuracy traceable to the relevant standard and maintained throughout the sensors lifecycle. CL.SYS.REQ.2007 and 2008 Calibrated and validated on-orbit with an SI-traceable system	CL.SYS.REQ.2010 Measurements from platforms in polar orbits: •Orbit Period: 5812.4 ± 0.25 seconds (609 km ± 200 m) •Inclination: 90± 0.1° •Eccentricity: ≤0.001 •Ground Track Repeat Cycle: 60.83 days (903 distinct paths) •Ground Track Error: ±20.0 km cross track at ascending node from target ground track established by the 60.83 day ground track repeat cycle. NOTE Orbit Definition considers science sampling requirements and reference intercalibration requirement
	Infrared spectra temperature and water vapor feedbacks cloud feedbacks decadal change of: •Temperature profiles •Water vapor profiles •Clouds, radiative fluxes •GHG radiative effects	CL.PRJ.REQ.1006 Infrared radiance spectra of the Earth and its atmosphere with: •Spectral coverage 200 – 2000 cm^{-1} •Spectral resolution 0.5 cm^{-1} unapodized •Systematic error that corresponds to ≤ 0.1 K radiance calibration uncertainty (k=3)	CL.SYS.REQ.2001 and 2005 Measure the Infrared Spectra: •Spectral range 200 – 2000 cm^{-1} •Spectral resolution 0.5 cm^{-1} unapodized •GIFOV no less than 25 km •Ground sampling interval no greater than 200 •Systematic error ≤ 0.100 Kelvin (k=3)	
	Solar reflected spectra cloud feedbacks snow/ice albedo feedbacks decadal change of: •Clouds •Radiative fluxes •Snow cover, sea ice, land use	CL.PRJ.REQ.1007 Solar spectral reflectance of the Earth and its atmosphere relative to the solar irradiance spectrum with: •Spectral coverage 320 to 2300 nm •Spectral resolution (8 nm) •Absolute uncertainty ≤ 0.3% relative to global mean reflected solar energy (k=2)	CL.SYS.REQ.2002 and 2006 Measure the Solar Reflected Spectra: •Spectral range 320 – 2300 nm •Spectral sampling 4 nm, resolution 8 nm •GIFOV ≤0.5 km by 0.5 km in nadir view •SNR > 33 for 380 to 900 nm, >20 elsewhere, for 0.3 reflectance, solar zenith angle 75° •Swath width ≥ 100 km •Polariz. sens.<0.5% (k=2) <1000nm, else <0.75% (k=2) >1000nm, •Radiometric calibration uncertainty ≤0.3% of albedo and within individual bands •Angle variation <25%, knowledge <10% IFOV •Geolocation knowledge <1 km on ground •Match RI sensors' view <5 min and <1 deg	CL.SYS.REQ.2100 Observations made from Earth orbiting observatories
	GNSS-RO decadal change of temperature profiles	CL.PRJ.REQ.1008 Atmospheric refractivity with: •Annual means in 10º latitude zones •Uncertainty of 0.03% (k=1) for 5-20 km altitude in these zones	CL.SYS.REQ.2003 Measure the phase delay rate of GNSS transmitted signal occulted by the atmosphere: •Altitudes 5-20 km •Uncertainty ≤0.5 mm/sec CL.SYS.REQ.2004 Measure averaged microwave refractivity: •Over 1 year 10° latitudinal zones, over all longitudes, •Altitudes 5–20 km •Uncertainty ≤0.03% in these zones	CL.SYS.REQ.2103 Consumables for 5 years
	Reference inter-calibration •Broadband CERES •Operational sounders (e.g. CrIS, IASI) •Operational imagers (e.g. VIIRS, AVHRR, Landsat)	CL.PRJ.1.REQ.1009 Provide data to climate relevant operational sensors that will be used to improve the accuracy of their measurements.		

Backup Slides