Calibration Accuracy for Cimate-Quality Data Sets from Space Observations

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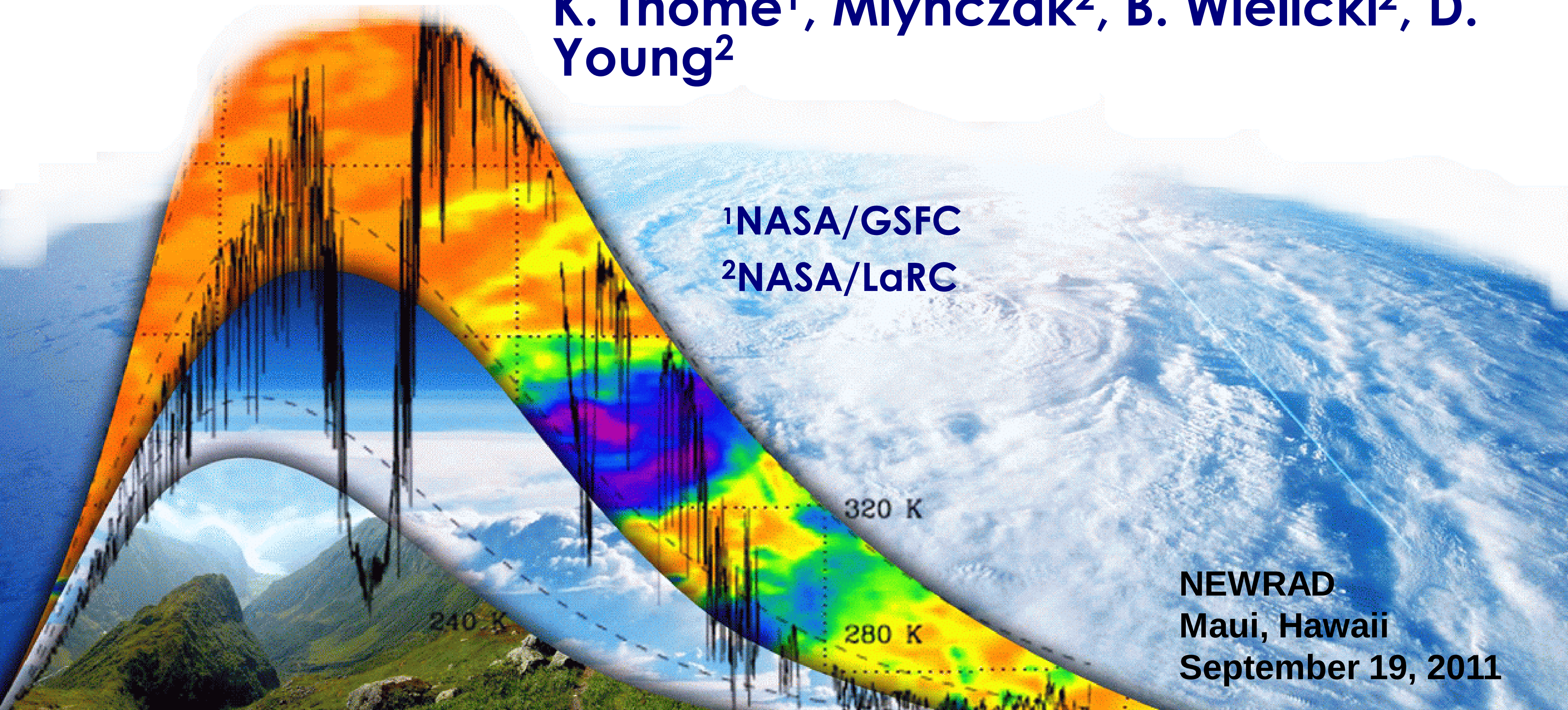

NEWRAD
Maui, Hawaii
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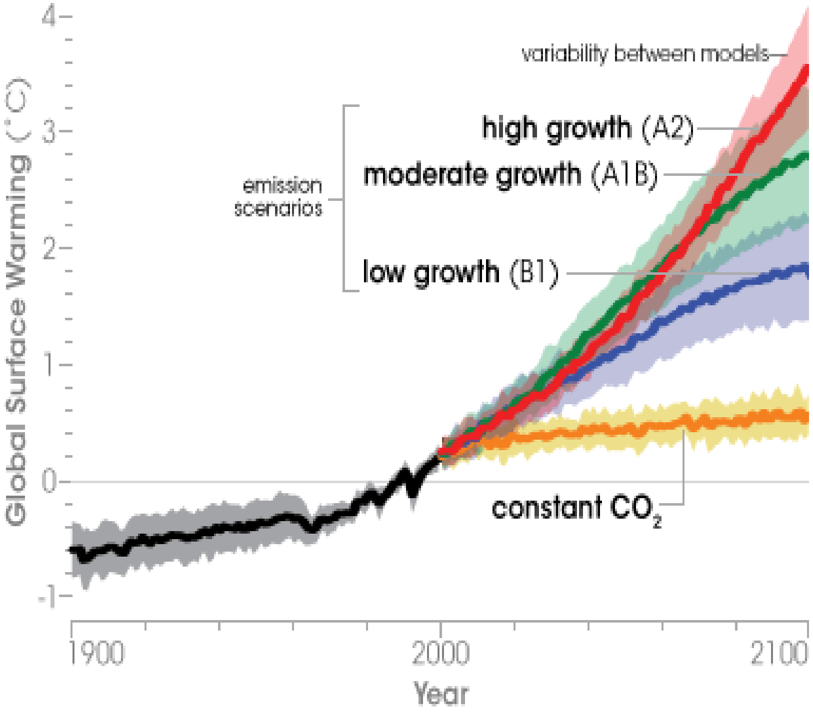
Talk overview

Climate quality data records require high accuracy and SI traceability

- One goal is to understand climate change projections
- Summarize methods to determine the observing requirements
    - Reflected solar and IR
    - SI-traceable uncertainty
    - Temperature to 0.07 K (*k*=2)
    - Reflectance to 0.3% (*k*=2)
- Instrument approaches and calibration methods

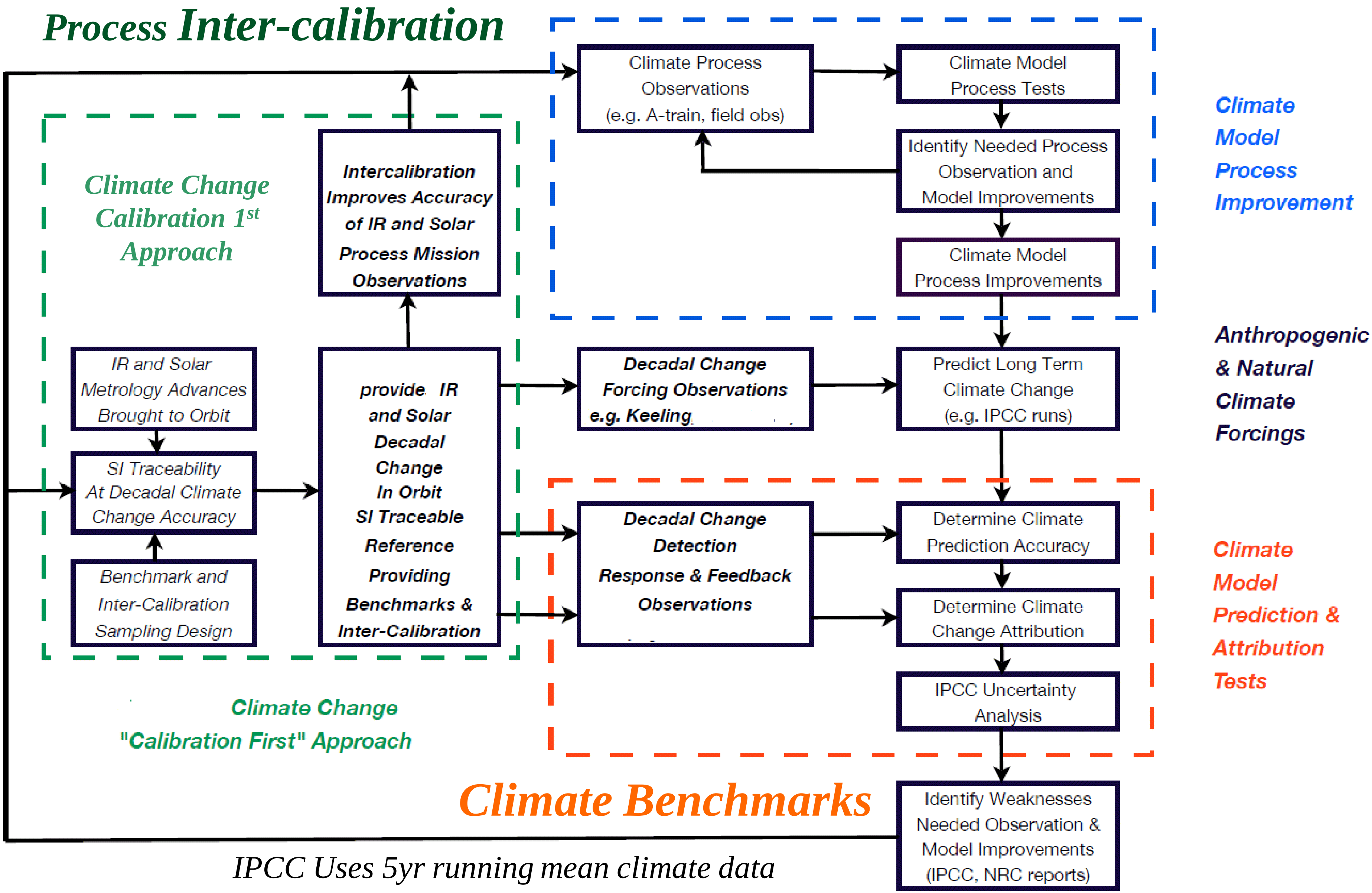


Climate model test and decadal change

Most powerful test of climate model prediction accuracy is decadal change observations

- Accuracy required at large time and space scales
  - Zonal annual, not instantaneous field of view
  - Very different than typical process missions
- Questions are
  - How long a data record is needed?
  - What variables are key?
  - What accuracy relative to perfect observing system is needed?
- How are the above determined?

Climate Science and Observations



Process Inter-calibration

Climate Change Calibration 1st Approach

Intercalibration Improves Accuracy of IR and Solar Process Mission Observations

IR and Solar Metrology Advances Brought to Orbit

SI Traceability At Decadal Climate Change Accuracy

Benchmark and Inter-Calibration Sampling Design

provide IR and Solar Decadal Change In Orbit SI Traceable Reference Providing Benchmarks & Inter-Calibration

Climate Process Observations (e.g. A-train, field obs)

Climate Model Process Tests

Identify Needed Process Observation and Model Improvements

Climate Model Process Improvements

Climate Model Process Improvement

Decadal Change Forcing Observations e.g. Keeling

Predict Long Term Climate Change (e.g. IPCC runs)

Anthropogenic & Natural Climate Forcings

Decadal Change Detection Response & Feedback Observations

Determine Climate Prediction Accuracy

Determine Climate Change Attribution

IPCC Uncertainty Analysis

Climate Model Prediction & Attribution Tests

Climate Change "Calibration First" Approach

Climate Benchmarks

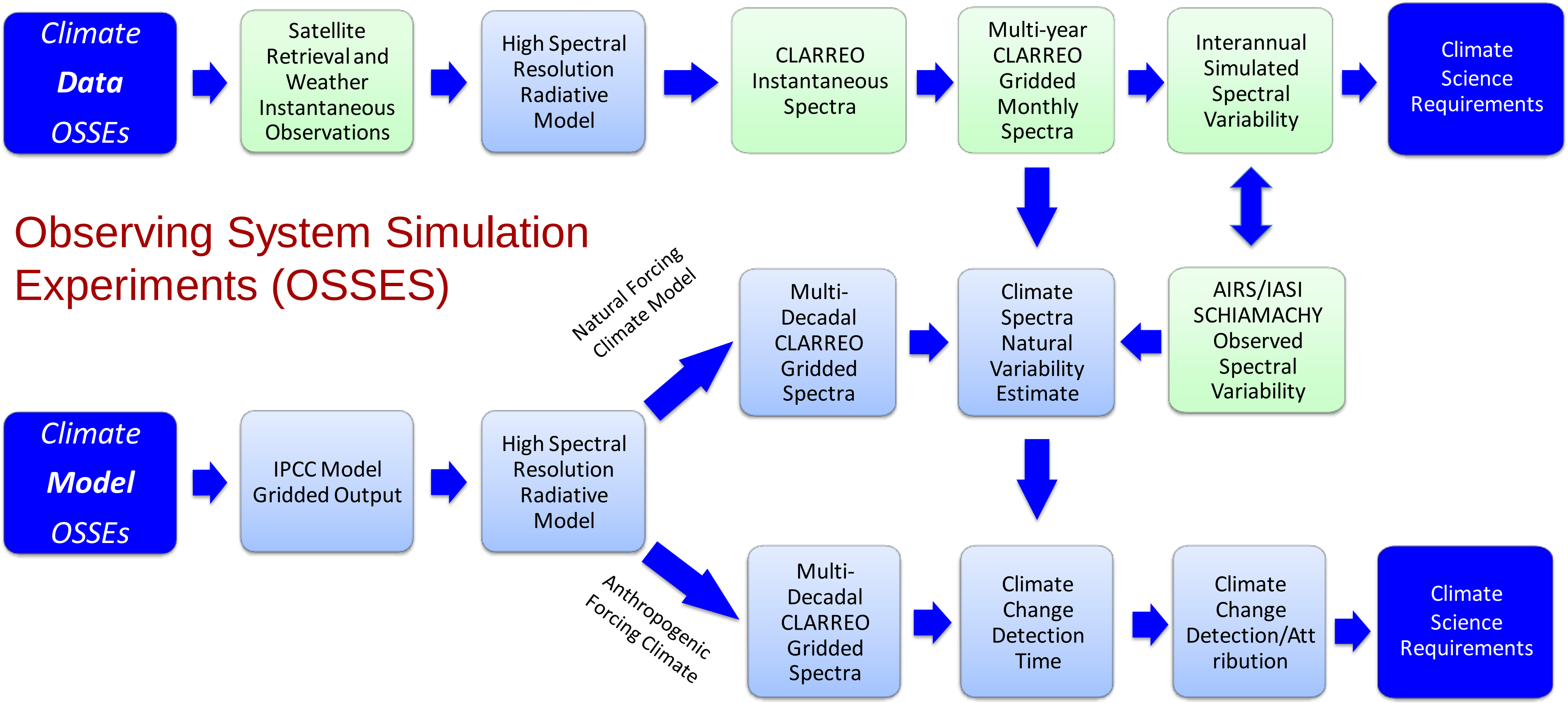
Identify Weaknesses Needed Observation & Model Improvements (IPCC, NRC reports)

IPCC Uses 5yr running mean climate data

Climate science requirements

Observations and climate model predictions combined to develop requirements

Observing System Simulation Experiments (OSSES)



Climate ***Data*** *OSSEs*

Satellite Retrieval and Weather Instantaneous Observations

High Spectral Resolution Radiative Model

CLARREO Instantaneous Spectra

Multi-year CLARREO Gridded Monthly Spectra

Interannual Simulated Spectral Variability

Climate Science Requirements

AIRS/IASI SCHIAMACHY Observed Spectral Variability

Climate Spectra Natural Variability Estimate

Multi-Decadal CLARREO Gridded Spectra

Natural Forcing Climate Model

Climate ***Model*** *OSSEs*

IPCC Model Gridded Output

High Spectral Resolution Radiative Model

Anthropogenic Forcing Climate

Multi-Decadal CLARREO Gridded Spectra

Climate Change Detection Time

Climate Change Detection/Attribution

Climate Science Requirements

Feedbacks Drive Sampling Requirements

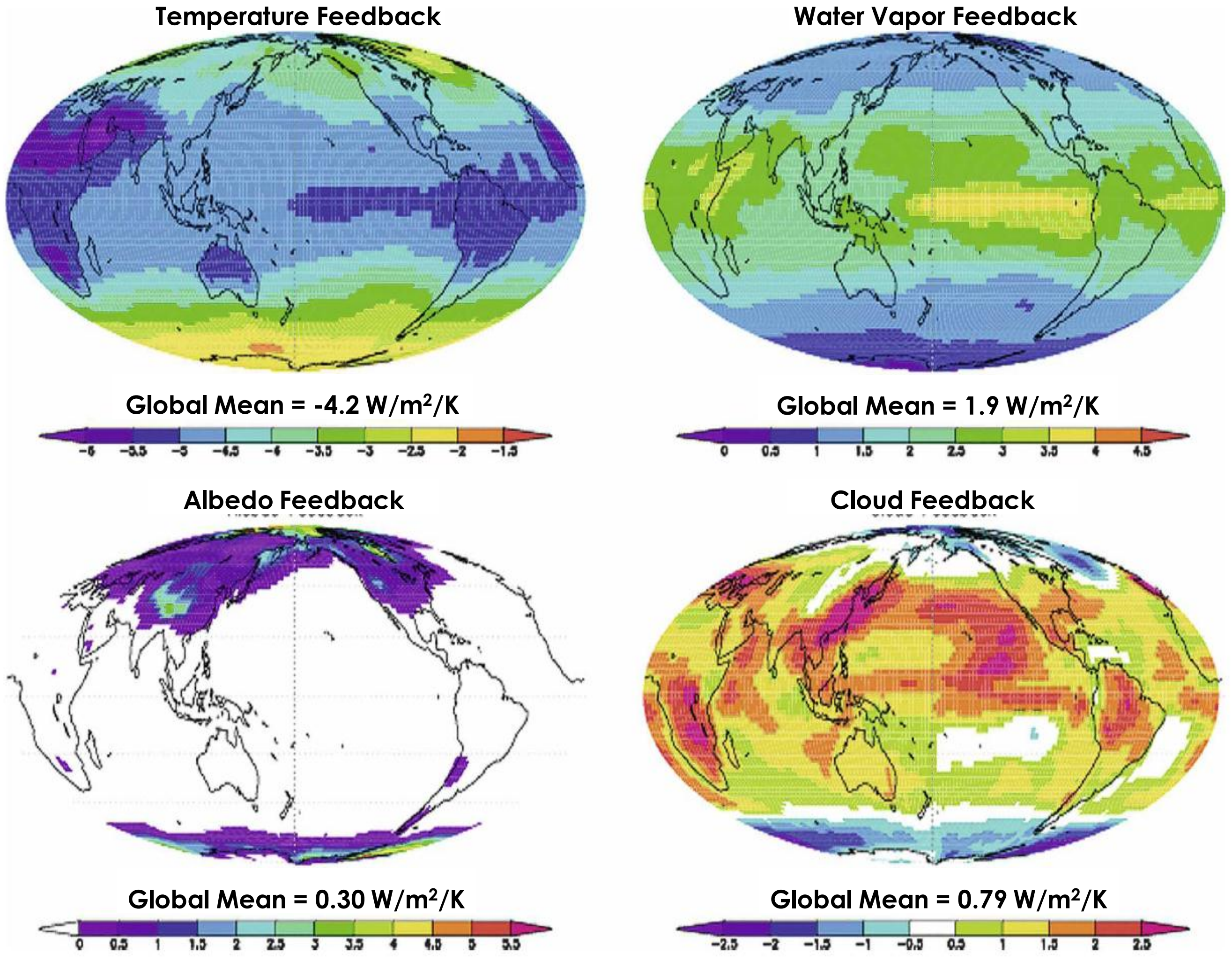


FIG. 8. Multimodel ensemble-mean maps of the temperature, water vapor, albedo, and cloud feedback computed using climate

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)

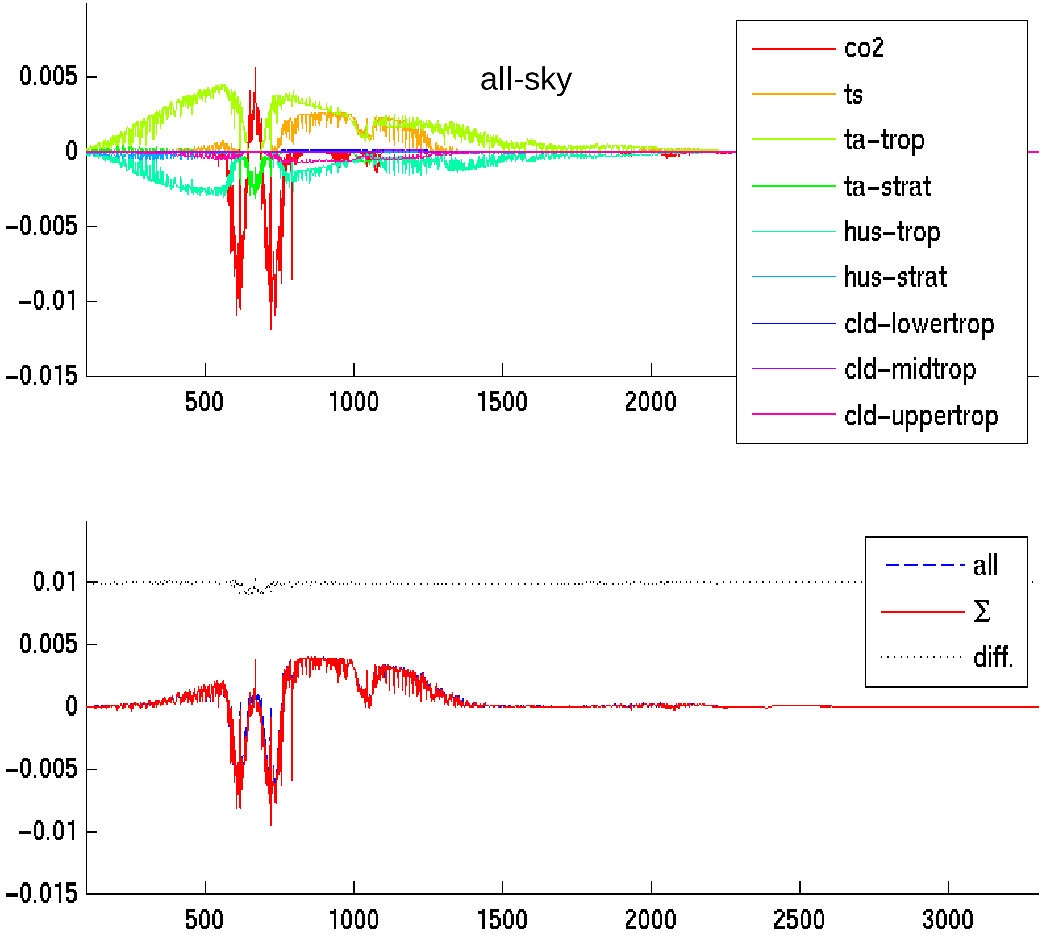
Zonal annual means of land and ocean for lapse rate, water vapor, and surface albedo feedbacks

1000 km regional scale required for cloud feedbacks

Seasonal cycle required for reflected solar: cloud feedback, snow/ice albedo feedback

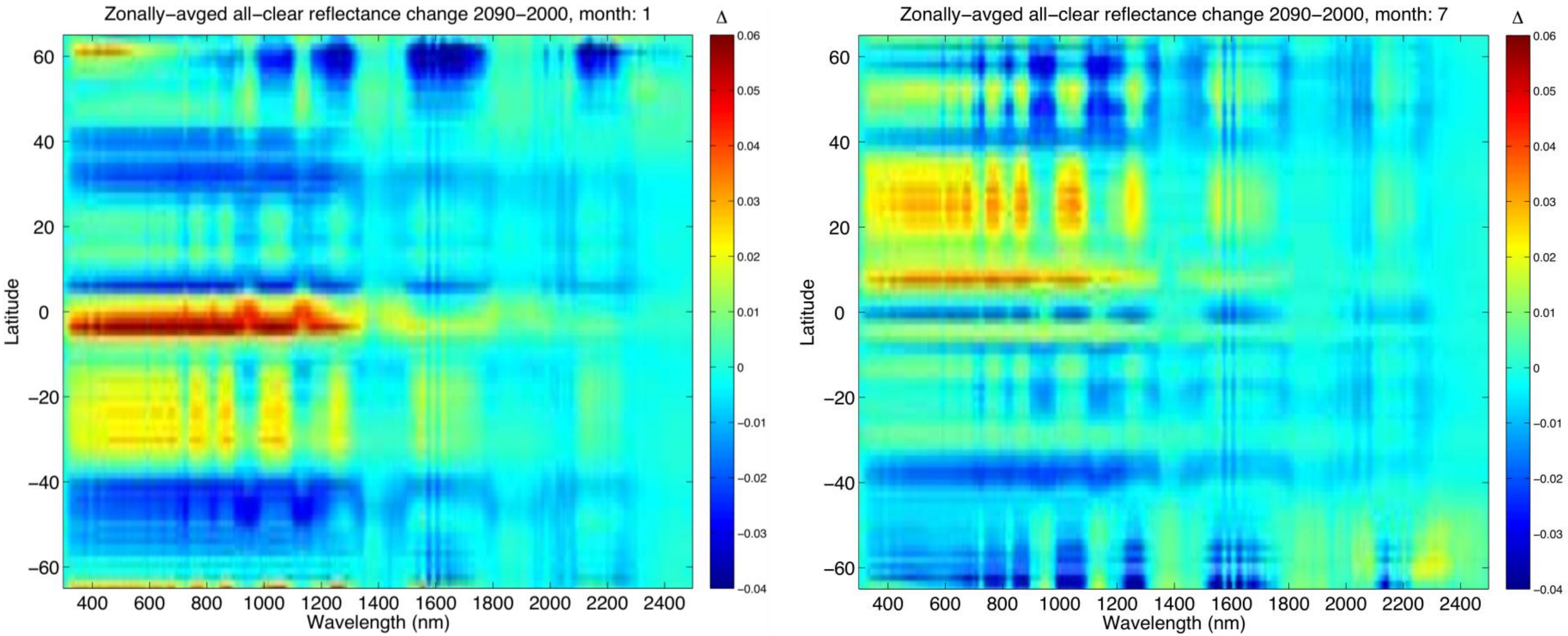
IR OSSEs

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



- Doubled CO2 change of all-sky global spectral radiance from T(z), q(z), CO2, clouds, for the CFMIP CCCMA coupled climate model
- Examined linear sum of components versus total
- Eliminates the requirement for global clear-sky observations (Huang and Leroy, 2009)

RS OSSEs



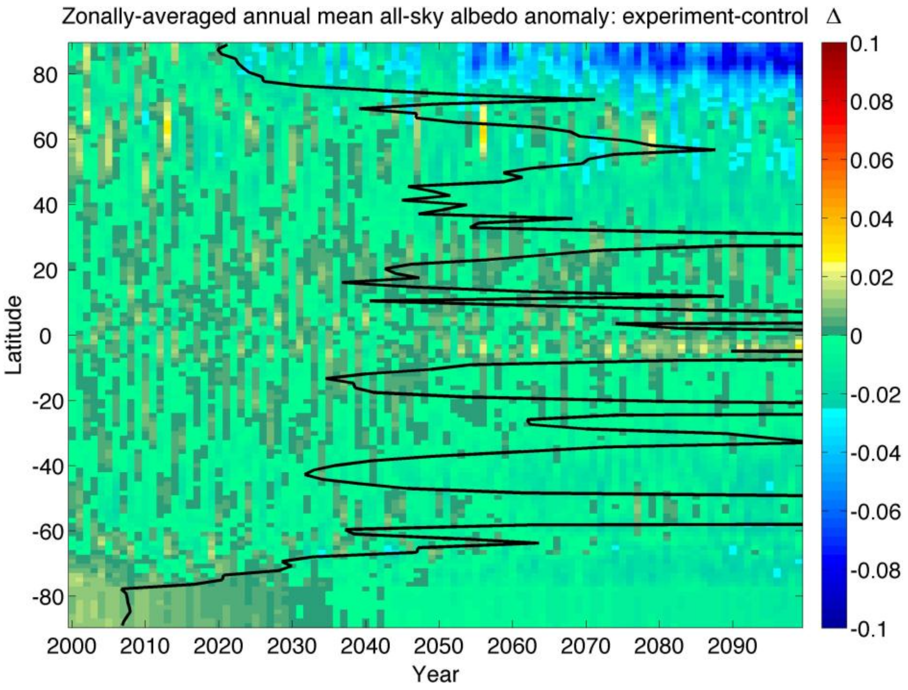
Collins and Feldman, AGU Fall Meeting, 2010

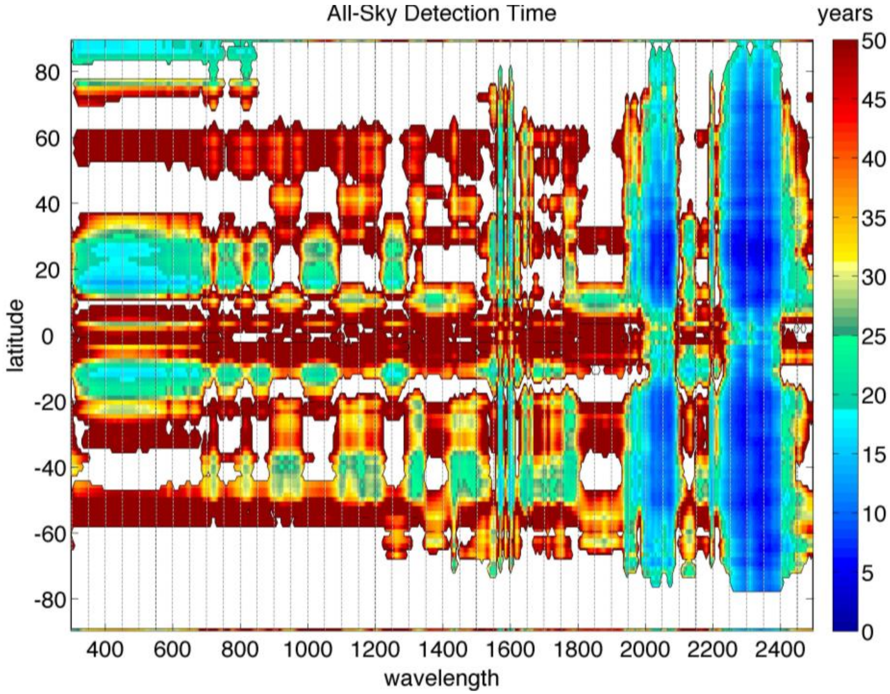
Studies demonstrate linearity & information content of decadal change solar-reflected radiance signals

- U-Cal Berkeley, LASP, and LaRC

RS OSSEs

Δ All-sky spectral albedo evaluation shows time to detect (95% confidence)





Spectral measurements *shorten* time to detection over tropics and subtropics.

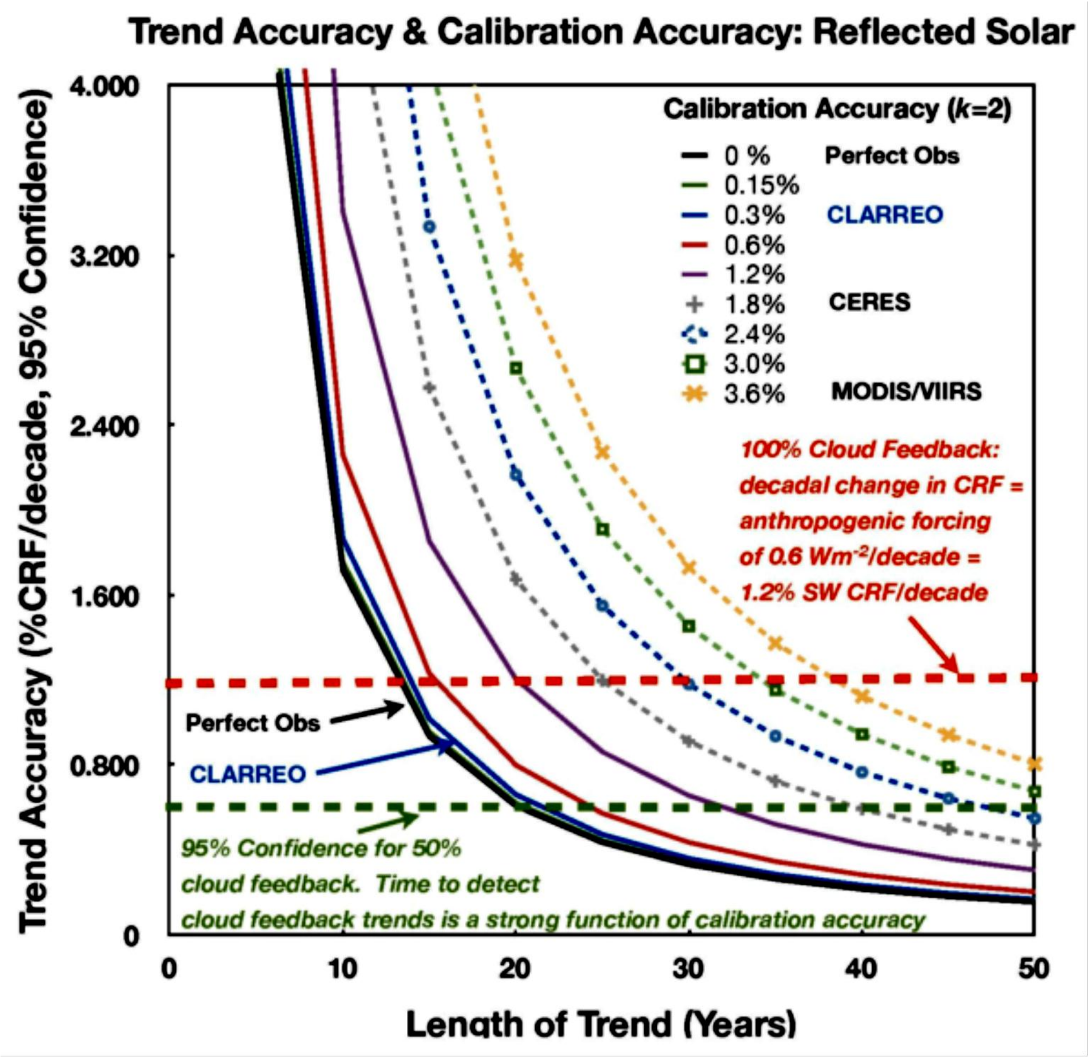
Collins et al, AGU Fall Meeting 2010

Accuracy Requirements

- Instrument absolute accuracy requirements are derived with the goal of achieving measurements
  - Within 20% of a perfect climate observing system
  - Time to detect trends within 15% of perfect observing system
- 0.1 K (*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 accuracy of 0.1K (*k*=3) for temperature profile for 5km to 20km altitudes.
- SI traceable observations to survive short gaps in record

Accuracy requirements

Accuracy requirements can be inferred relative to natural variability & time to detect


Trend Accuracy & Calibration Accuracy: Reflected Solar

100% Cloud Feedback: decadal change in CRF = anthropogenic forcing of 0.6 Wm^{-2}/decade = 1.2% SW CRF/decade

95% Confidence for 50% cloud feedback. Time to detect cloud feedback trends is a strong function of calibration accuracy

- Traceable uncertainties from decadal change observation to SI standards, at decadal change accuracy levels
- Accuracy requirements driven by a time to detect above natural variability

Measurement approach

Benchmark climate data records provide the decadal change observations

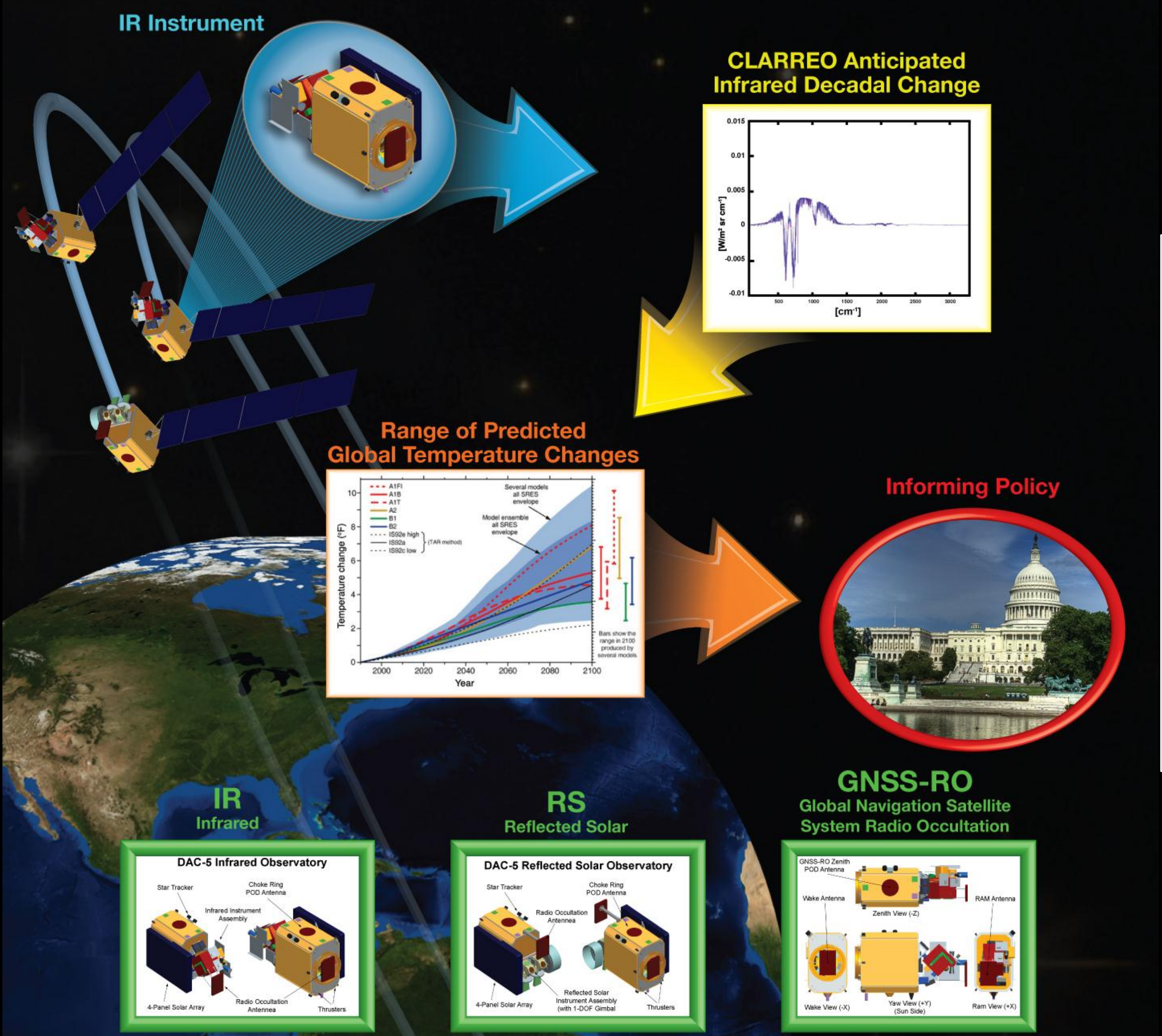
- Benchmarks can be formed in two complementary ways
  - Well-calibrated, highly accurate sensor (e.g. TRUTHS, CLARREO) for direct data collection
  - Well-calibrated sensor calibrates operational sensors
- Dual approach provides test analogous to using independent measurements and analysis in metrology
- Accuracy of benchmark observations is required only at large time and space scales

Verification Systems Provide SI Traceability

SI Traceability: Unbroken chain of comparison with stated uncertainties

- Partially met through traditional methods
  - Blackbody and deep space for radiance calibration
  - Lunar views
  - Temperature sensors to detect and correct for detector package changes
  - Preflight calibration
- On-orbit verification system
  - Quantify sources of bias
    - Polarization effects
    - Instrument line shape
    - Stray light
  - Verify accuracy through known sources

CLARREO: Calibrating Planet Earth

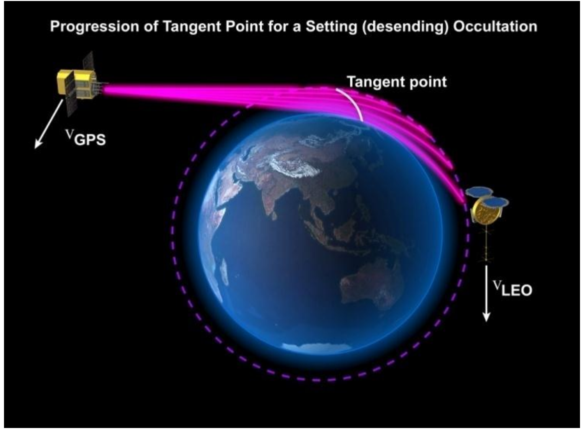


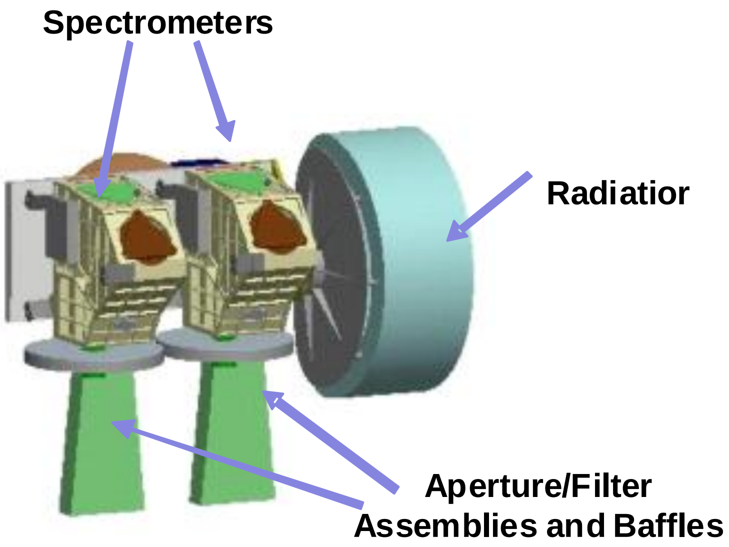
CLimate
Absolute
Radiance &
REfractivity
Observatory

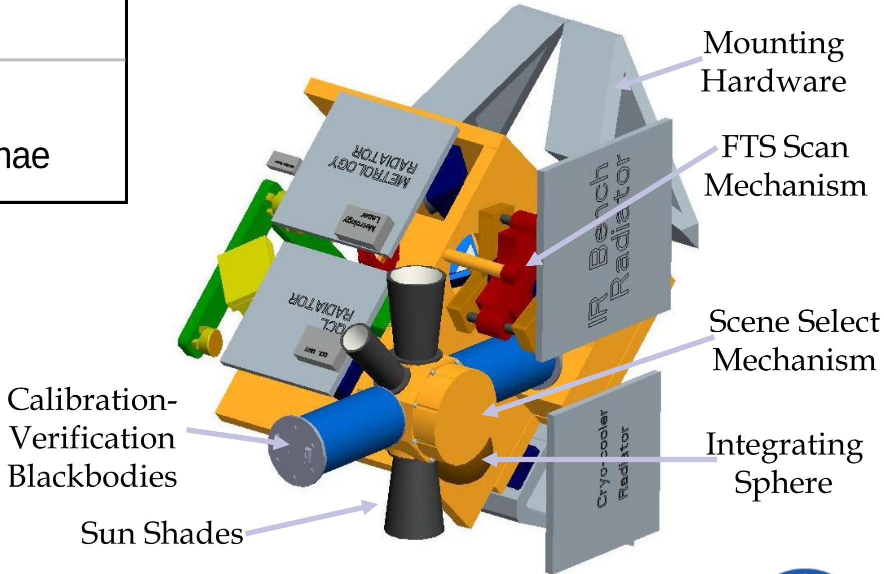
CLARREO Mission Overview

Payload Suite

Instrument	Features	
Infrared Spectrometer	Type	Fourier transform spectrometer
	Spectral Range	5 to 50 micron
	Configuration	Single combined instrument
Reflected Solar Spectrometer	Type	Grating spectrometer
	Spectral Range	320-2300 nanometer
	Configuration	Two box design
GNSS Radio Occultation System	Signal Range	GPS and Galileo
	Configuration	Receiver Two occultation antennae







IR Instrument Concept Design (BB Radiator and Enclosure Partially Removed)

CLARREO Project update

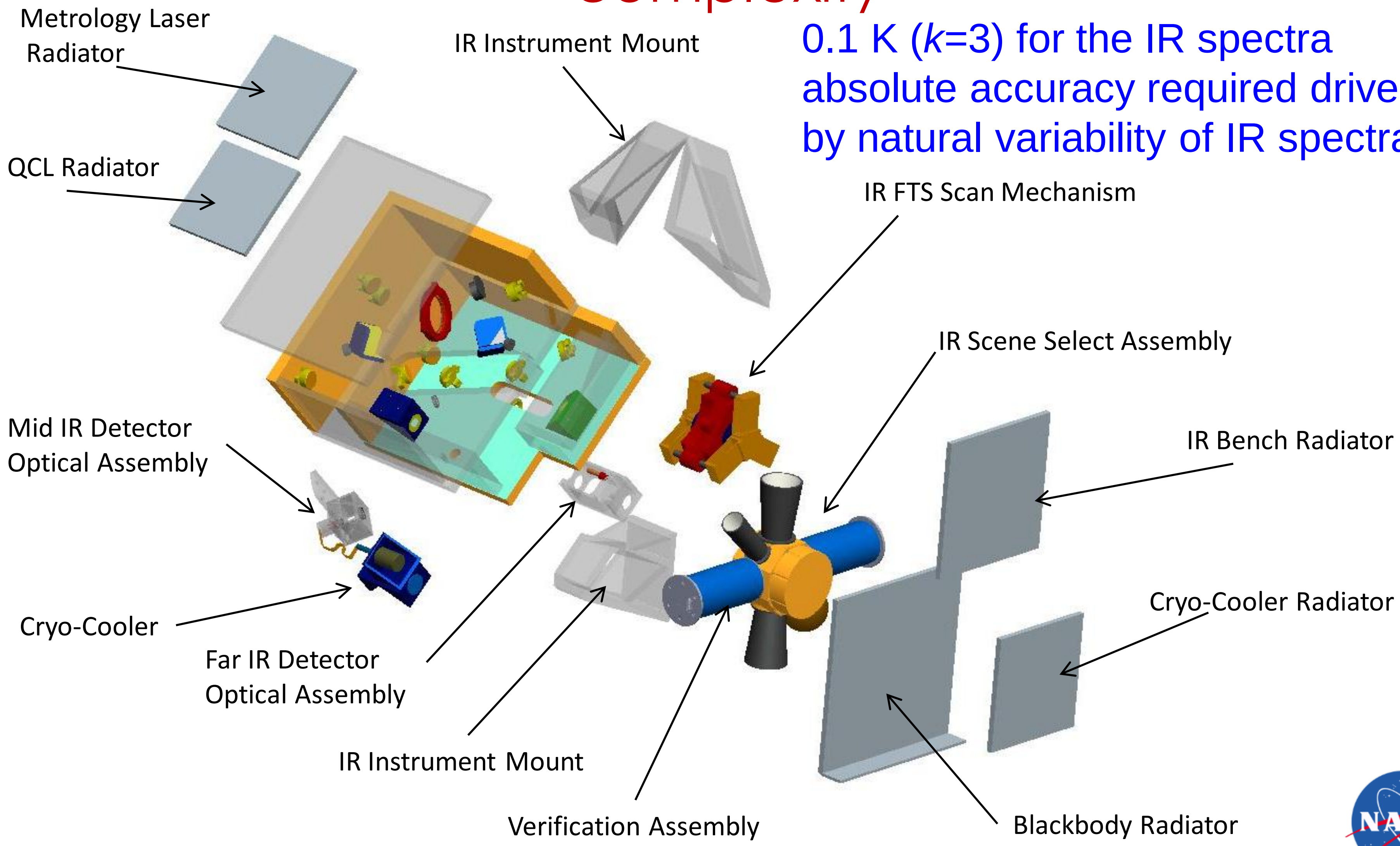
It has been an up and down ten months for CLARREO

- Demonstrated readiness to begin Phase A at a successful Mission Concept Review in November 2010
- Science Definition Team selected January 2011
- Unfortunately, FY2012 NASA budget removed $1.2 billion from proposed NASA Climate Initiative in FY2012 - FY2015
    - NASA was directed not to proceed to Phase A for CLARREO in FY2011
    - CLARREO was placed in “Extended Pre-Phase A” from FY2012-FY2016
- Funding will continue to allow work to concentrate on
    - Advancing CLARREO science, including continuation of Science Definition Team
    - Exploring cost-effective alternatives for achieving some portion of the CLARREO science objectives
    - Reducing risk for achieving on-orbit SI-traceability
    - Continuing engagement with the user community (GSICS, CEOS) and potential international partners

IR Instrument Suite

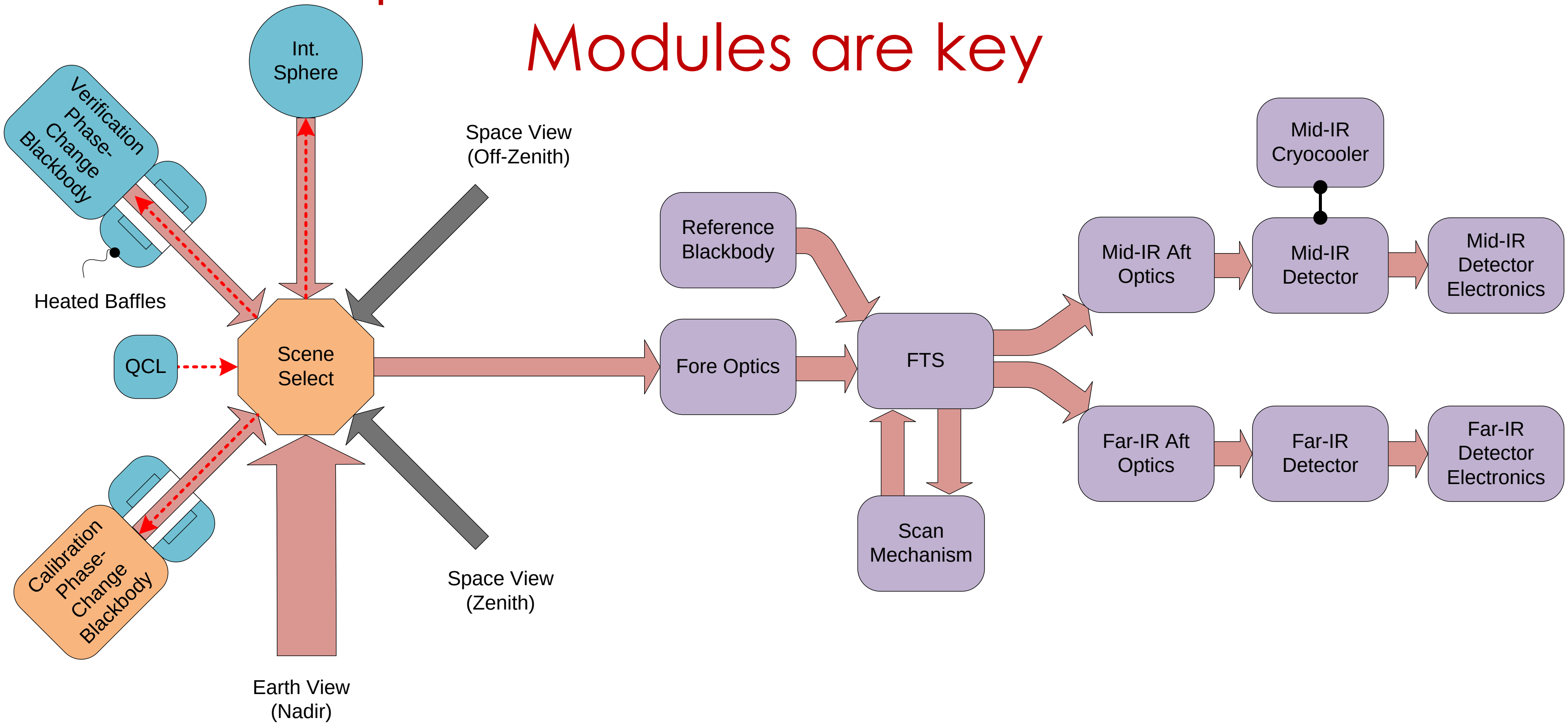
Instrument suite is of moderate size and complexity

0.1 K (k=3) for the IR spectra absolute accuracy required driven by natural variability of IR spectra.



IR Concept

Electro-Optical and Calibration-Verification Modules are key

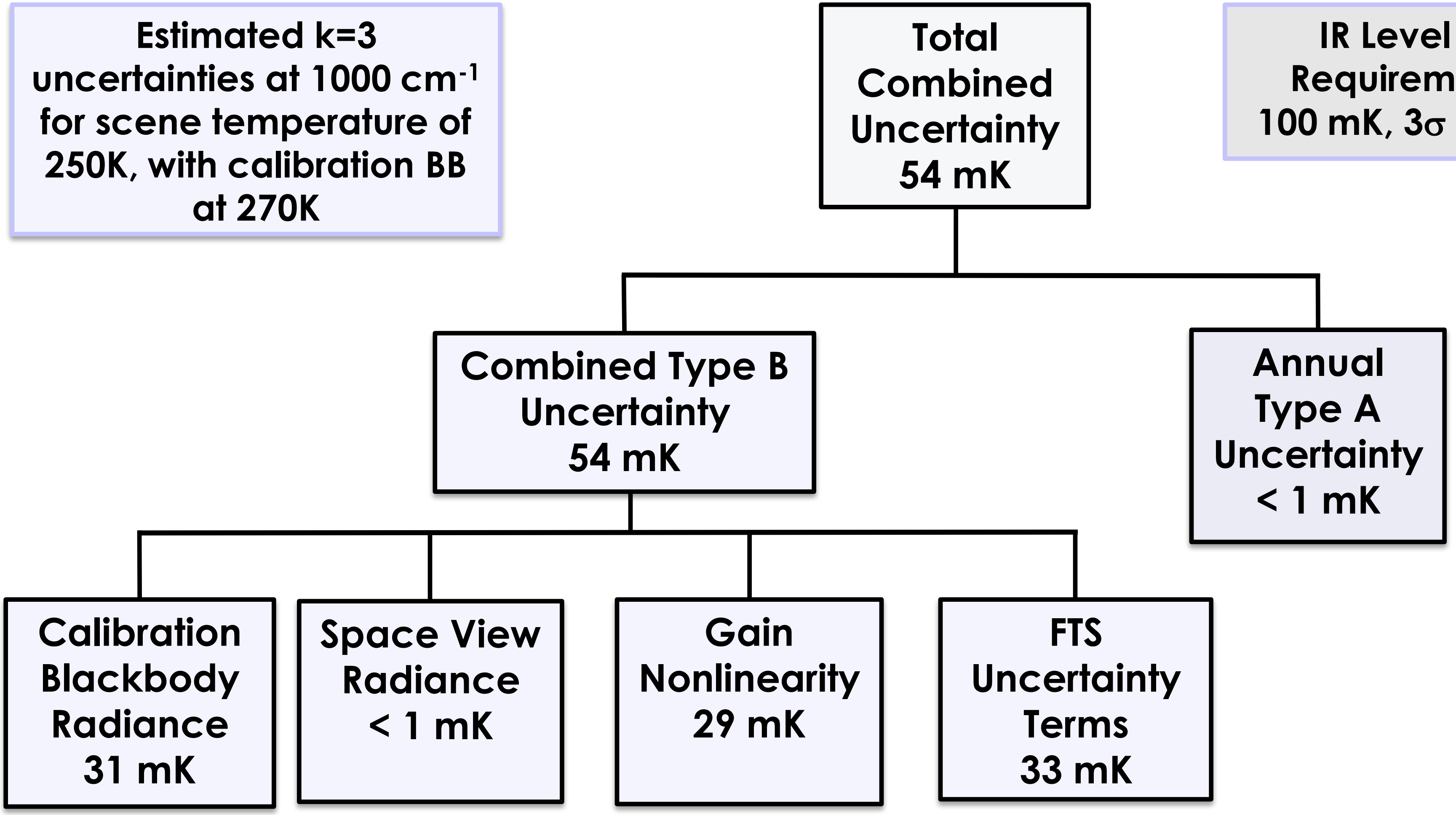

Int. Sphere
Verification Phase-Change Blackbody
Heated Baffles
QCL
Scene Select
Calibration Phase-Change Blackbody
Earth View (Nadir)
Space View (Off-Zenith)
Space View (Zenith)
Reference Blackbody
Fore Optics
FTS
Scan Mechanism
Mid-IR Aft Optics
Mid-IR Cryocooler
Mid-IR Detector
Mid-IR Detector Electronics
Far-IR Aft Optics
Far-IR Detector
Far-IR Detector Electronics

🟪 ***Electro-Optical***
🟧 ***Calibration/Collection***
🟦 ***Verification***

IR Error budget

Estimated k=3 uncertainties at 1000 cm^{-1} for scene temperature of 250K, with calibration BB at 270K

IR Level 1 Requirement
100 mK, 3σ (k=3)



Total Combined Uncertainty
54 mK

Combined Type B Uncertainty
54 mK

Annual Type A Uncertainty
< 1 mK

Calibration Blackbody Radiance
31 mK

Space View Radiance
< 1 mK

Gain Nonlinearity
29 mK

FTS Uncertainty Terms
33 mK

On-Orbit Calibration of Verification Blackbody

- Referenced to International Temperature Scale (ITS) through pure materials (water, gallium, mercury)
- Thermistors in blackbody continuously calibrated providing fundamental tie to SI through Kelvin

$$L_{BB}(v,T_{BB}) = \varepsilon_{BB}(v) * \frac{2hv^3}{c^2} * \frac{1}{(e^{(hv/kT_{BB})} - 1)}$$

Planck Equation

Emissivity

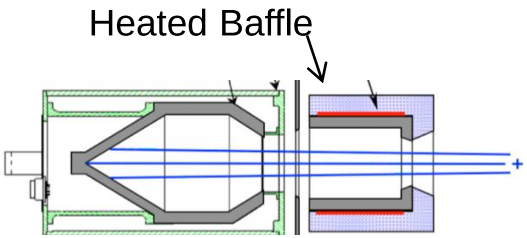
Temperature

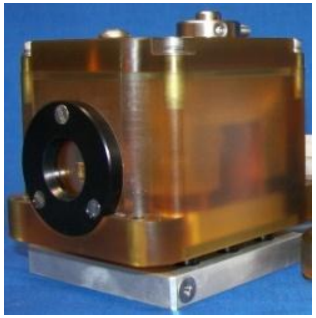
3 Phase Change Cells Provide SI Traceable Fixed Points (-40°C, 0°C, 30°C)

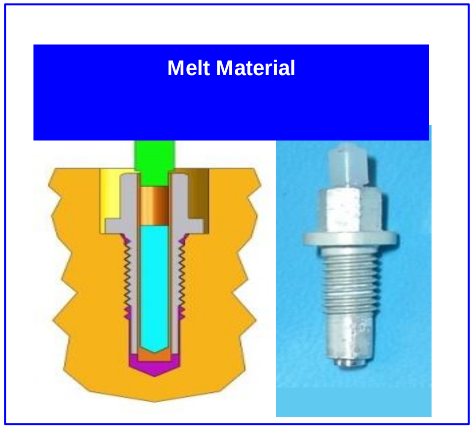
Cavity Emissivity Measurement

Quantum Cascade Laser (QCL)

Phase Change Cells





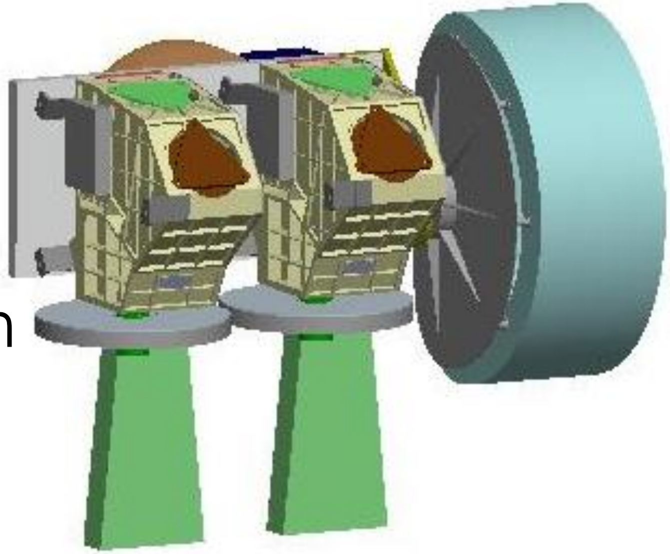


SI (Kelvin)-Based IR Radiance Scale Realization

RS instrument

Reflectance must be traceable to SI standards at an absolute uncertainty <0.3%

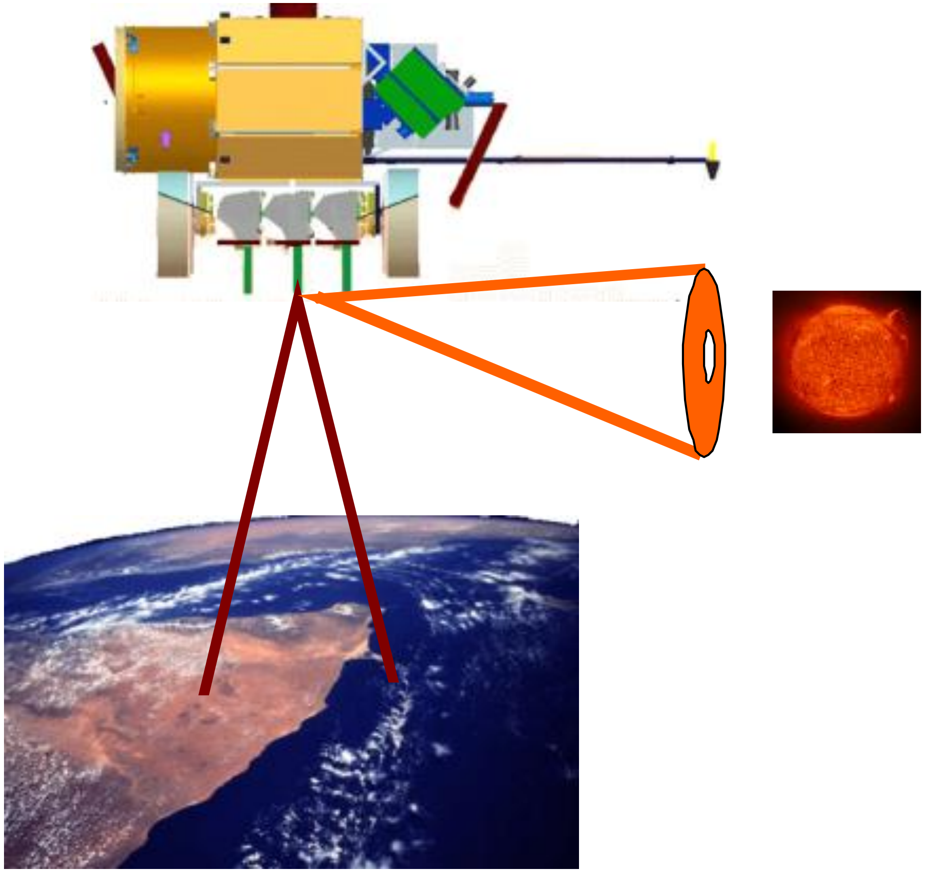
- Reflectance obtained from ratio of radiance while viewing earth's surface to measurements of irradiance while viewing the sun
- Spectral range from 320 to 2300 nm
- 500-m GIFOV with 100-km swath
- Goal of sensor design is to reduce complexity for accurate calibration
- Spectrometer approach with two separate entrance apertures
- Commonality of design of two boxes aids in calibration



Reflectance approach

- Retrieve reflectance via ratio of earth-view data to solar-view data
  - Single detector scans entire solar disk
  - Response of ith detector is

$$R^{sensor}_{i,\lambda} = \frac{\sum_{x_{solar}} \sum_{y_{solar}} S^{solar}_{i,\lambda}(x'_{solar}, y'_{solar})}{(T_{attenuator} A_{attenuator}) E_{solar}}$$



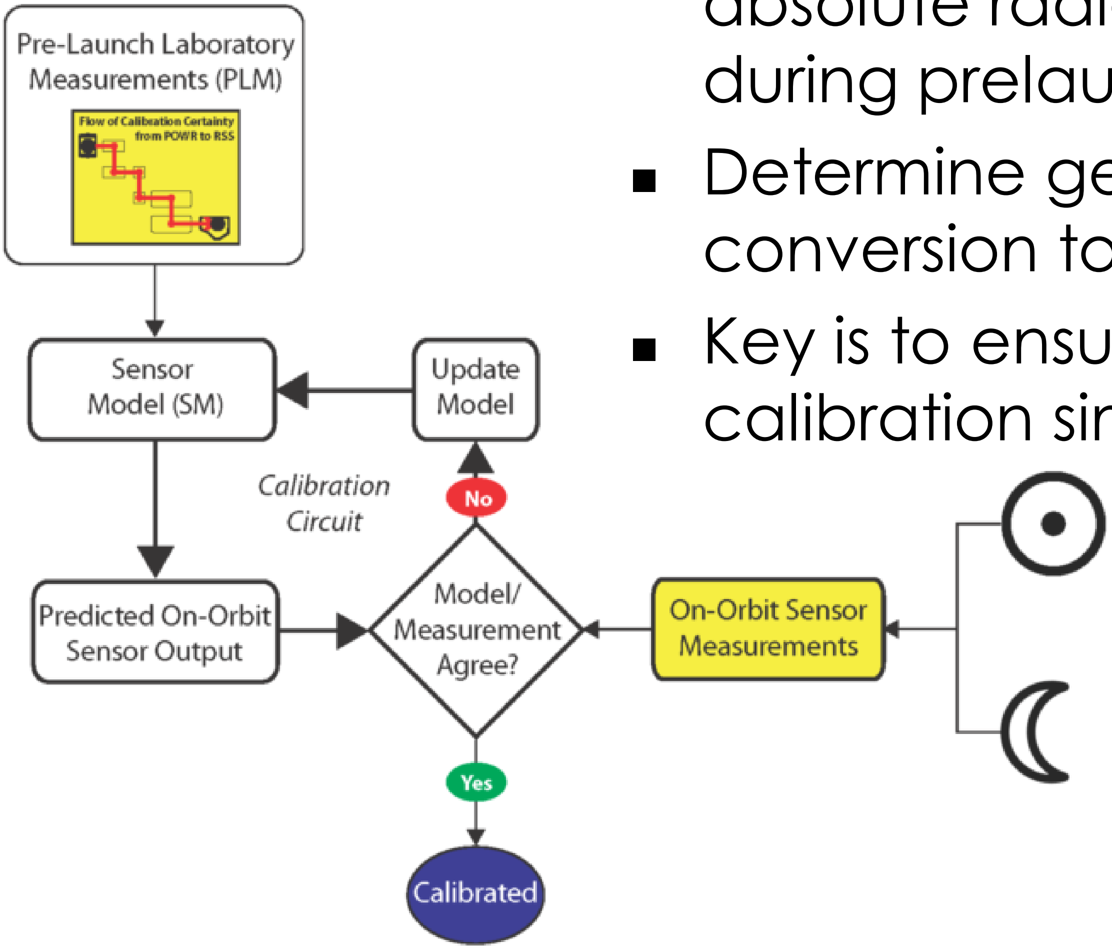
- Bidirectional reflectance distribution function (BRDF) is

$$BRDF^{earth}_{i,\lambda} = \frac{L^{earth}_{i,\lambda}}{E_{sun}\cos\theta_{solar}} = \frac{S^{earth}_{i,\lambda}}{R^{sensor}_{i,\lambda} A_{sensor} \Omega_{sensor}} \quad \frac{(T_{attenuator} A_{attenuator}) R^{sensor}_{i,\lambda}}{\cos\theta_{solar} \sum_{x_{solar}} \sum_{y_{solar}} S^{solar}_{i,\lambda}(x'_{solar}, y'_{solar})}$$

Calibration approach

Successful transfer to orbit through accurate prediction of sensor behavior

- Characterize sensor to SI-traceable, absolute radiometric quantities during prelaunch calibration
- Determine geometric factors for conversion to reflectance
- Key is to ensure prelaunch calibration simulates on-orbit sources


Pre-Launch Laboratory Measurements (PLM)

Flow of Calibration Certainty from POWR to RSS

Sensor Model (SM)

Update Model

Calibration Circuit

No

Predicted On-Orbit Sensor Output

Model/ Measurement Agree?

On-Orbit Sensor Measurements

Yes

Calibrated

Key error terms

Developed a preliminary error budget based on a nominal design for the RS sensor

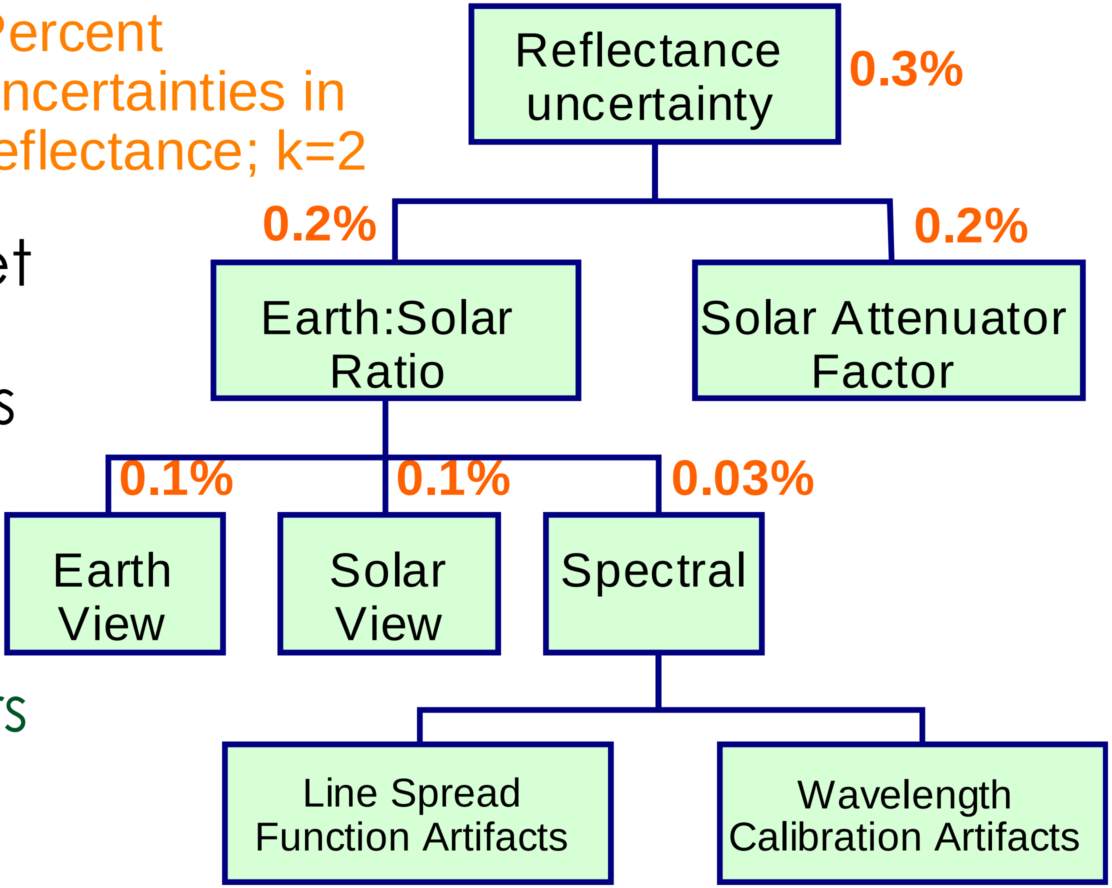
- Key uncertainties are
  - Geometry differences between the solar and earth views
  - Knowledge of attenuator behavior when viewing the sun
  - Sensor behavior
    - Detector linearity
    - Noise behavior
  - Polarization

$$BRDF_{i,\lambda}^{earth} = \frac{S_{i,\lambda}^{earth}}{R_{i,\lambda}^{sensor} A_{sensor} \Omega_{sensor}} \frac{(T_{attenuator} A_{attenuator}) \left\langle R_{\lambda}^{sensor} \right\rangle}{\cos\theta_{solar} \sum_{k} \sum_{l} S_{k,l}^{solar} r_{k,\lambda}^{flat\ field}} \frac{a_{sensor}^{straylight} \omega_{sensor}^{straylight} a_{attenuator}^{straylight}}{r_{i,\lambda}^{flat\ field} r_{i,\lambda}^{nonlinearity} r_{i,\lambda}^{polarization}}$$

SIRCUS-based Error Budget

- Radiometric calibration requirements of RS instrument can be met with currently-available approaches
- Requires inclusion of NIST-based methods
  - Detector-based transfer radiometers
  - Narrow-band SIRCUS aproaches
  - Hyperspectral image projector-based scene projections

Percent uncertainties in reflectance; k=2



Reflectance uncertainty **0.3%**

0.2% Earth:Solar Ratio

0.2% Solar Attenuator Factor

0.1% Earth View

0.1% Solar View

0.03% Spectral

Line Spread Function Artifacts

Wavelength Calibration Artifacts

Summary

Climate-quality data records are achievable with current technology

- Climate OSSEs are invaluable in the definition of mission requirements
- Give confidence that the measurement approach would meet the goals of the Decadal Survey
- Climate model OSSEs should be used to provide more rigorous climate observing system requirements where possible including perturbed physics ensembles
- Lessons learned from CLARREO mission definition are applicable to other missions
- A goal of CLARREO pre-Phase A efforts is to ensure that these lessons are not lost

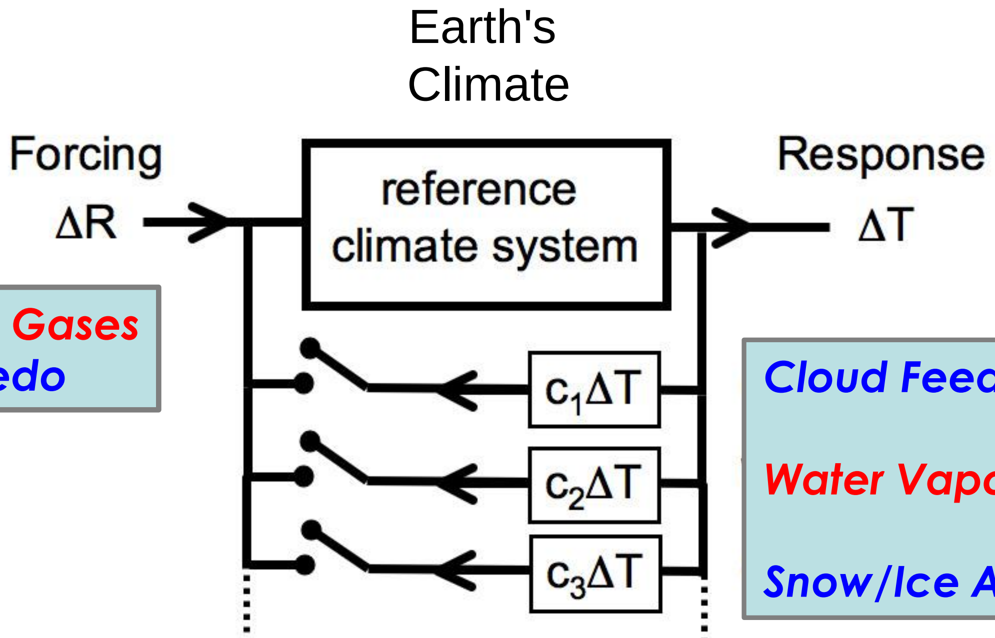
Backup Slides

Forcing, Response, Feedback

100% of science value is in the data accuracy

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

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



Roe and Baker, 2007

- *Greenhouse Gases*
- *Surface Albedo*

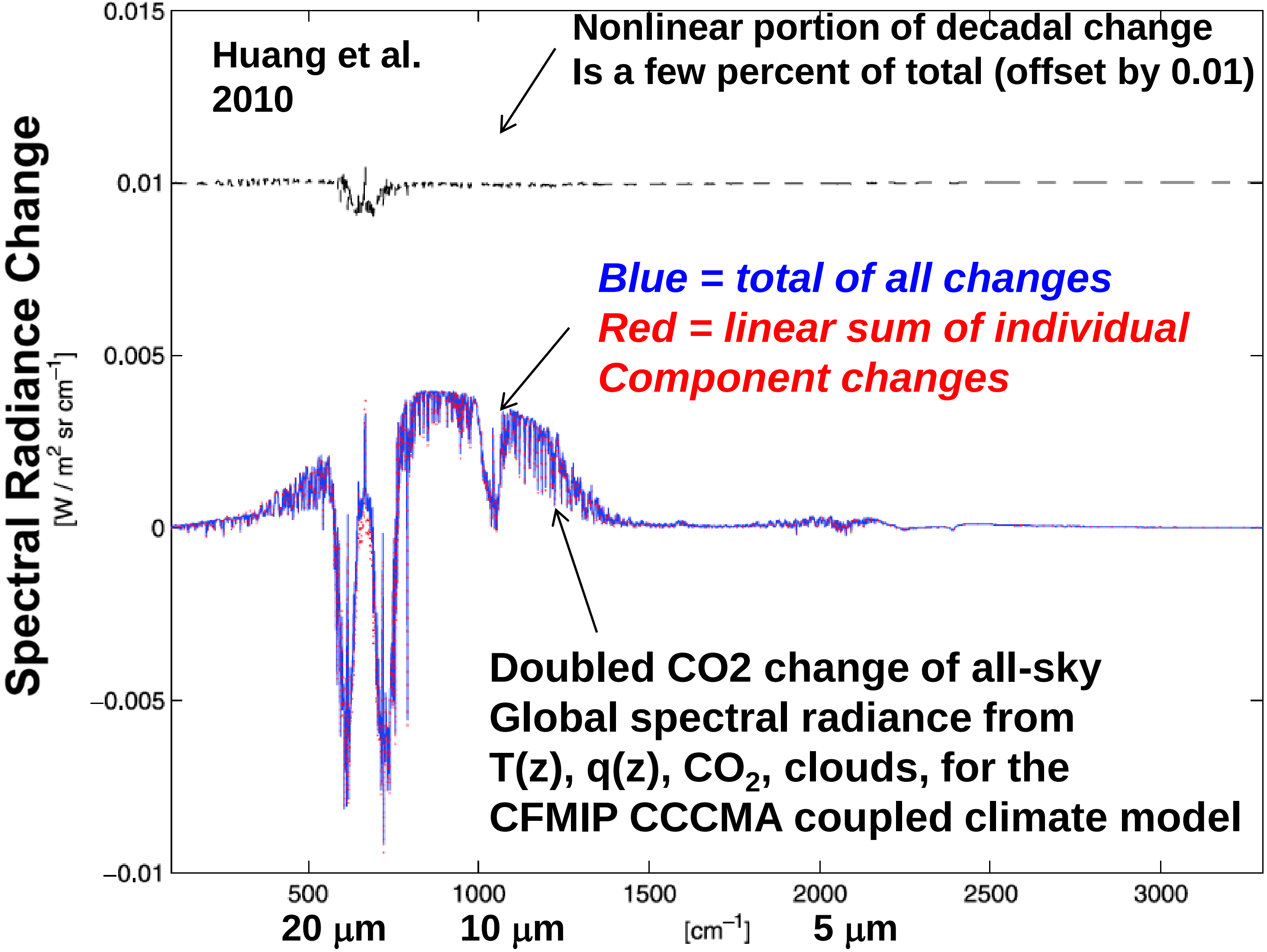
Cloud Feedback

Water Vapor/Lapse Rate Feedback

Snow/Ice Albedo Feedback

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

Spectral Decadal Change is Linear



**Huang et al.
2010**

**Nonlinear portion of decadal change
Is a few percent of total (offset by 0.01)**

Blue = total of all changes
***Red = linear sum of individual
Component changes***

**Doubled CO2 change of all-sky
Global spectral radiance from
T(z), q(z), CO_2, clouds, for the
CFMIP CCCMA coupled climate model**

***Instantaneous
changes are
nonlinear:
decadal
change is
highly linear***

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