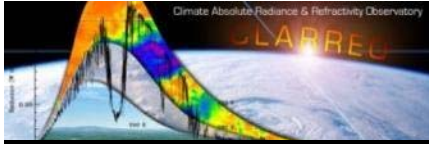

NASA CLARREO Mission

**Sixth National Workshop on the
Science of Climate Change
INCOIS, Hyderabad, India
*Sept 1-2, 2014***

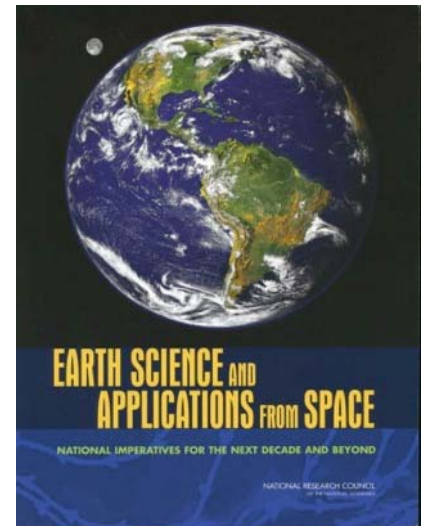
***Bruce Wielicki
NASA Langley Research Center***



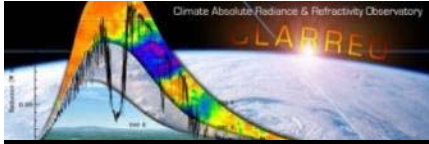
CLARREO Solves the Climate Accuracy Challenge



- Insufficient absolute accuracy remains an Achilles Heel for climate change observations and therefore climate model testing, climate model predictions of future change, and societal policy decisions.
- Current instruments typically rely on overlap and much lower confidence stability arguments. Gaps seriously degrade climate records
- *CLARREO is the SI traceable high accuracy rigorous answer for the entire solar and infrared spectrum ("NIST in orbit") that dominate Earth's climate change. CLARREO bridges gaps. GSICS needs CLARREO as its reference standard (WMO letter). ECMWF for assimilation bias reference (letter).*
- The economic net present value of advancing climate change knowledge for societal decisions by CLARREO like accuracy is estimated using the Interagency Memo on the Social Cost of Carbon as \$3 to \$20 Trillion (2007 U.S dollars depending on discount rate assumed).
- *CLARREO is the cornerstone of the Climate Observation System. Accuracy is a broad system enabler.*



CLARREO does for climate change observations what GPS did for navigation



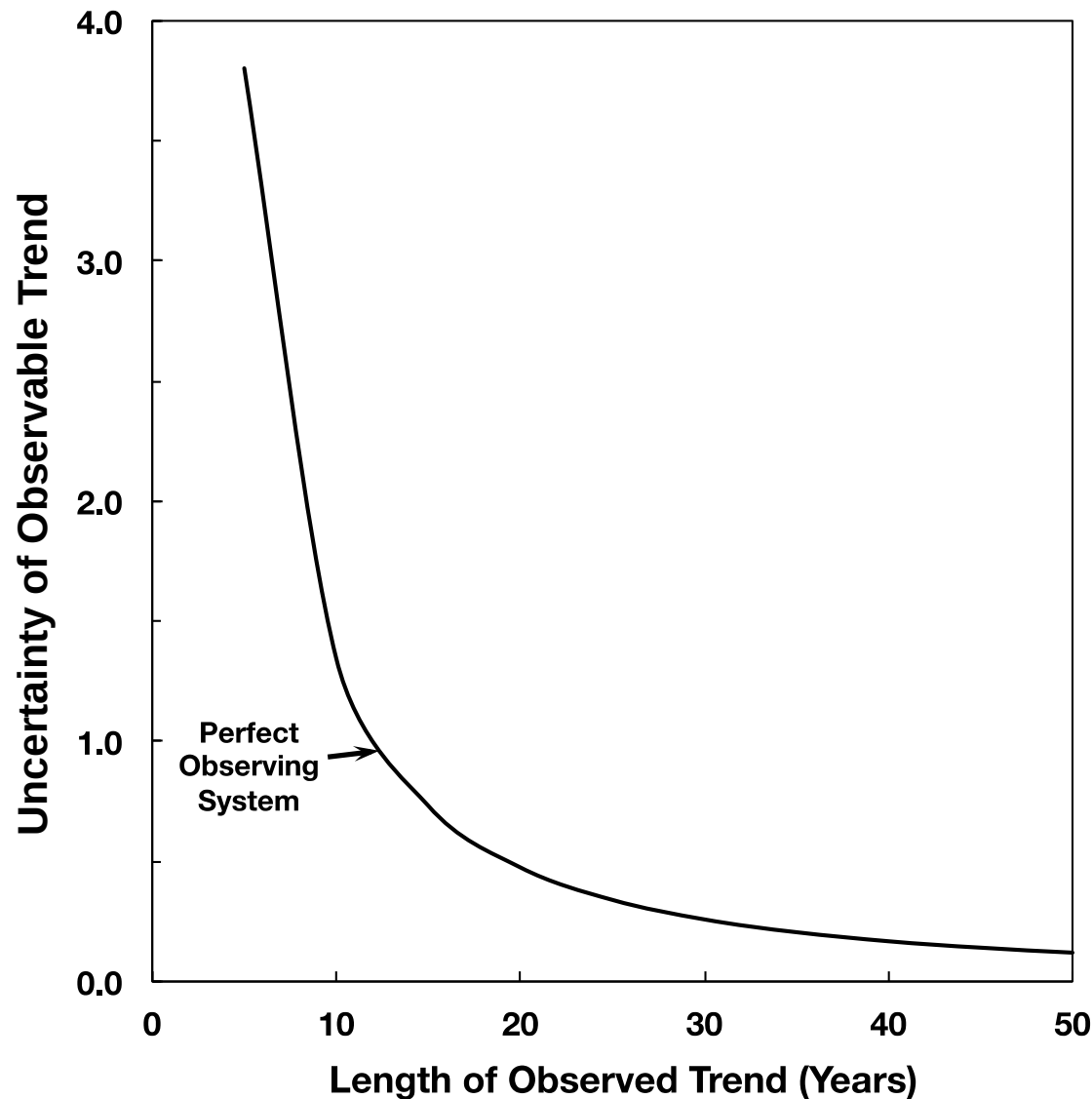
Benefits of CLARREO



- CLARREO provides the first high accuracy full spectra ($> 95\%$ of energy) across the reflected solar and infrared Earth emissions; includes climate change observations of temperature/water vapor profiles, cloud properties, broadband radiation, surface properties (ocean/land)
- Provides new and unique spectral fingerprints of climate change for direct climate model testing (no retrieval required)
- Provides the anchor for the World Meteorological Organization (WMO) Global Space based Inter-Calibration System (GSICS). The first SI standard transfer radiometer in orbit to match spectral response, space, time, and angle of view during orbit crossings for reference intercalibration of other Earth sensors in all LEO and GEO orbits.
- Near Term Benefits include:
 - First Far Infrared spectrum observations will verify upper atmosphere water vapor greenhouse effect and feedback, cirrus effects (Far Infrared is 50% of IR energy)
 - Absolute accuracy will improve bias corrections in current weather models
 - Improved consistency and calibration across a wide range of earth sensors and their ocean, land, and atmosphere applications throughout the solar and IR from LEO to GEO

Climate Change Benchmarks Critical for 5 to 100 Years into the Future

Accuracy Requirements of the Climate Observing System



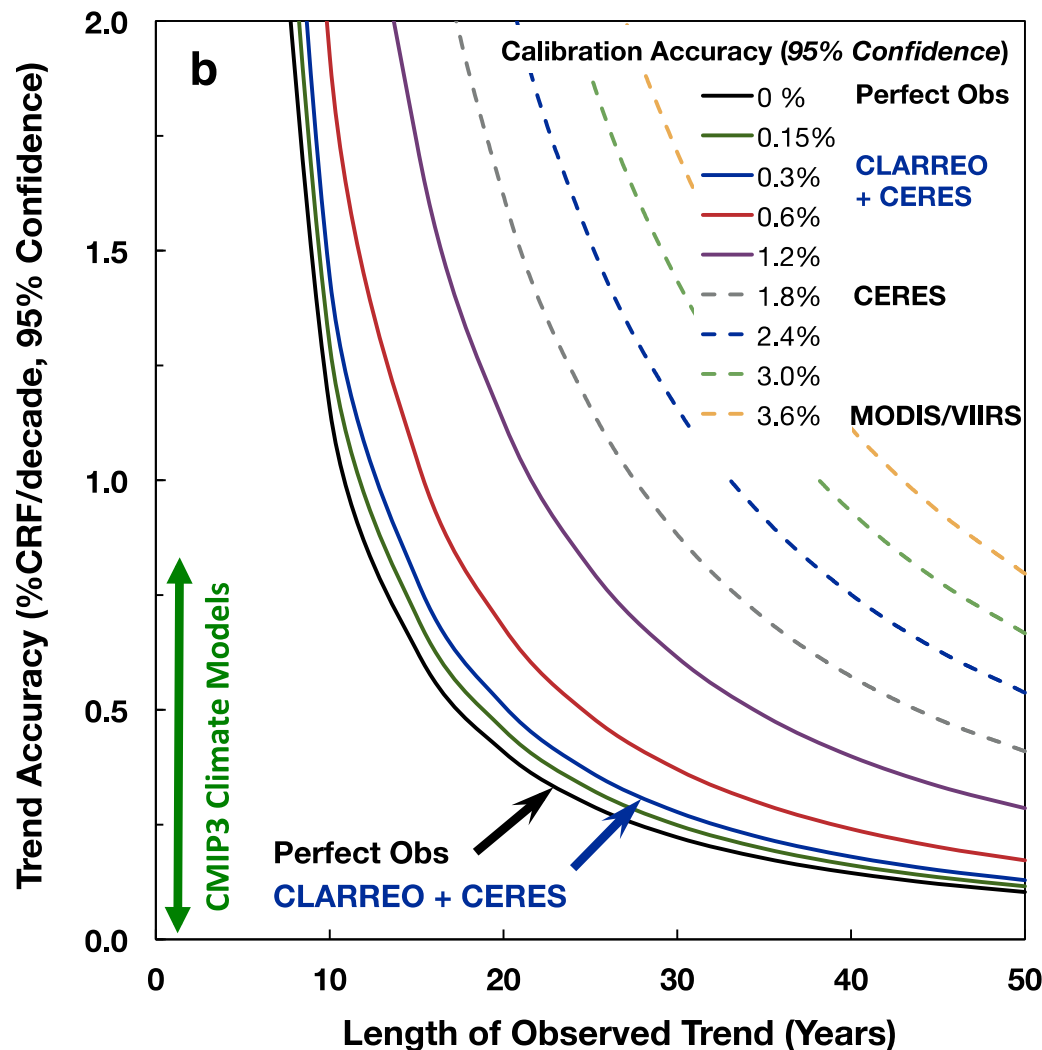
The length of time required to detect a climate trend caused by human activities is determined by:

- *Natural variability*
- *The magnitude of human driven climate change*
- *The accuracy of the observing system*



Even a perfect observing system is limited by natural variability

Reflected Solar Accuracy and Climate Trends



Climate Sensitivity Uncertainty is a factor of 4 (IPCC, 90% conf) which = factor of 16 uncertainty in climate change economic impacts

Climate Sensitivity Uncertainty = Cloud Feedback Uncertainty = Low Cloud Feedback = Changes in SW CRF/decade (y-axis of figure)

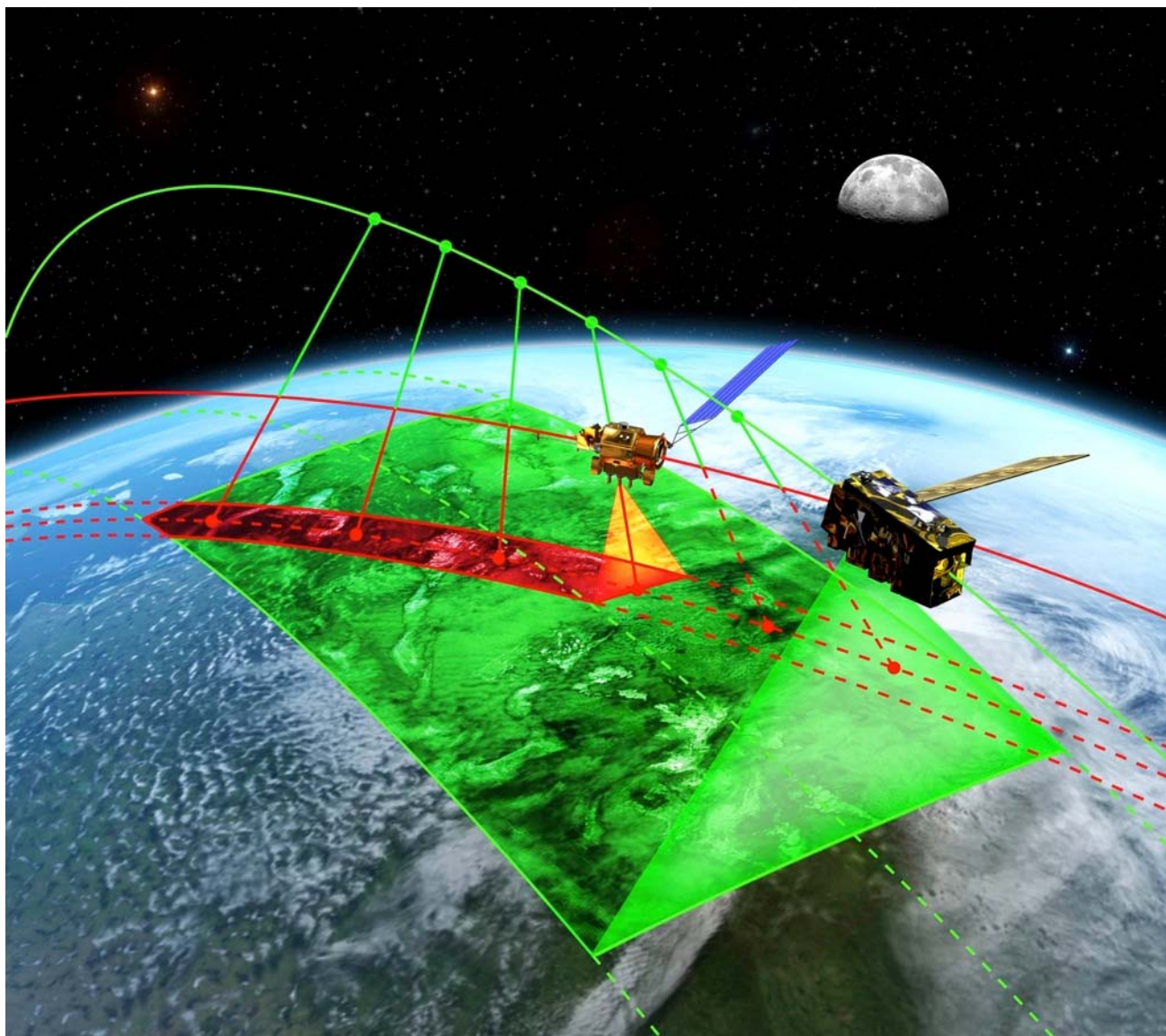
Higher Accuracy Observations = CLARREO reference interval of CERES = narrowed uncertainty 15 to 20 years earlier

Wielicki et al. 2013, Bulletin of the American Meteorological Society



High accuracy is critical to more rapid understanding of climate change

Calibration Reference Spectrometers (IR/RS) for Global Climate, Weather, Land, Ocean satellite instruments



Provide spectral, angle, space, and time matched orbit crossing observations for all leo and geo orbits critical to support reference intercalibration

Endorsed by WMO & GSICS (letter to NASA HQ)

Calibrate Leo and Geo instruments relevant to climate sensitivity:

- JPSS: VIIRS, CrIS, CERES**
- METOP: IASI, AVHRR**
- Geostationary imagers/sounders**

CLARREO Provides "NIST in Orbit": Transfer Spectrometers to SI Standards

The Grand Challenge

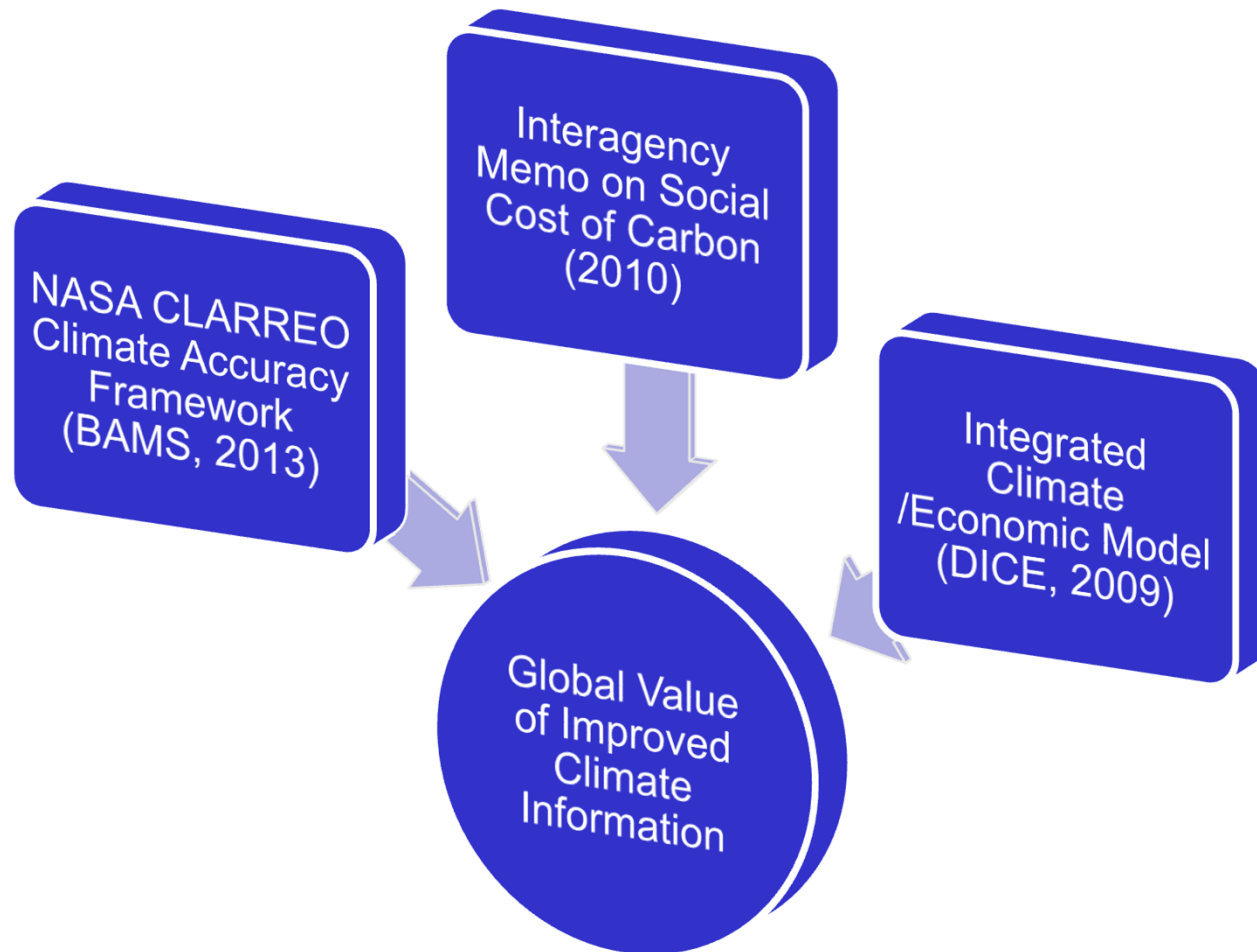
- *We have no global climate observing system (unlike weather)*
- *We will be controlling Earth's climate (indirectly or directly) as long as human civilization survives on the planet.*
- *What is the economic value to society of solving this Grand Challenge of climate sensitivity? Can we estimate it?*



The Three Laws of Climate Change

Economics, Economics, Economics

Climate Science Value of Information (VOI) Calculation

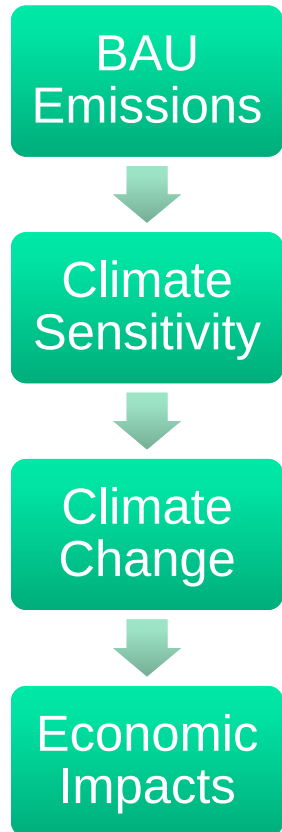


Cooke et al., Journal of Environment, Systems, and Decisions, July 2013, paper has open and free distribution online.

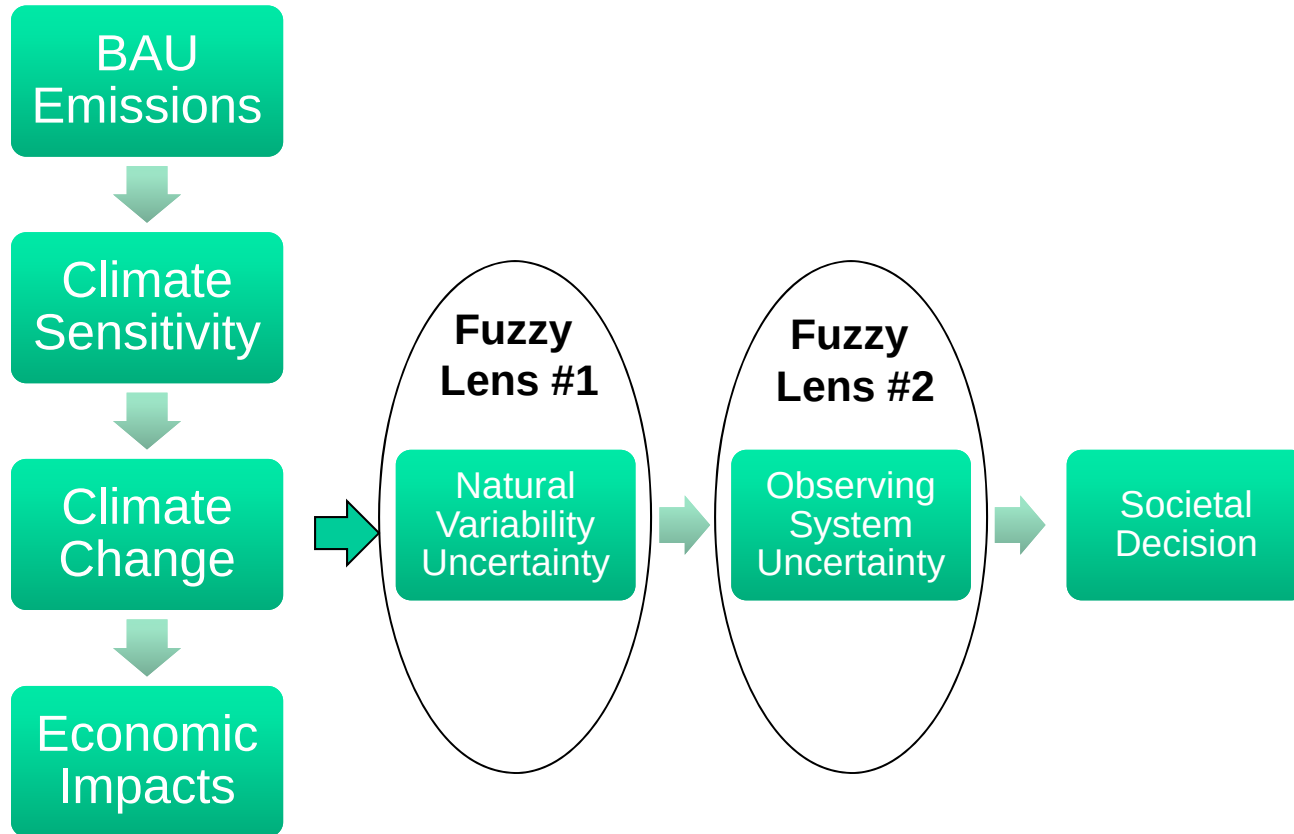


New Interdisciplinary Integration of Climate Science and Economics

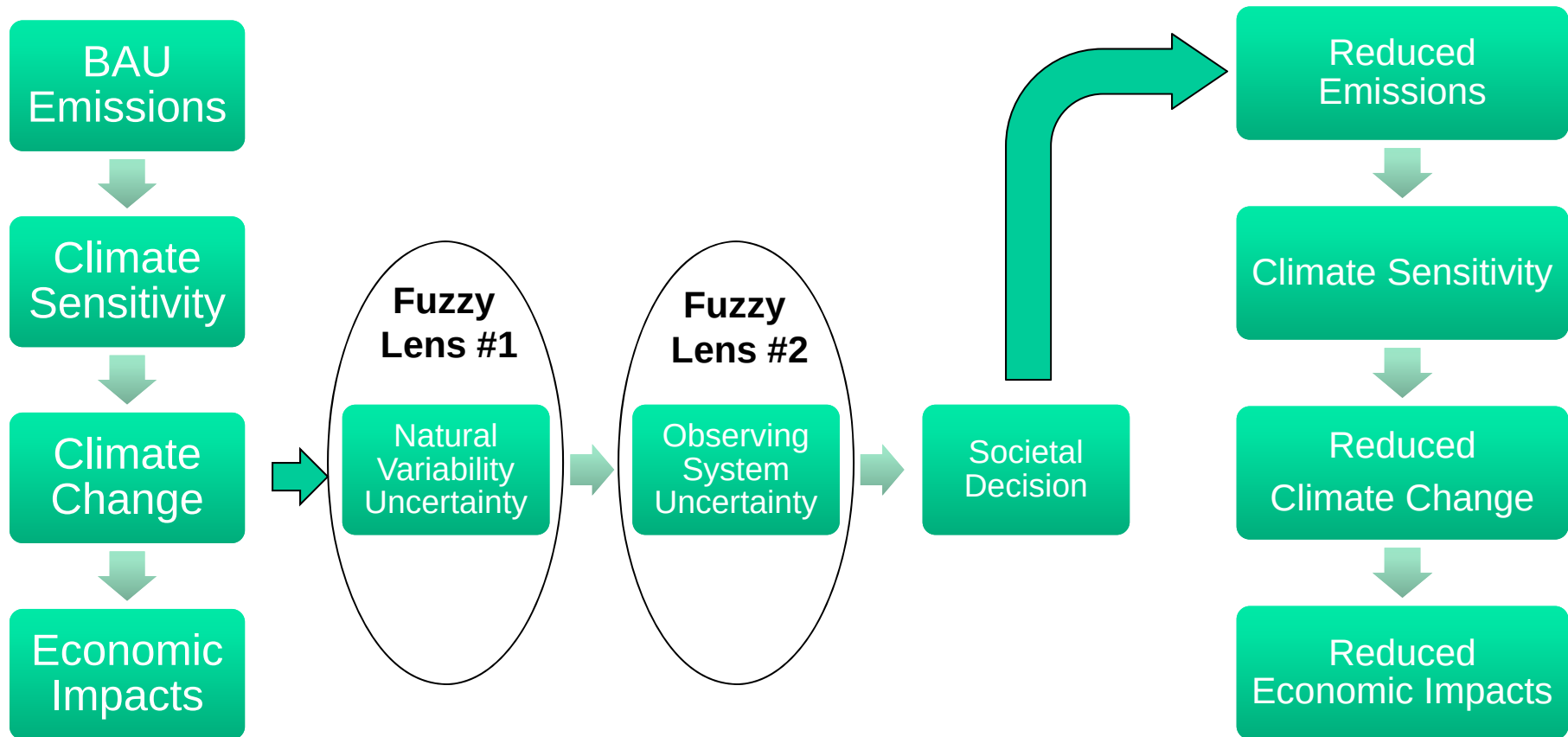
VOI Estimation Method



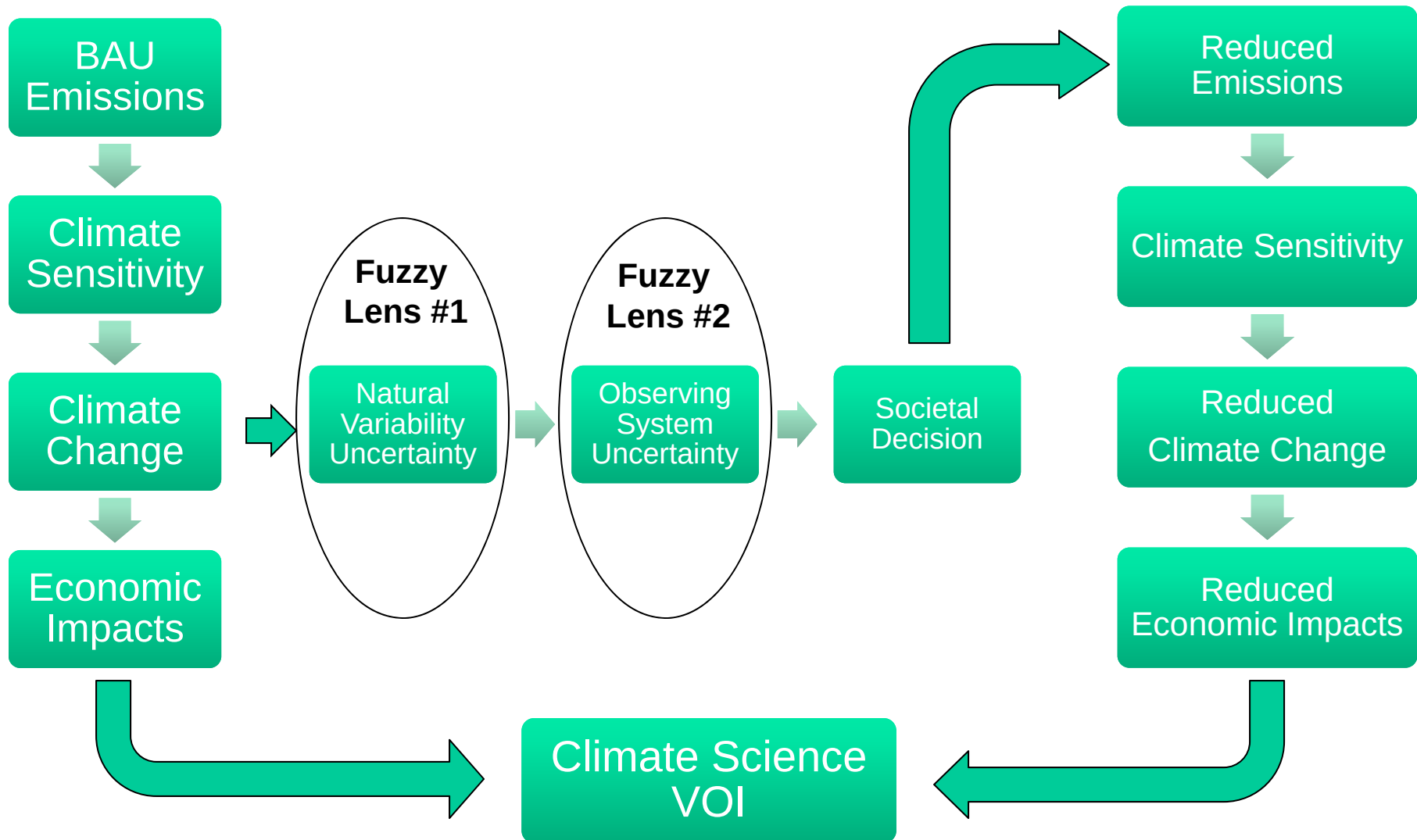
VOI Estimation Method



VOI Estimation Method



VOI Estimation Method



Economics: The Big Picture

- World GDP today ~ \$70 Trillion US dollars
- Net Present Value (NPV)
 - compare a current investment to other investments that could have been made with the same resources
- Discount rate: 3%
 - 10 years: discount future value by factor of 1.3
 - 25 years: discount future value by factor of 2.1
 - 50 years: discount future value by factor of 4.4
 - 100 years: discount future value by factor of 21
- Business as usual climate damages in 2050 to 2100: 0.5% to 5% of GDP per year depending on climate sensitivity.



VOI vs. Discount Rate

Run 1000s of economic simulations and then average over the full IPCC distribution of possible climate sensitivity

Discount Rate	CLARREO/Improved Climate Observations VOI (US 2015 dollars, net present value)
2.5%	\$17.6 T
3%	\$11.7 T
5%	\$3.1 T

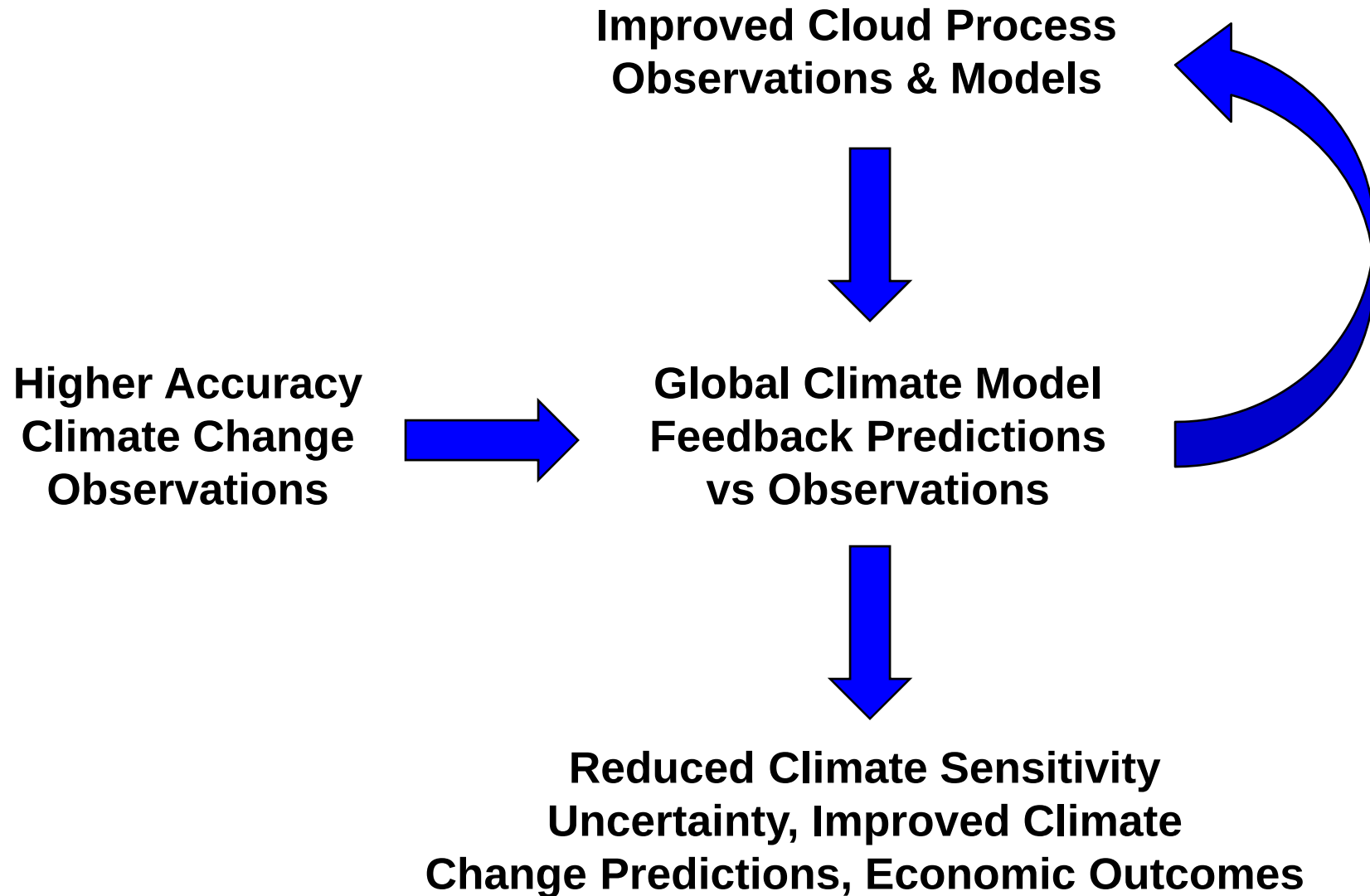
*Additional Cost of an advanced climate observing system:
~ \$10B/yr worldwide*

*Cost for 30 years of such observations is ~ \$200 to \$250B in NPV
For a payback ratio of ~ \$50 per \$1 invested*



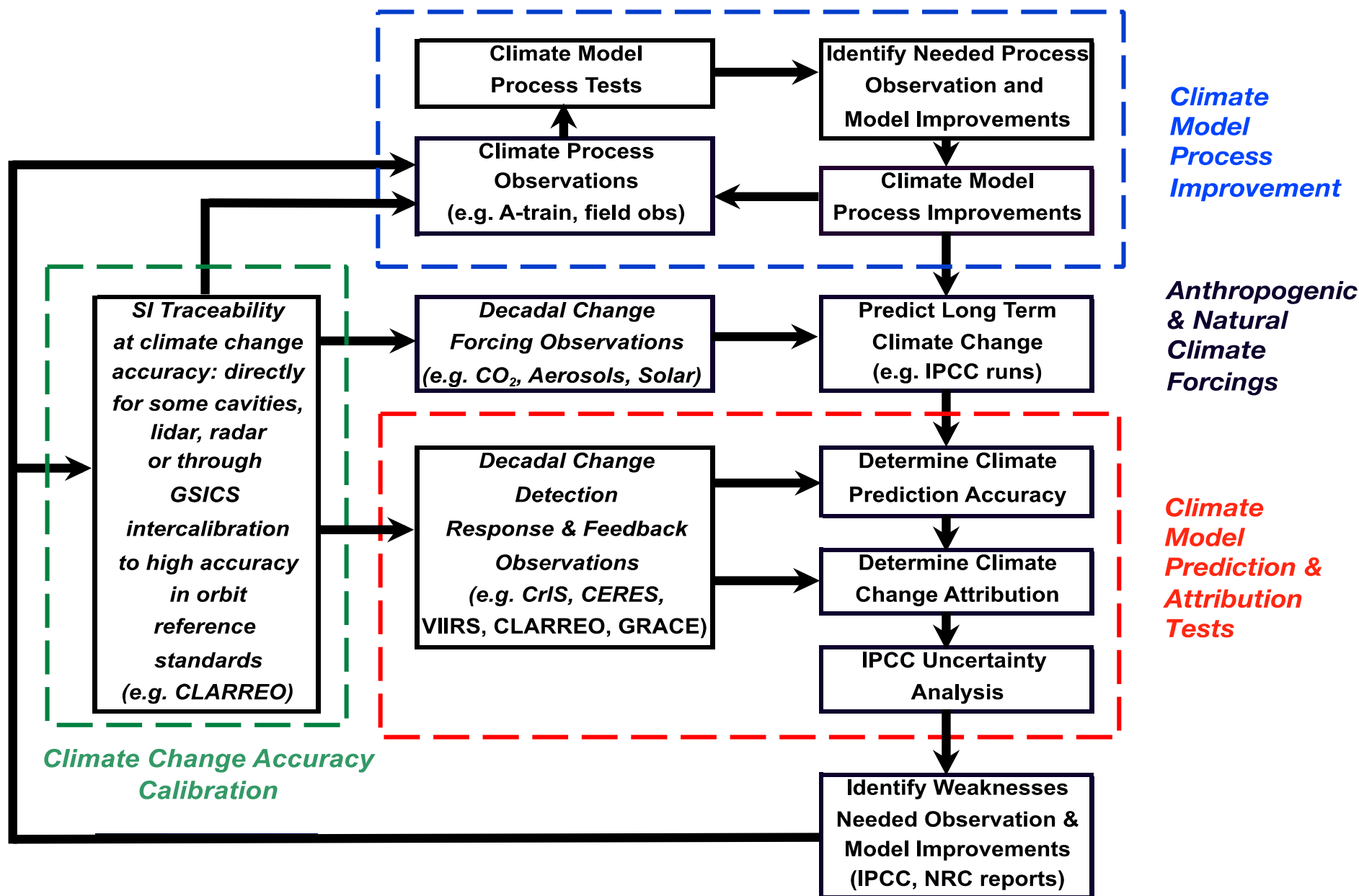
Even at the highest discount rate, return on investment is very large

The Grand Challenge: Climate Sensitivity

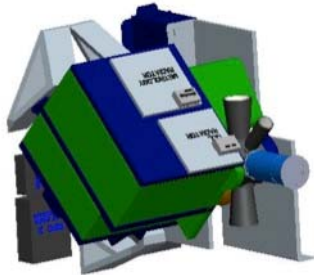


Backup Slides

Decadal Change Climate Science



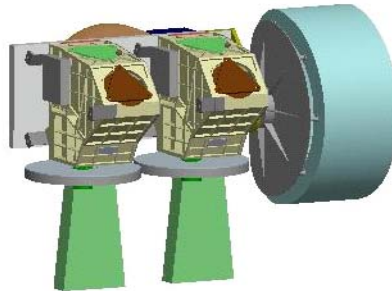
CLARREO: NIST in Orbit



**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
- 25 km nadir fov, 1 earth sample every 200 km
- **Mass: 76 Kg**
- **Power: 124 W**



**Reflected Solar (RS)
Instrument Suite**

*Two Grating Spectrometers
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 res
- 300 m fov, 100 km swath
- **Mass: 67 Kg**
- **Power: 96 W**
- **Power and Mass are total for both spectrometers**



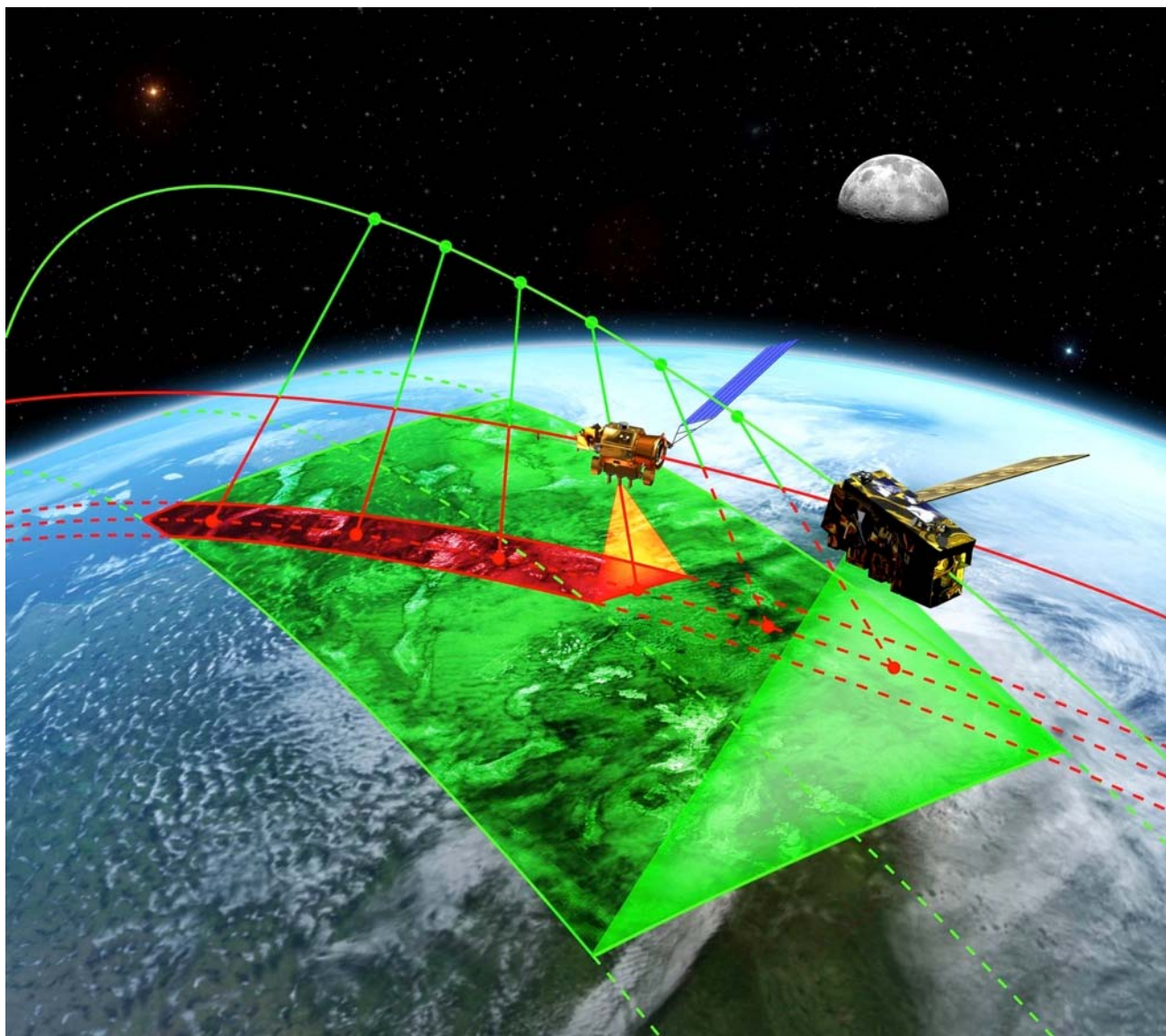
**GNSS
Radio Occultation
Receiver**

*GNSS Receiver, POD
Antenna, RO Antennae*

- Refractivity uncertainty 0.03% ($k=1$) for 5 to 20 km altitude range. (Equivalent to 0.1K ($k=3$) for temperature)
- 1000 occultations/day
- **Mass: 18 Kg**
- **Power: 35 W**

Small Instruments, Higher Accuracy, Climate Change Sampling Only

Calibration Reference Spectrometers (IR/RS) for Global Climate, Weather, Land, Ocean satellite instruments



Provide spectral, angle, space, and time matched orbit crossing observations for all leo and geo orbits critical to support reference intercalibration

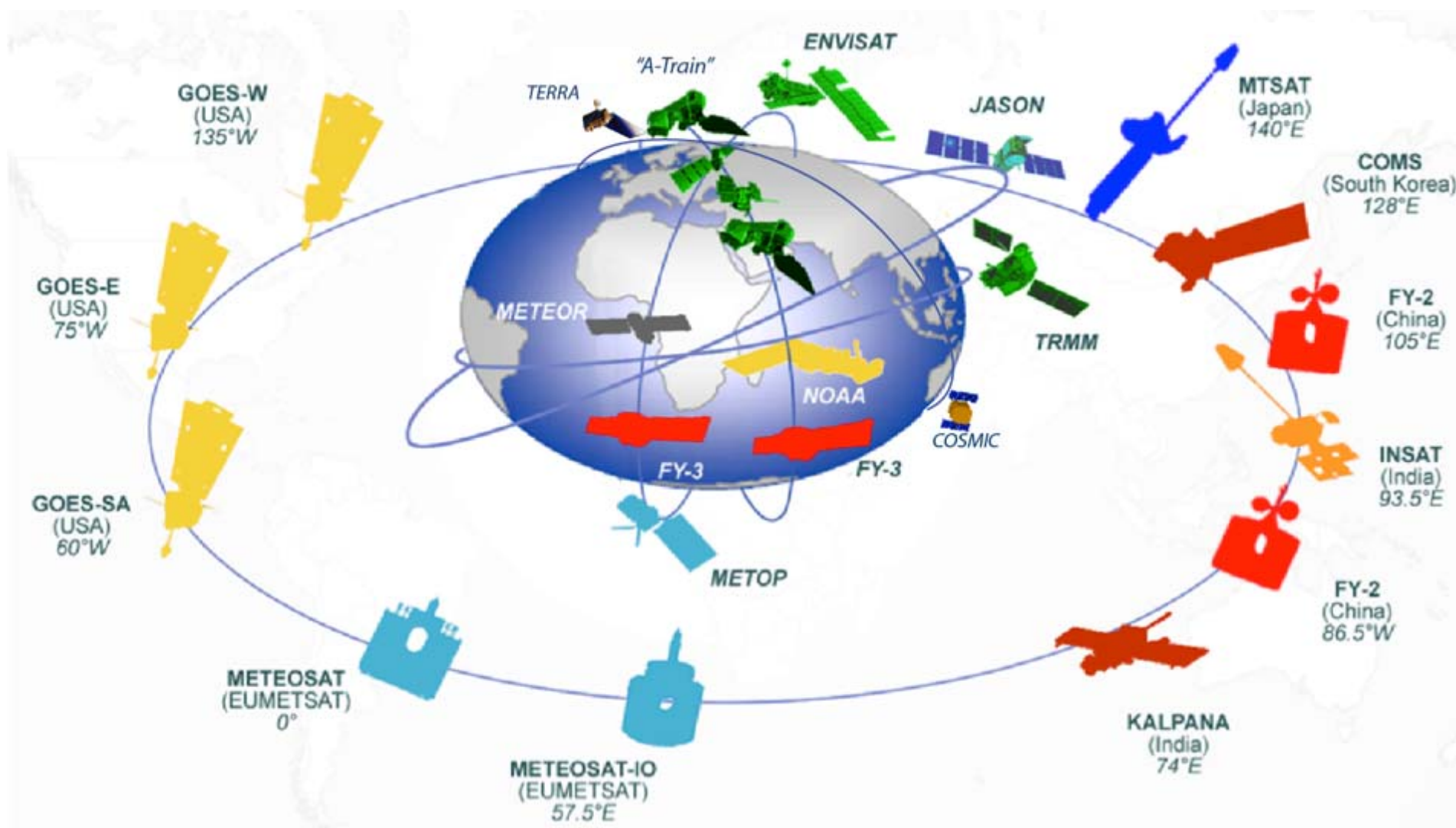
Endorsed by WMO & GSICS (letter to NASA HQ)

Calibrate Leo and Geo instruments: e.g.

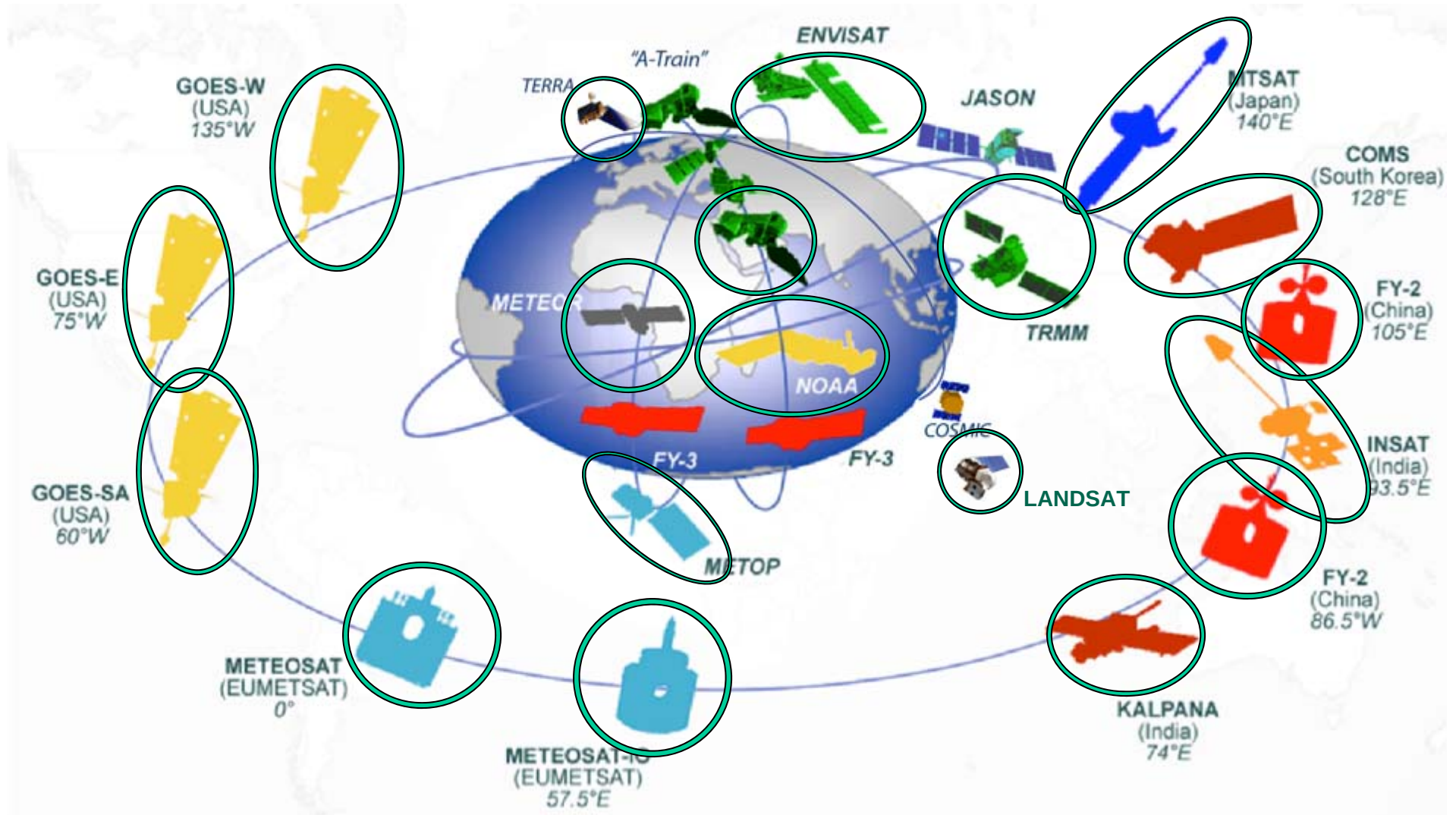
- JPSS: VIIRS, CrIS, CERES**
- METOP: IASI, AVHRR**
- Landsat, etc land imagers**
- Ocean color sensors**
- GOES imagers/sounders**

CLARREO Provides "NIST in Orbit": Transfer Spectrometers to SI Standards

Global Satellite Observations

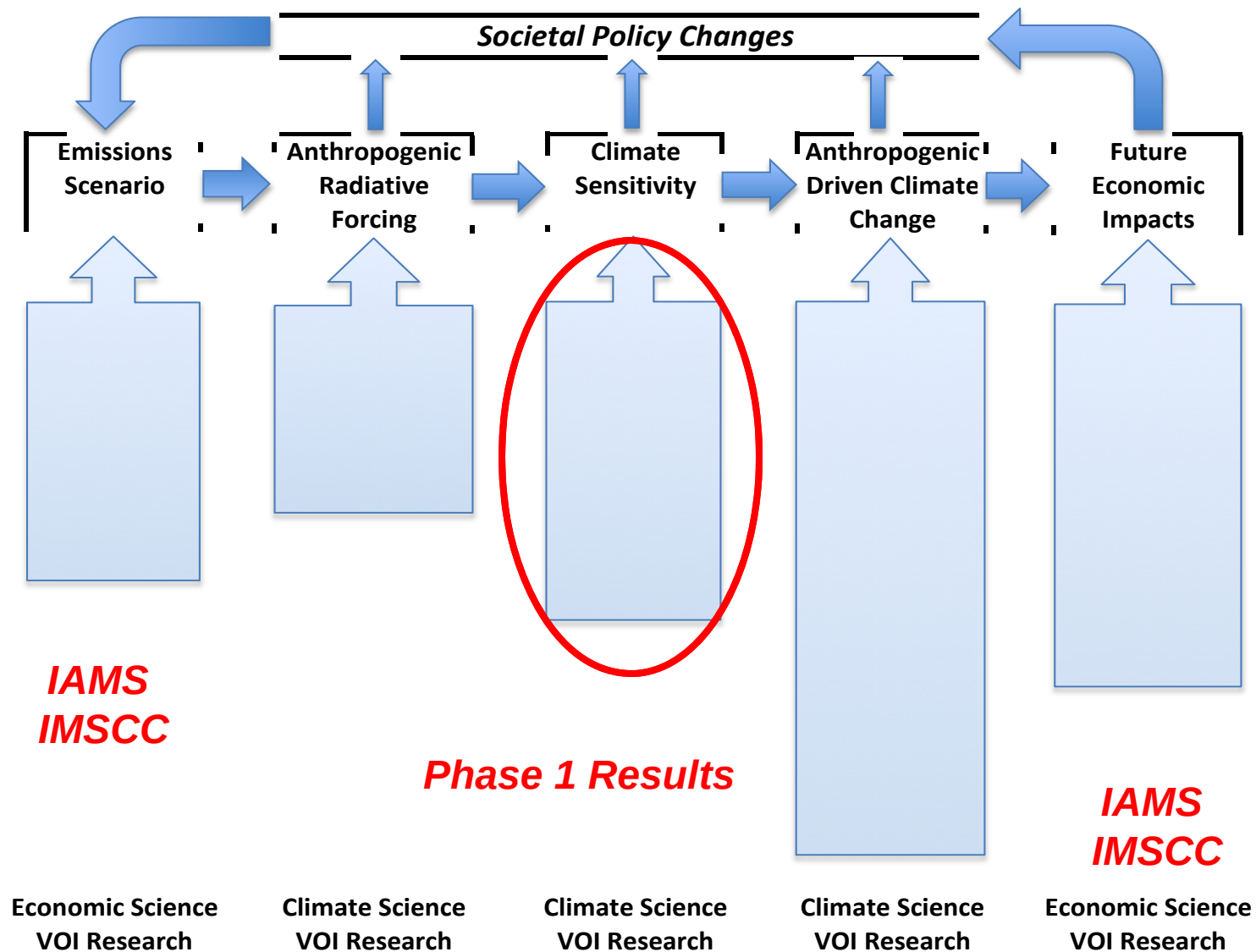


Intercalibration to CLARREO for Climate Change Accuracy

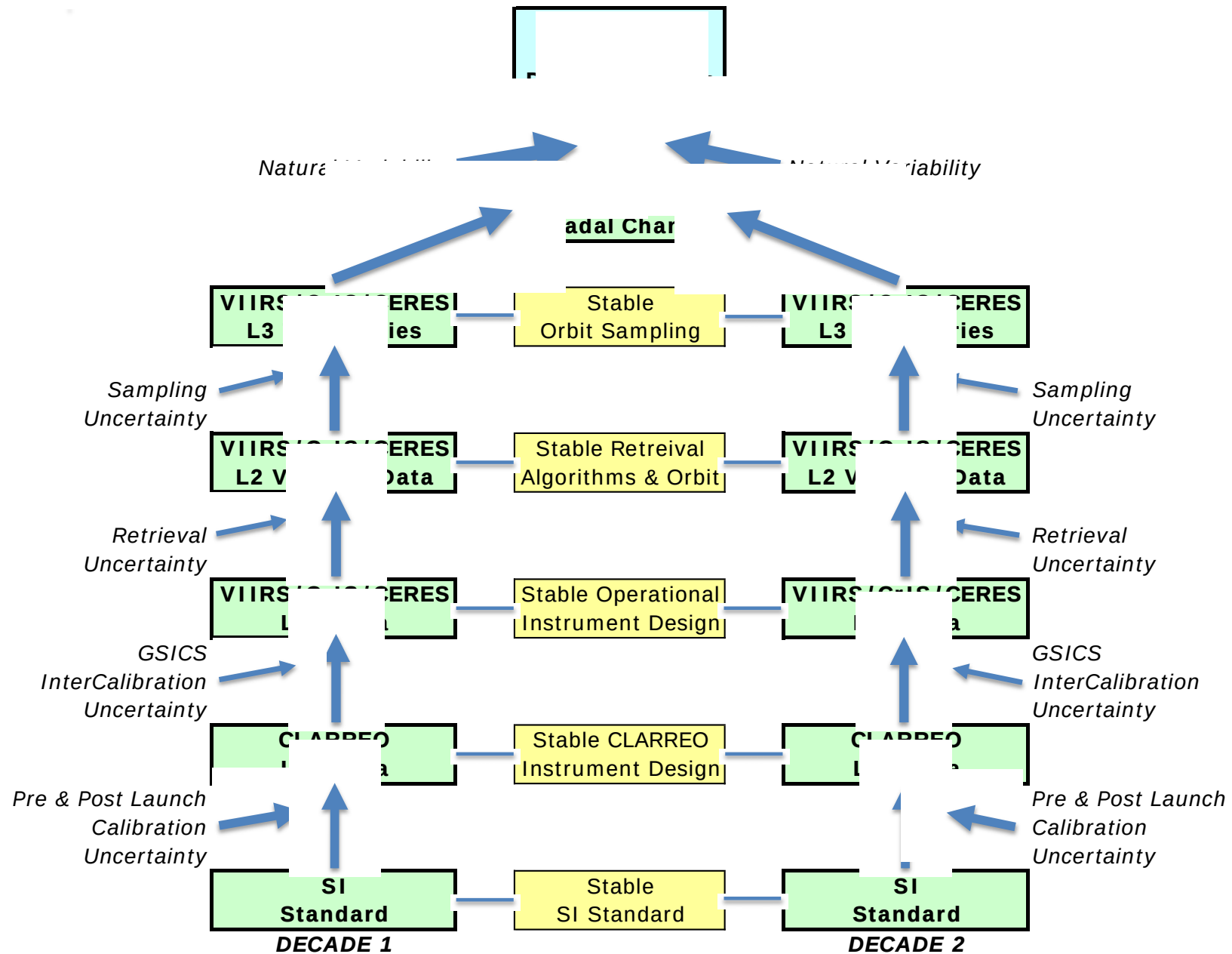


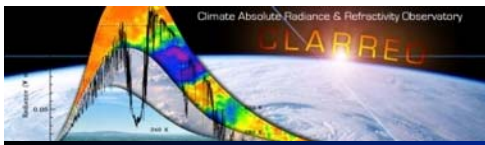
Intercalibration of 30 to 40 instruments in LEO and GEO orbits

Value of Climate Science Observations

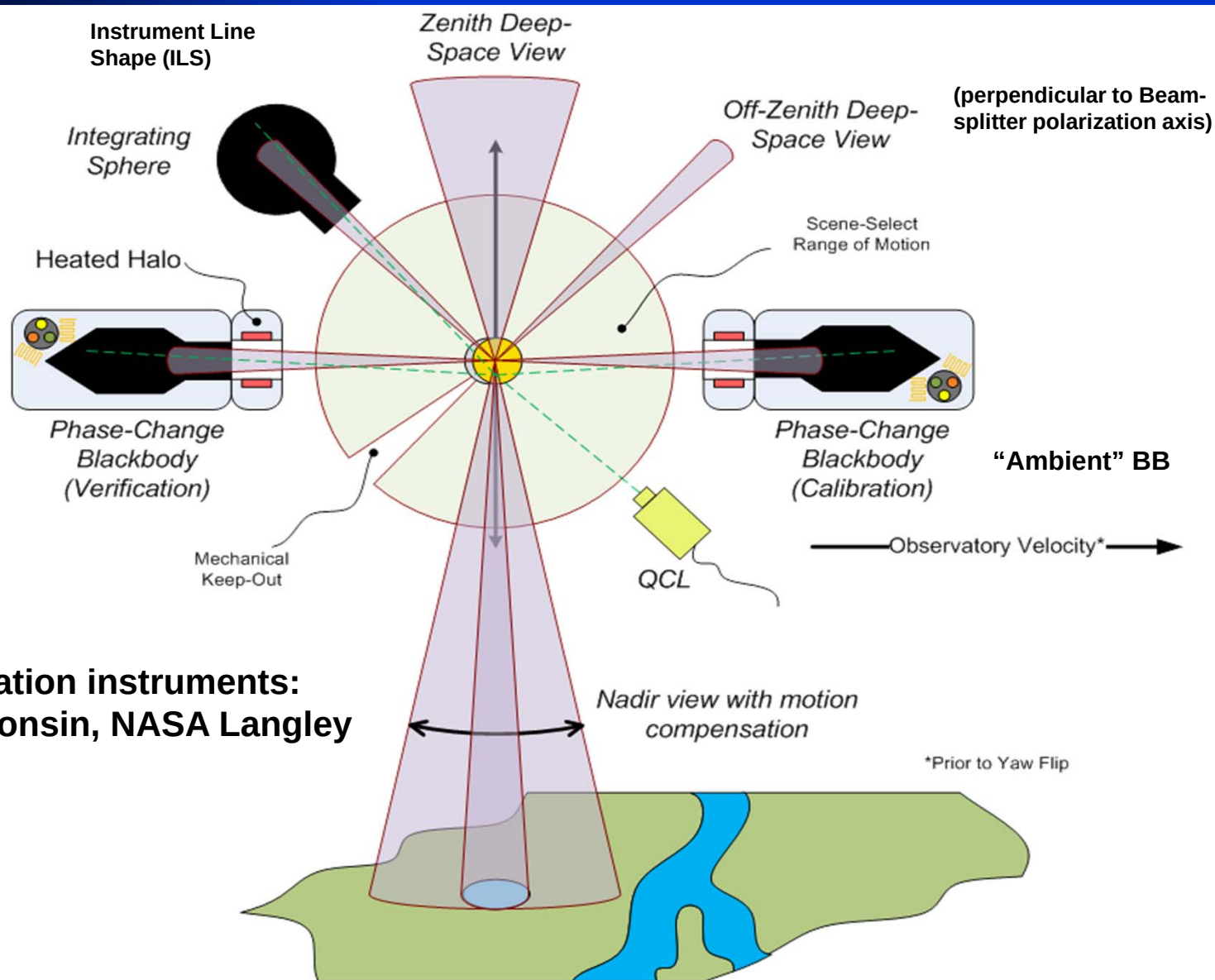


Decadal Change Reference Intercalibration Benchmarks: Tracing Mission Requirements



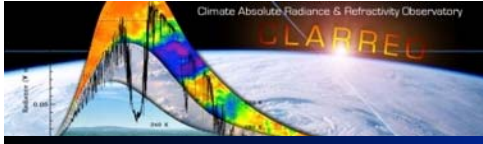


IR On-orbit Verification

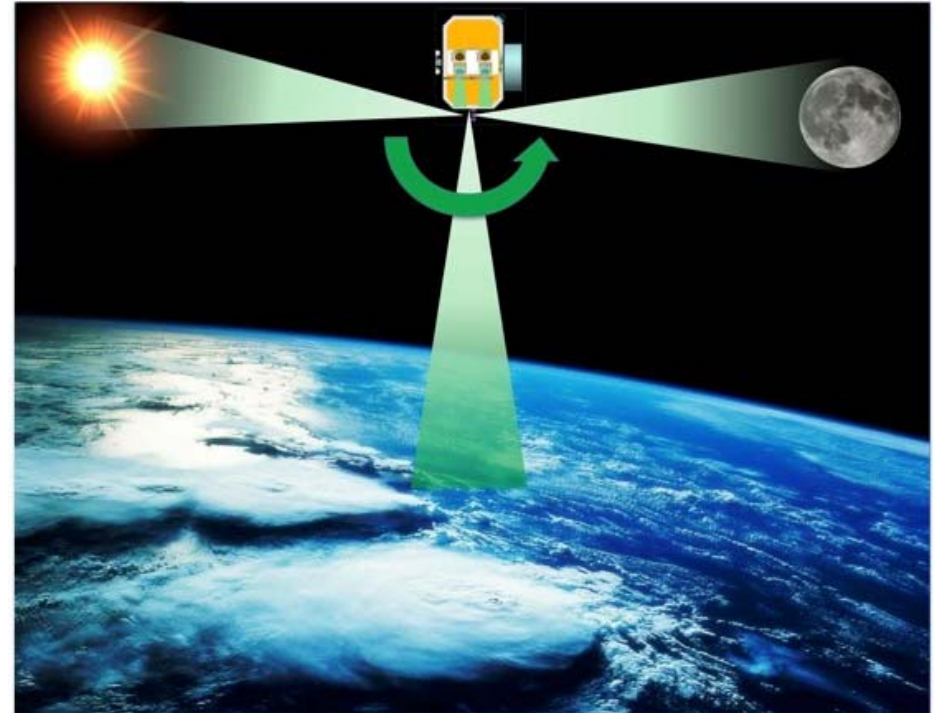
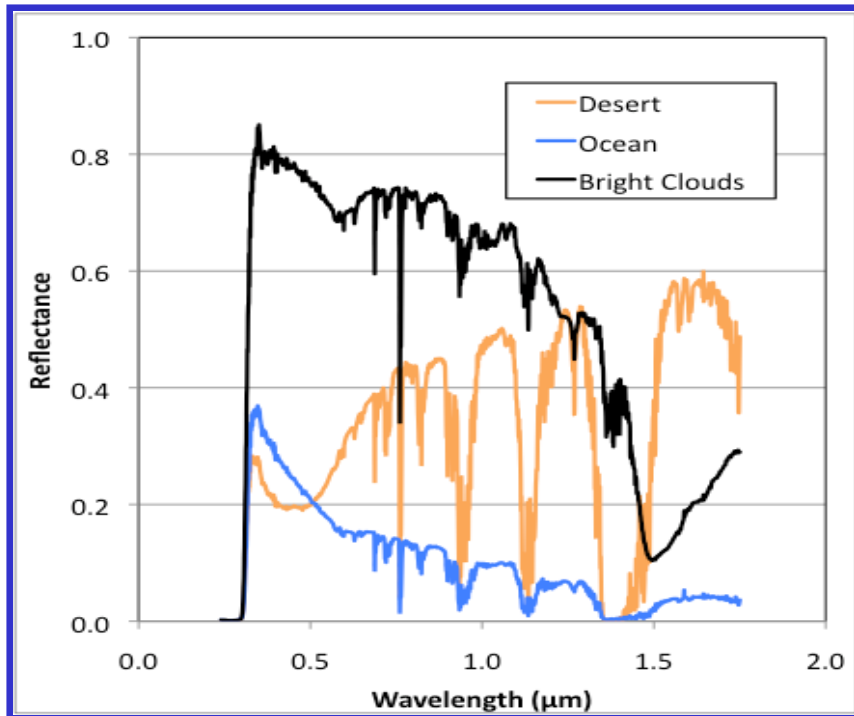


Demonstration instruments:
Univ Wisconsin, NASA Langley

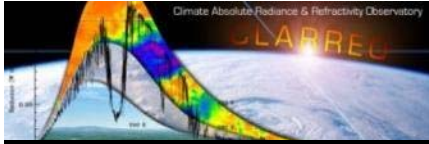
SI Traceable Accuracy 0.1K ($k=3$) all Earth Scene Temps (190 to 320K)



CLARREO Reflected Solar Measurements



- Calibration accuracy attained using the Sun as a calibration reference standard
- Attenuator verification relies on lunar views without attenuator
- Lunar/solar disks and stars used to verify stray light performance
- No scanning mirrors: observe the moon/sun with same optics path as Earth
- Provides reference intercalibration for operational sensors
- Spectral Range 320 – 2300 nm, 8 nm spectral resolution (4 nm sampling)
- CU LASP concept (Kopp/Pilewskie) demonstrated with IIP instrument. GSFC CDS
- 0.3% with 95% confidence (i.e. $k=2$)



Climate Absolute Radiance & Refractivity Observatory (CLARREO)

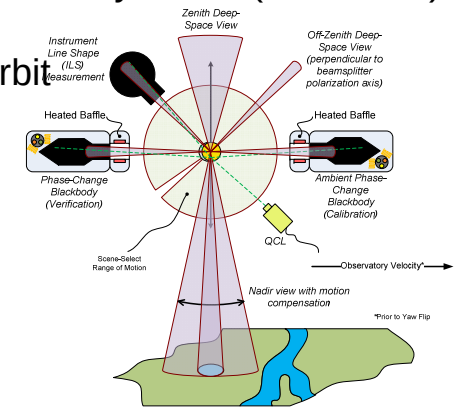


Science Objectives:

- Enable more accurate observations of climate change (by factors of 5 to 10)
- Enable more rapid climate change observation (by 15 to 20 yrs) and narrow uncertainty in climate sensitivity through improved accuracy
- Provide the first spectral observation of the Earth's water vapor greenhouse effect and the first spectral fingerprints of climate change
- Provide the reference intercalibration benchmark for the WMO Global Space-based Inter-calibration System (GSICS) to tie 30 to 40 Earth viewing sensors in LEO and GEO orbits to higher accuracy standard on-orbit

Instruments/Mission:

- Full 320 – 2300 nm reflected solar spectrum with 4nm sampling, accuracy 0.3% (95% conf.)
- Full 200 – 2000 cm^{-1} infrared spectrum with 0.5 cm^{-1} sampling, accuracy 0.07K (95% conf.)
- Radio Occultation (TriG)
- 90° polar or 57° ISS orbit
- Accuracy of climate change trends within 20% and time to detect climate trends within 15% of a perfect observing system.

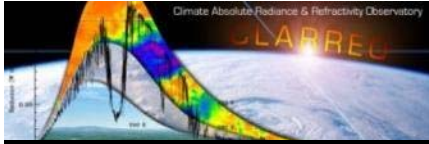


Project Approach:

- Tier 1 Decadal Survey Mission
- Passed Mission Concept Review in Nov 2010. Currently in pre-phase A.
- Advance measurement design maturity (all components now TRL 6) and incorporate NIST recent calibration advances
- Focus on lower cost, smaller instruments with ability to achieve required accuracy on-orbit
- Focus on alternative implementation options (e.g., ISS achieves 70% of MCR baseline science value at 40% of cost).

Project Team:

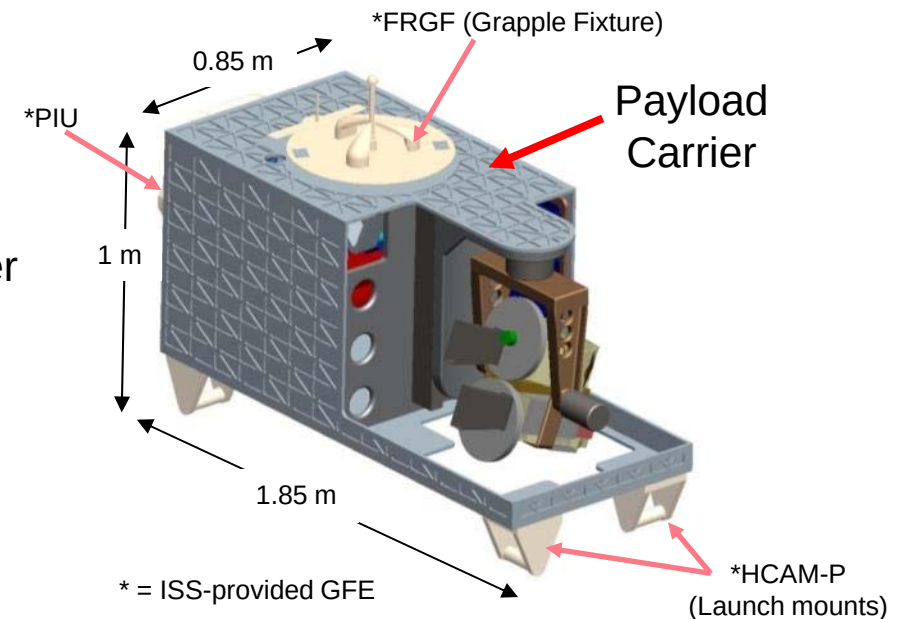
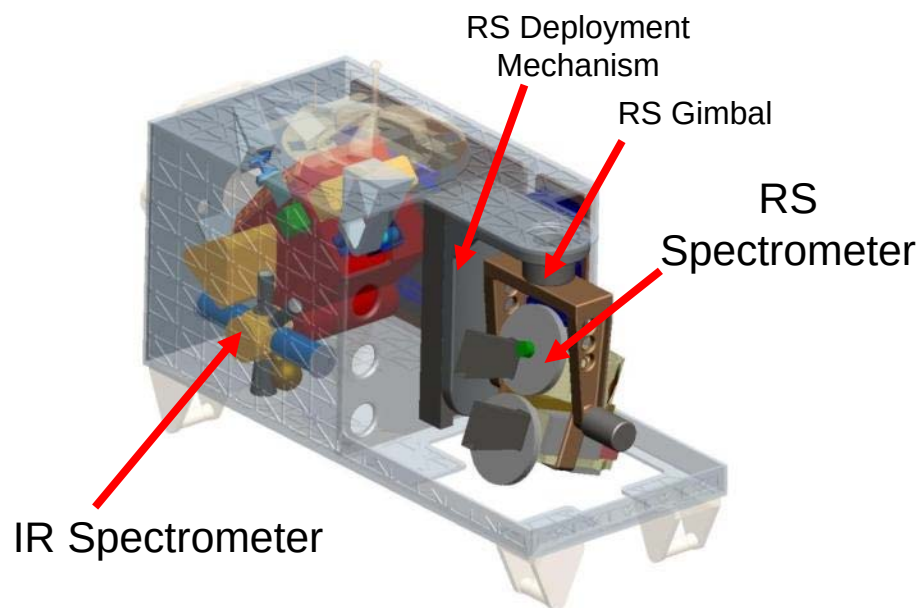
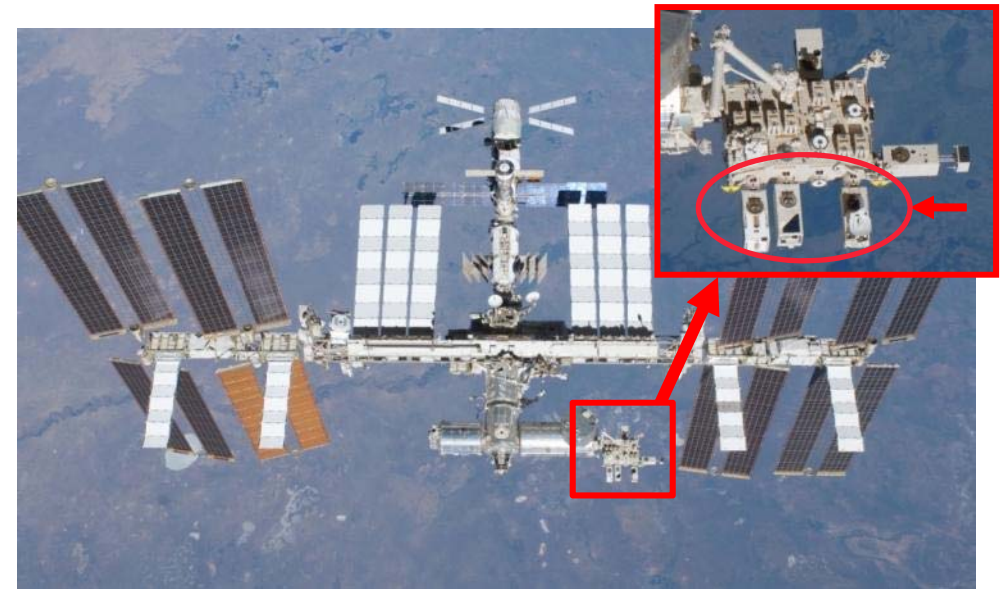
- Langley: Project Management, Systems Engineering, Science Team Lead, Data Center, Infrared Spectrometer Lead
- NASA Goddard: Reflected Solar Spectrometer Lead
- JPL: GNSS Radio Occultation Lead
- Competitively selected Science Definition Team (7 Universities + NASA + International partners)
- Government Partners: NIST, NOAA
- UK NPL, Imperial College, NCEO
- WMO GSICS

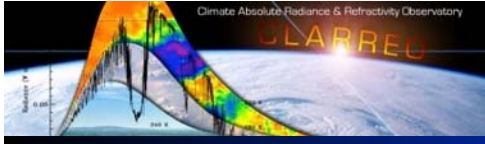


ISS Mission Concept



- Selected the Japanese Experiment Module Exposed Facility (JEM-EF) for this study
 - L/V, installation and JEM-EF interfaces defined and provided by ISS
 - Other ISS locations viable, but ram-side of JEM-EF is optimal for maximizing viewing opportunities
- Dual-instrument payload approach demonstrated by NRL's HREP





CLARREO Mission Status

- Passed Mission Concept Review Nov 2010
- Science Definition Team selected in Jan 2011
- NASA Earth Science budget reduction in Feb 2011 has caused a delay.
- Remains in pre-phase A studies, no current launch date
- 2 RS and 2 IR instrument calibration demonstration systems underway (CU-LASP/GSFC for RS, UW/LaRC for IR)
- Climate Model OSSEs and Intercalibration simulation studies
- Alternative less costly mission studies: ISS best option to date
- International collaboration options with UK, Italy in study
- *No climate observing system: factor of 3 to 4 underfunded*

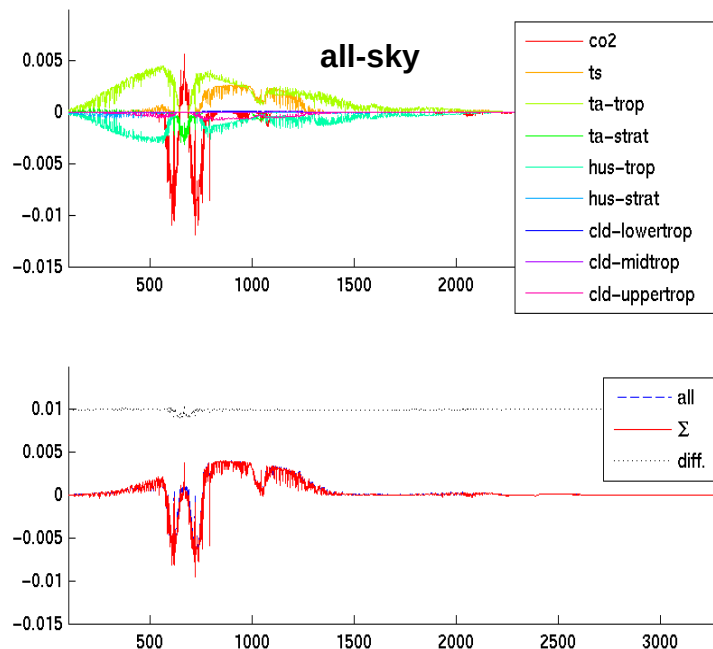


Climate OSSEs- Observing System Simulation Experiments

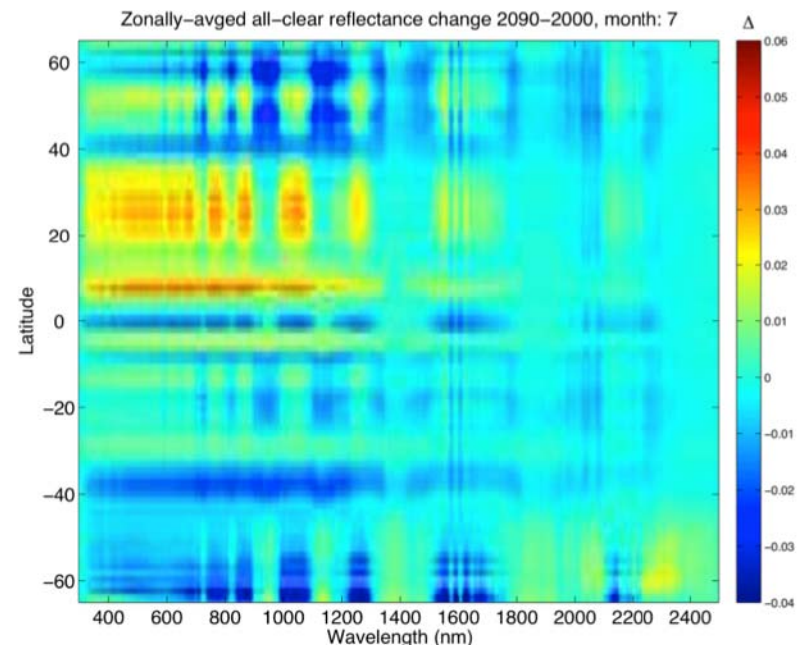
Climate modelers were identified by the Decadal Survey as primary data users
OSSEs were begun with 3 modeling groups (GISS, GFDL, U-Cal Berkeley) to determine measurement requirements

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). 10 journal papers to date.

- 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)



Why a Science Value Matrix?

- Science is a cost/value proposition with uncertainty in both *costs* and *value*
 - Cost can be determined with ~ 30% uncertainty and is always addressed
 - Science value or priority for mission elements of design are rarely addressed, but could be and often should be
- CLARREO has developed a new science value matrix concept to assist in:
 - Understanding cost/value
 - Understanding robustness of mission options
 - Understanding how one aspect of the mission (e.g. instrument accuracy) relates to others (science goals, climate record length, orbit sampling, instrument noise)
 - Understanding the impact of baseline vs threshold mission
 - Optimizing the mission design for cost/schedule/risk
 - Eliminating mission requirements "creep"
 - Communicating the mission design trades to NASA HQ
 - Moving the CLARREO science team discussions from "I feel" or "I think" or "I'm sure" to more quantitative basis on mission requirements
 - Improving and quantifying communication between scientists and engineers



A Science Value Matrix is a valuable tool to optimize mission design

Science Value Metrics

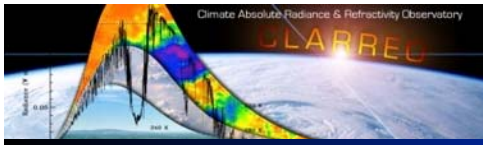
- **Science Value of a Science Objective =**

$$\textit{Science Impact} * \textit{Trend Accuracy} * (\textit{Record Length})^{0.5} * \textit{Verification} * \textit{Risk}$$

- Science Impact
 - Uniqueness of CLARREO contribution
 - Importance of science objective to reducing climate change uncertainties
- Accuracy
 - Accuracy in decadal change trends for a given record length
- Climate Record Length
 - Sqrt(record length) reduction in noise from natural variability
- Verification
 - SI traceable calibration verification
 - Independent instruments, analysis, observations (CCSP chapter 12, metrology)
- Risk
 - Technological, budget, schedule, flexibility of mission options



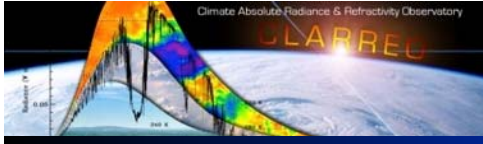
Instrument Absolute Accuracy set for < 20% Trend Accuracy Degradation



Original Decadal Survey Mission: IR/IR/RO, IR/IR/RO, 2 year gap, IR/IR/RS/RS/RO

					Decadal Survey Mission: IR/RO, IR/RO, 2yr gap, IR/RO/RS					
CLARREO		Related Decadal Change Climate Variable	Science Impact Factor*		Calibration Verification Factor	Climate Record Length ^{0.5} 70% Prob	1 IR FTS	1 Solar	1 GPS	IRS + IRS
Decadal Change							per S/C	per S/C	per S/C	
Science Objective							1 S/C	1 S/C	1 S/C	Total
							Trend	Trend	Trend	Mission Science Value
Cloud Feedback SW		Reflected SW flux, albedo	2		1.9	2.1	0	1.05	0	8.3
		Solar Cloud Properties								
Cloud Feedback LW		Earth Emitted LW flux	1		2.0	2.5	1.03	0.00	0	5.1
		IR cloud properties								
Cloud Feedback Net		Net Cloud Radiative Forcing	5		1.9	2.0	1.03	1.05	0	20.4
Temperature Response & Lapse Rate Feedback		Temperature Profile	3		2.0	2.5	1.03	0	1.0	15.1
Water Vapor Response & Water Vapor Feedback		Water Vapor Profile	3		2.0	2.5	1.03	0	0.2	18.3
Aerosol Direct Radiative Forcing		Aerosol Radiative Forcing	1.5		1.9	2.1	0	1.0	0	5.9
		Aerosol Properties								
Snow & Ice Albedo Feedback		Reflected SW flux, albedo	1.5		1.9	2.1	0	1.05	0	6.2
		Snow/Ice Cover, Cloud Cover								
Land Albedo Change & Radiative Forcing		Reflected SW flux, albedo	0.5		2.0	2.1	0	1.05	0	2.2
Vegetation Index Change		Vegetation Index	1		2.0	2.1	0	1.05	0	4.3
Science Value of Individual Components (IR, RS, RO)							28.1	26.9	10.4	
Science Value of combined IR/RS science (net cloud feedback)							20.4			
Total Mission Science Value Metric										85.8
Percent of Mission Science Value of Individual Components (IR, RS, RO)							33%	31%	12%	
Percent of Mission Science Value of combined IR/RS science							24%			
Total Mission Science Value as Percent of Decadal Survey Reference Mission										100%

 Original Decadal Survey Mission defined as 100% science value



CLARREO Mission Options

Mission	% of CLARREO MCR Baseline Mission Science	Mission Cost Estimate (\$RYM)
Decadal Survey Concept (2007) (11 instruments, 4 spacecraft, 4 launches)	112%	~ \$1.6B Launches 2017, 2019
MCR Baseline Mission Concept (6 instruments, 4 smaller spacecraft or 2 larger)	100%	\$800 - \$1000 + Launch Vehicle(s) Launches 2018, 2020
MCR Minimum Mission Concept (3 instruments, 1 spacecraft, e.g. DAC-4 free flyer)	62%	\$675 - \$750 + Launch Vehicle Launch 2021
ISS Mission Concept (2 instruments on ISS, RO is obtained from COSMIC-2)	73%	\$400 - \$440 cost includes launch EV-2 ISS full cost guidelines

Cost estimates are full mission cost in real year dollars.

For MCR baseline and minimum mission, launch vehicle not included



ISS is highest science value/cost