# CLARREO Pathfinder Mission: Calibrating Climate Observing Systems of the Future

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**FORUM Workshop**
**Florence, Italy – October 23, 2018**

# CLARREO Pathfinder Mission: Calibrating Climate Observing Systems of the Future

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# OUTLINE

- The CLARREO Concept
- The Climate Sensitivity Challenge
- The Cloud Feedback Challenge
- Reducing uncertainty through improved calibration of sensors
- Economic value of CLARREO and a dedicated Climate Observing System
- The CLARREO Pathfinder Mission
- Summary

# What is CLARREO?

- **Climate Absolute Radiance and Refractivity Observatory**
- **CLARREO**
  - Fundamental Precept – improved sensor calibration shortens time to detect trends in key climate parameters
  - Rather than try to build every sensor to climate accuracy, place a set of highly accurate sensors in orbit to calibrate all others
  - The economic value of CLARREO and a dedicated Climate Observing System is in the Trillions of dollars (U. S.) (1 \$T = $10^{12}$ \$)
- **CLARREO**
  - Is not a radiation budget mission, nor a cloud property mission, nor a replacement for CERES, VIIRS, MODIS, CrIS, etc.

# What is CLARREO?

## CLARREO's Overarching Objective

**To dramatically improve calibration of orbiting sensors**

***so as***

**To reduce time to detect trends in forcings and feedbacks**

***and thereby***

**Substantially reduce uncertainty in climate sensitivity**

***for***

**The benefit of all humanity**

# The Climate Sensitivity Challenge

- **Climate sensitivity uncertainty remains the most critical limit to future climate prediction impacts and costs. Estimated $5 to $20 Trillion U.S. dollar economic value to reduce this uncertainty at least a factor of 2 (Cooke et al. 2014, 2015, 2017; Hope, 2015)**

- **Cloud Feedback remains the dominant uncertainty in climate sensitivity (IPCC, 2013)**

- **Great effort but little progress on narrowing this uncertainty since the National Academy Charney Report in 1979: ~ 40 years. (5 IPCC reports)**

- ***But, we do now know a lot more about what can and cannot narrow the uncertainty***

# The Cloud Feedback Challenge

- **Process observations and models can help produce better climate models, *but only long term decadal observations of changes* in radiative fluxes and cloud properties have been shown to enable determination of cloud feedback in a wide range of climate models (Soden et al. 2008; Zelinka et al. 2012, 2013, 2017; Zhou et al. 2015)**

- **It is not clear that process observations *alone* can narrow uncertainty in climate sensitivity**
  - Weather scale cloud model verification is NOT climate scale model verification: apples and oranges
  - Producing a good weather model is not proof of a good climate change model.
  - OSSEs have not been done to show how process observations could in fact narrow uncertainty in climate sensitivity

# The Cloud Feedback Challenge

- **Our historical observations of decadal change in cloud properties and radiative fluxes from the 1970s through 2000 lack the instrument accuracy, stability, and consistent orbital sampling to constrain cloud feedback (5 IPCC reports)**

- **Our more recent long term observations (2000 to 2018) of cloud property change and radiative flux change (MODIS, CERES) are much more accurate in both sampling and calibration**
  - But they still have calibration drifts that only allow constraint of large positive or negative cloud feedbacks (Loeb et. 2016, 2018; Wielicki et al. 2013; Shea et al. 2017)
  - **To overcome the noise of natural variability in the system, 10 to 30 years of highly accuracy climate change data is needed to narrow uncertainty in cloud feedbacks** (Dessler and Loeb 2013, Zhou et al. 2015, Wielicki et al. 2013, Shea et al. 2017). Shorter for large feedbacks, longer for smaller feedbacks

# The Cloud Feedback Challenge

- The economic return on investment would range from 25:1 to 100:1 to develop a climate change observing system and maintain it for 30 years: e.g. tripling the current annual international climate research investment of ~ $4 Billion U.S. dollars/yr to a higher level of $12 Billion/yr. (Cooke et al. 2014, 2015, 2016, Weatherhead et al. 2017)

- We are currently set to continue the same approach that 40 years of effort have shown inadequate to narrow uncertainty in climate sensitivity and cloud feedback. There is no national or international plan to change this approach, or to build a rigorous climate change observing system (Weatherhead et al. 2017)

# Uncertainty in Trend Determination
# (Leroy et al., 2008; Equation 10)

$$\partial m = \left[12\left(\Delta t^{-3}\right) * \left(\sigma_{var}^{2}\,\tau_{var} + \sigma_{meas}^{2}\tau_{meas}\right)\right]^{1/2}$$

Trend uncertainty

Length of time series

Variance due to natural variability

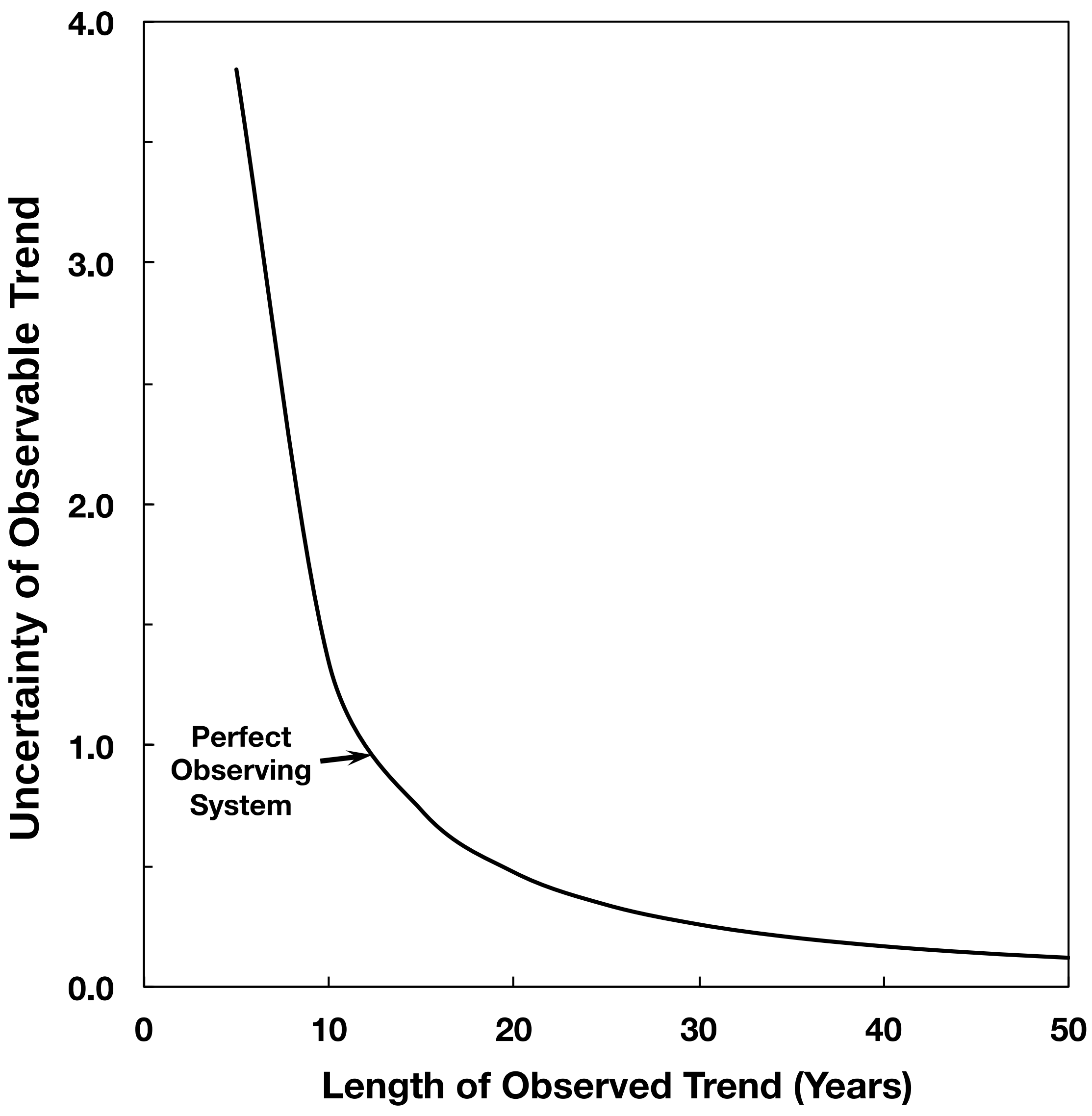
Measurement uncertainty

Correlation time for measurement uncertainty

Correlation time for natural variability

- **Trend uncertainty depends on *natural variability*, *measurement uncertainty*, *length of time series***
- **A perfect measurement (no error) requires a finite amount of time to overcome natural variability and achieve a desired trend uncertainty**
- **The longer the time series, the smaller the trend uncertainty**
- ***Reduce $\sigma_{meas}$ by improved calibration, reduce trend uncertainty & time-to-detect***

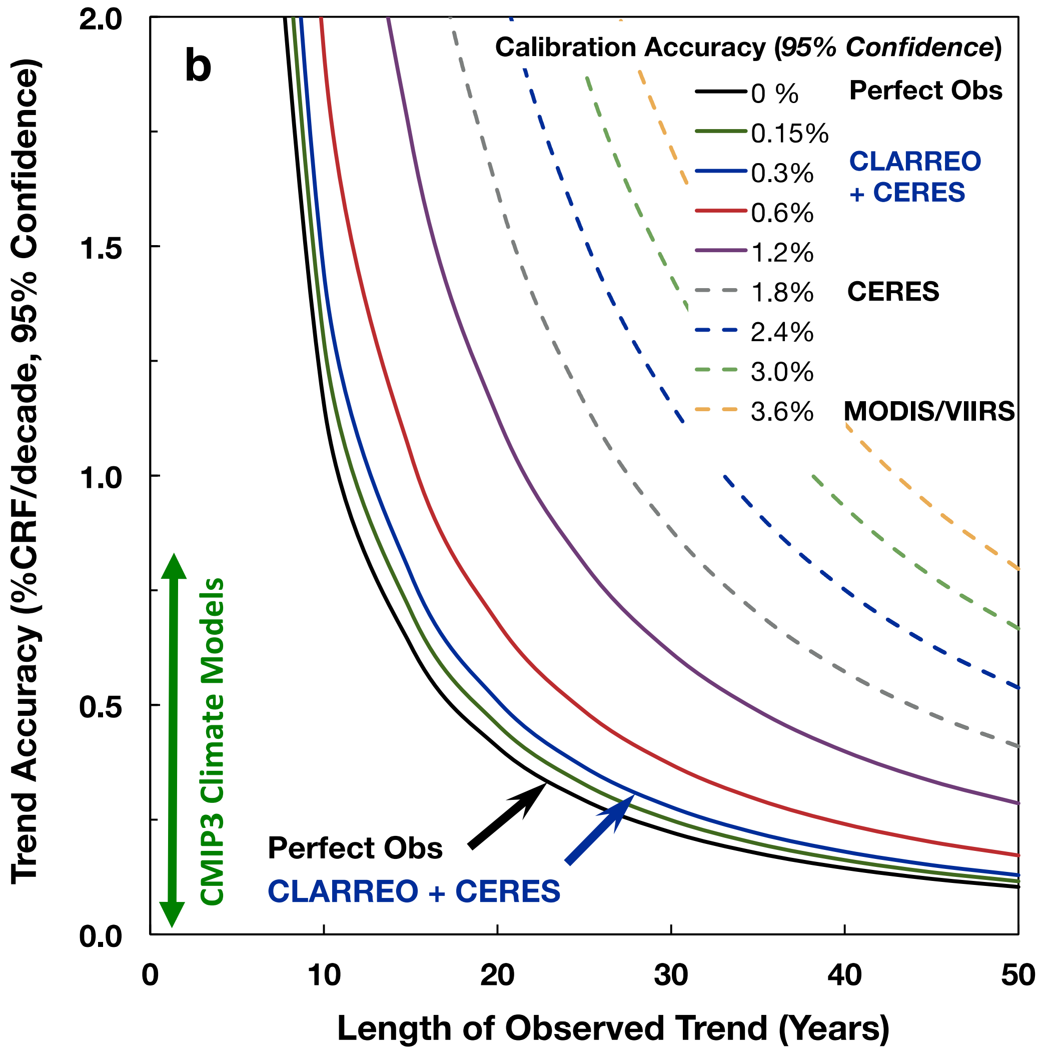
# Accuracy Requirements of a Climate Observing System




*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*

# 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)*

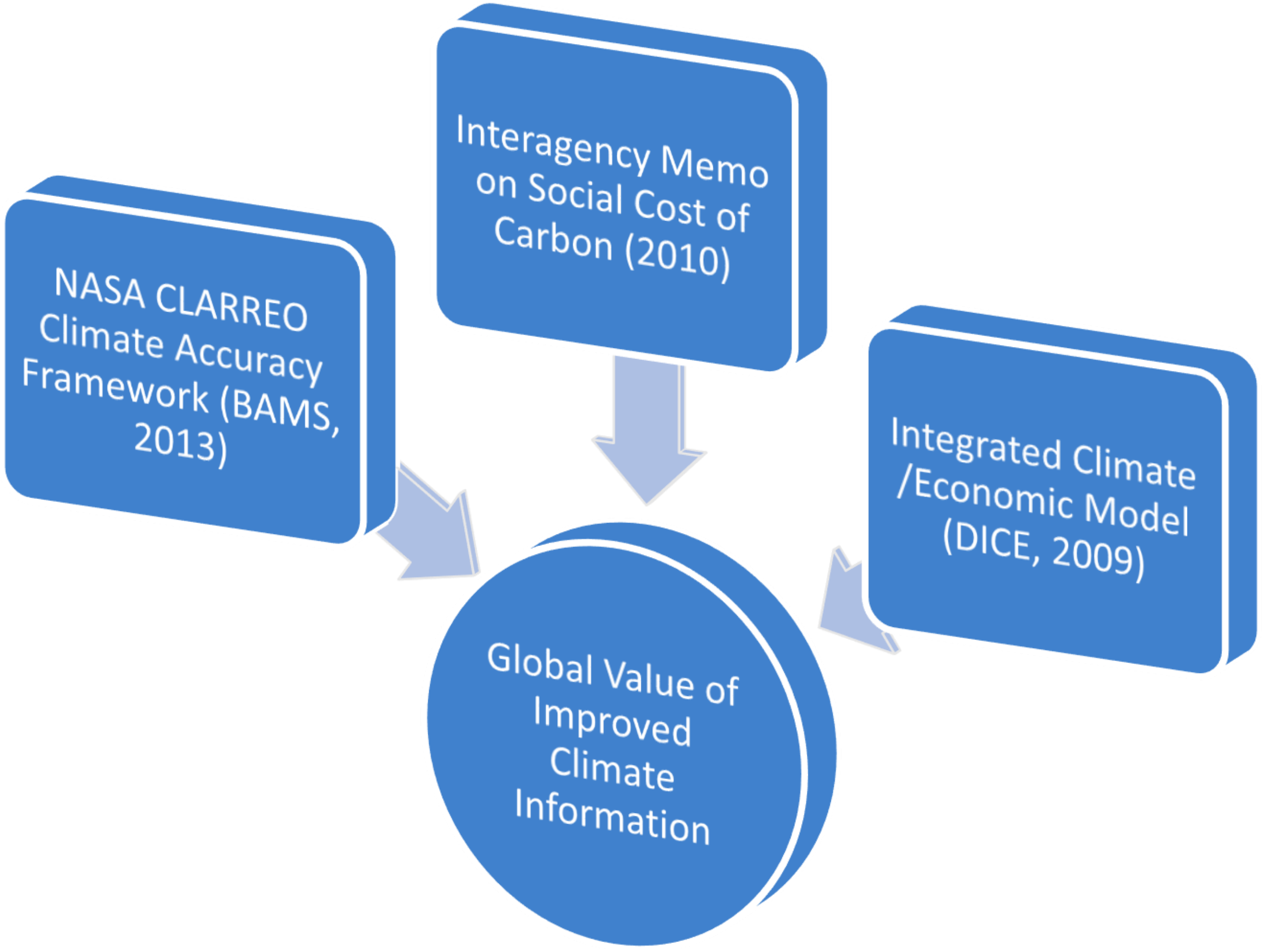
Higher Accuracy Observations = CLARREO reference intercal of CERES = *narrowed uncertainty 15 to 20 years earlier*

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

# Economic Value of Higher Accuracy Climate Change Observations

- **Two major sources of uncertainty in anthropogenic climate change trends**
  - *Natural variability (e.g. ENSO, PDO)*
  - *Observing system uncertainty (e.g. calibration shifts or drifts)*
- **Higher accuracy observations can accelerate time to detect climate change trends at a desired uncertainty level by 15 to 20 year**
  - *Example: higher accuracy cloud radiative forcing trends for cloud feedback to narrow uncertainty in climate sensitivity*
- **Aids societal decision making to optimize mitigation and adaptation costs**
- **3 recent studies of the economic value of higher accuracy climate obs:**
  - *Cooke et al., J. Environ. Systems and Decisions, 2014;*
  - *Cooke et al. Climate Policy, 2015;*
  - *Hope, Phil. Trans. Roy. Soc., 2015*
  - *Weatherhead et al., AGU Earth's Future, 2017*
- **Economic Value: $10 to $20 Trillion U.S. dollars in Net Present Value**
  - *For full climate observing system (3X current investment) 50:1 return on investment*
  - *CLARREO Pathfinder is an initial step toward a true climate observing system*

# What is the right amount to invest in climate science?




*Cooke et al., Journal of Environment, Systems, and Decisions, 2014, paper has open and free distribution online: doi:10.1007/s10669-013-9451-8.*
*Cooke et al., Climate Policy, 2015,* ISSN: 1469-3062, Cooke et al. 2016

# VOI Estimation Method

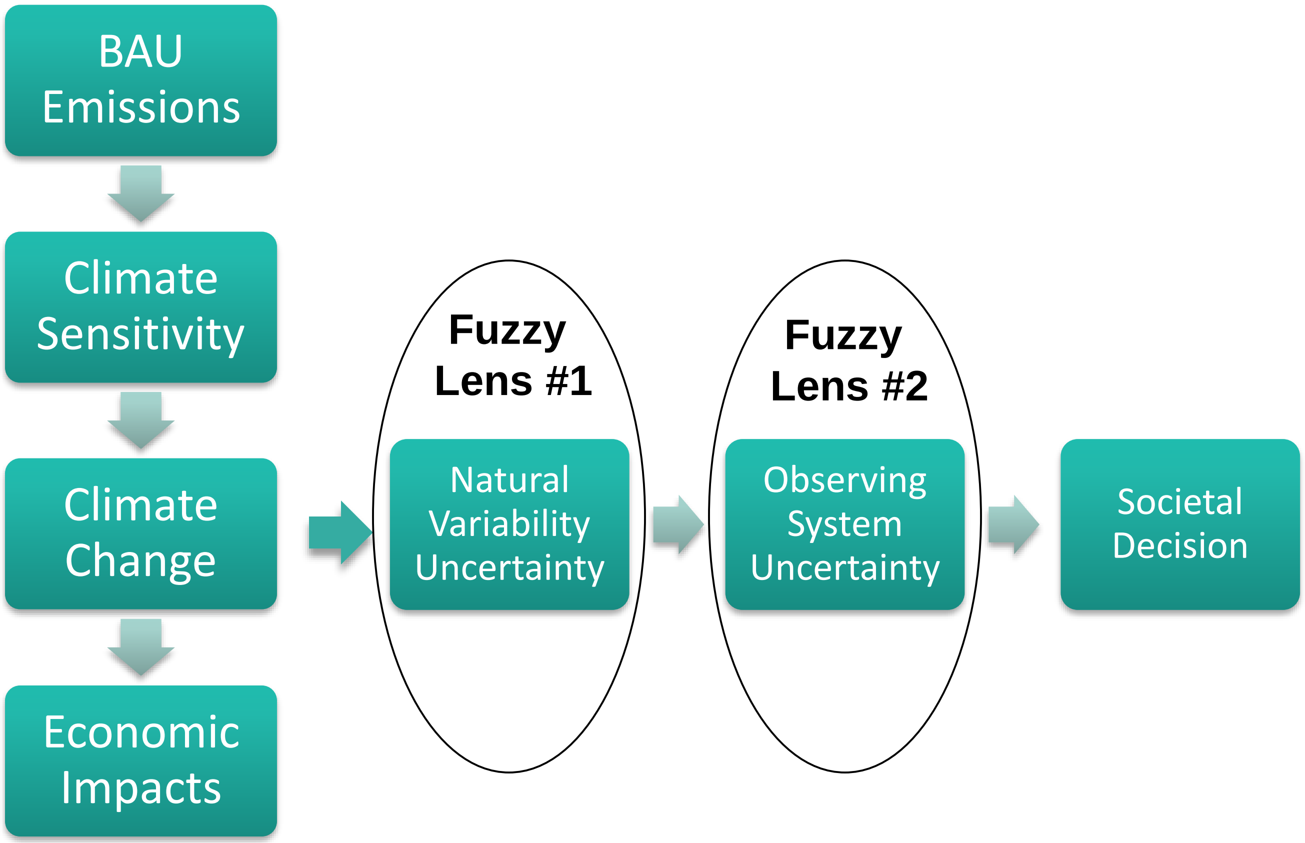
BAU Emissions

Climate Sensitivity

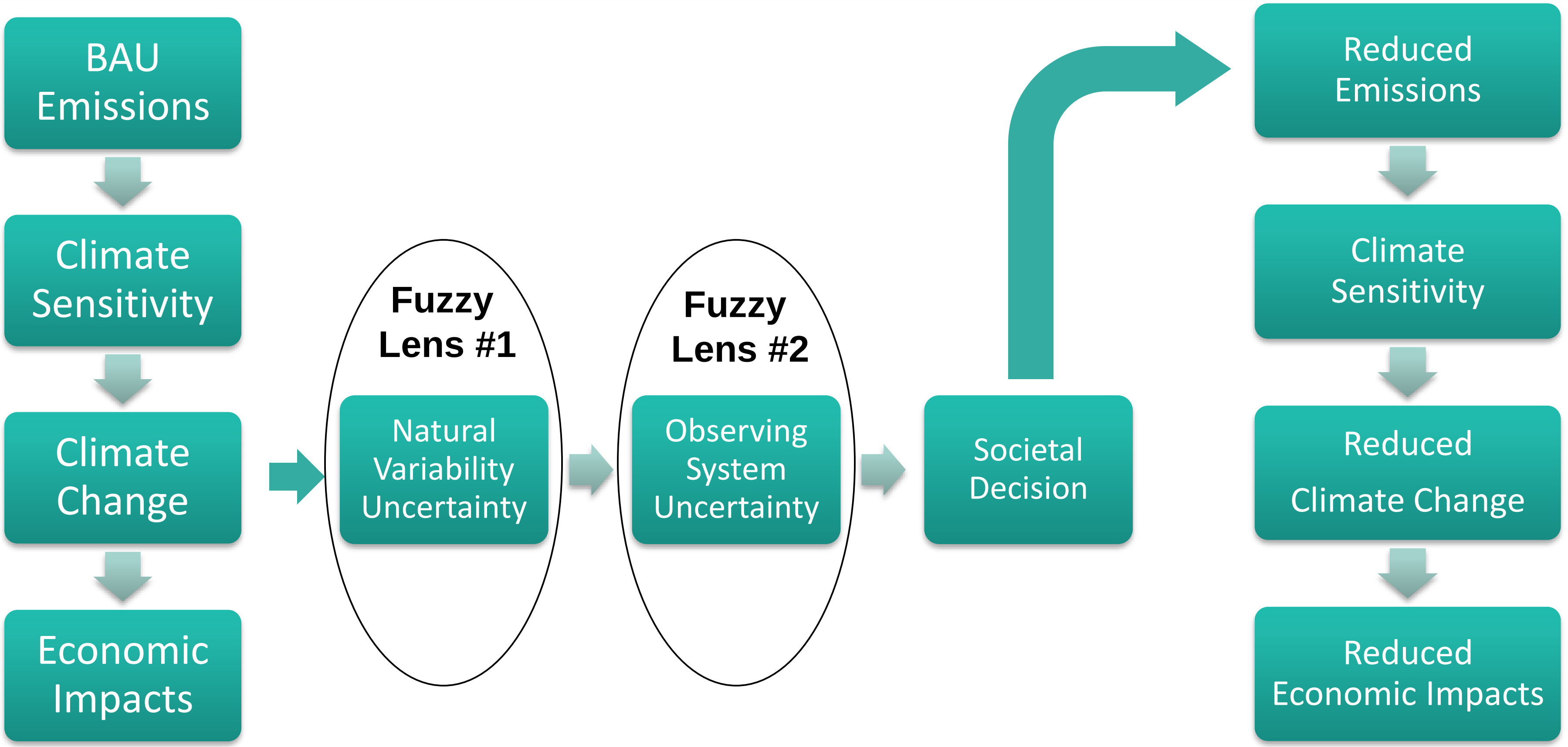
Climate Change

Economic Impacts

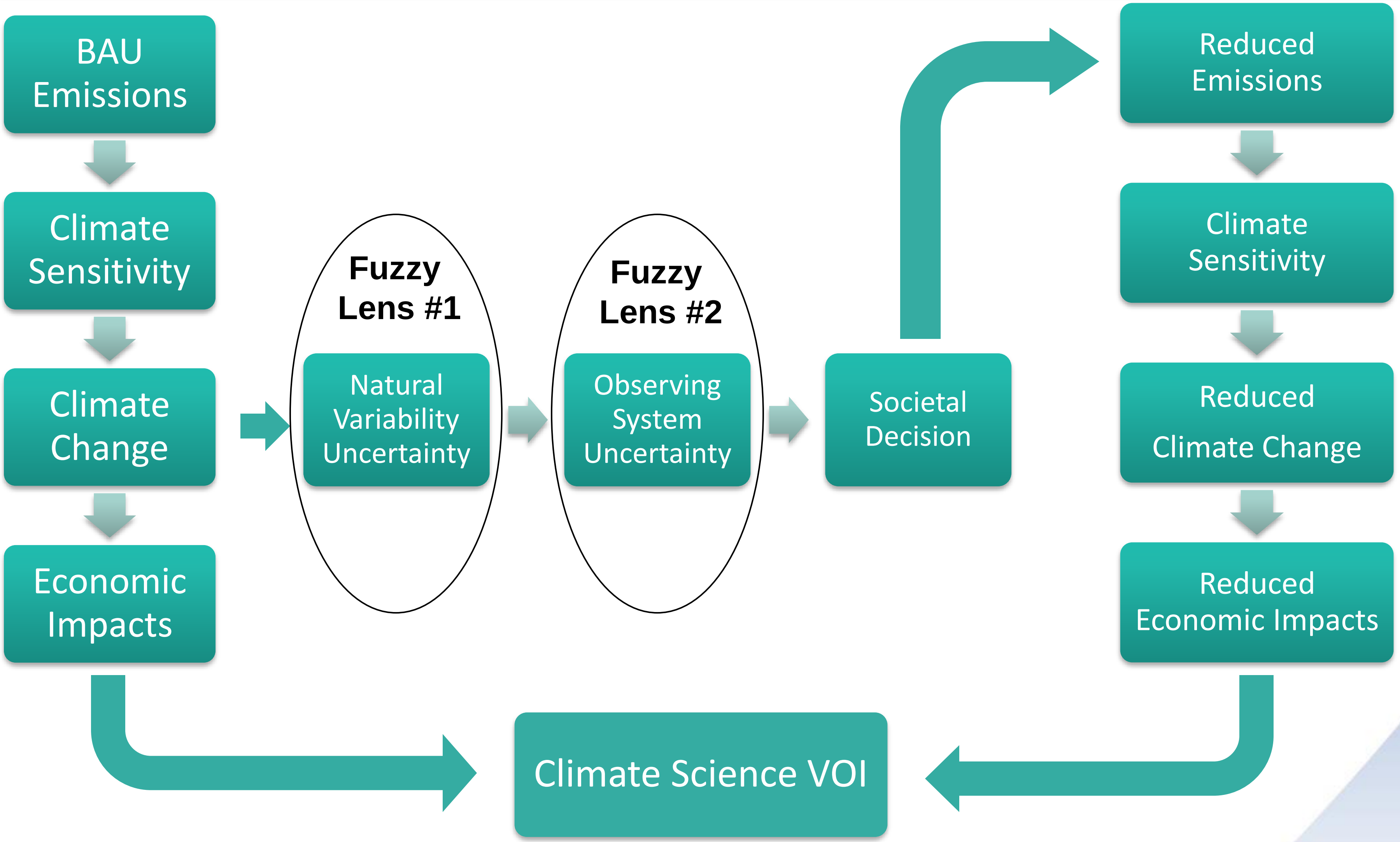
# VOI Estimation Method



# VOI Estimation Method



# VOI Estimation Method



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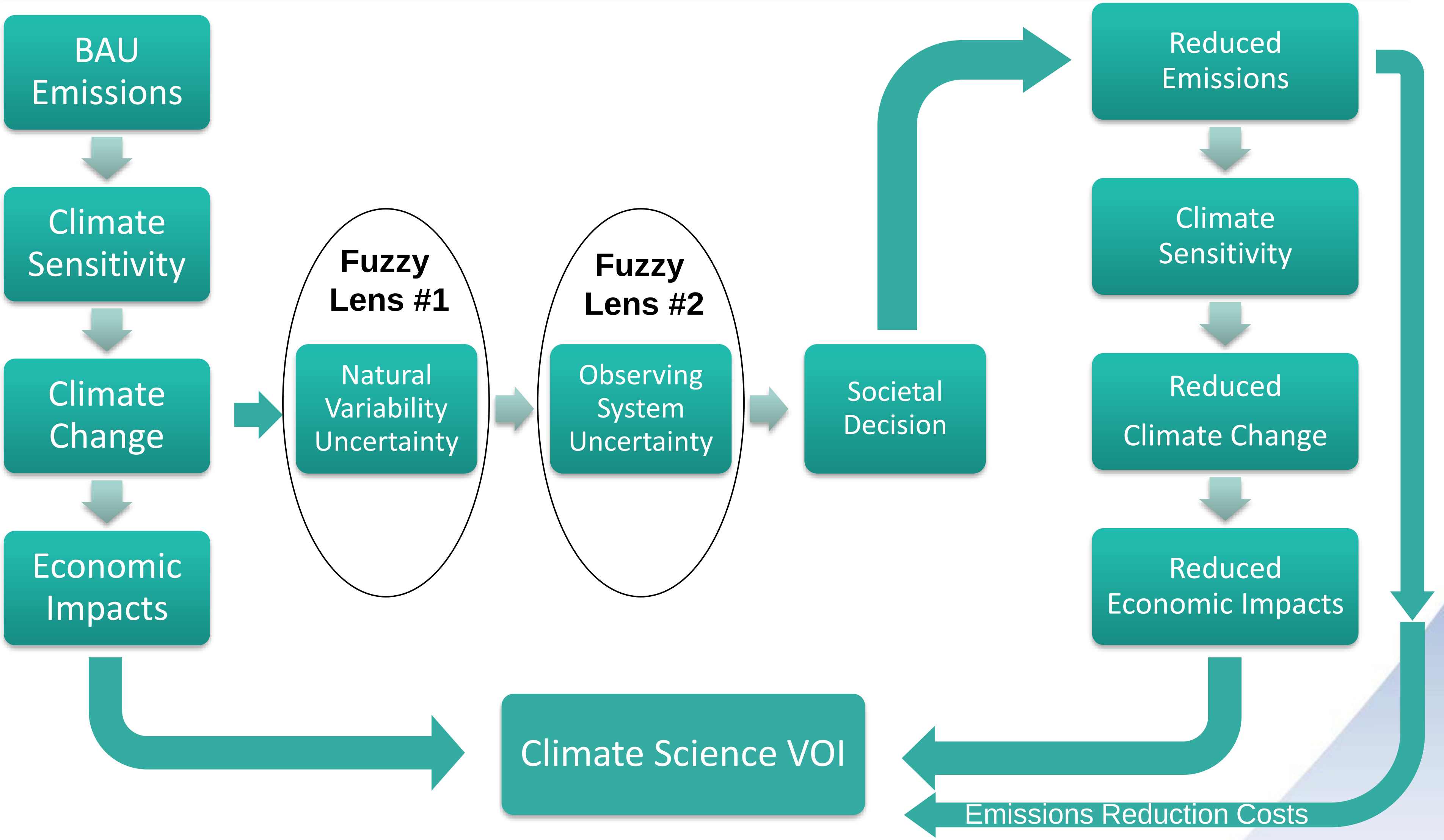

# Economics: The Big Picture

- **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<br>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 (NPV)***

# 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) |
|---|---|
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***Advanced Climate Observing System:***

***Return on Investment: $50 per $1***

***Cost of Delay: $650B per year***

# Decadal Change Trends

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

- Climate change requirements can be very different than a typical NASA Earth Science process mission interested in retrievals at instantaneous fields of view at high space/time resolution, *where instrument noise issues may dominate instantaneous retrievals*

# The Cloud Feedback Challenge – A Significant First Step

## The CLARREO Pathfinder Mission

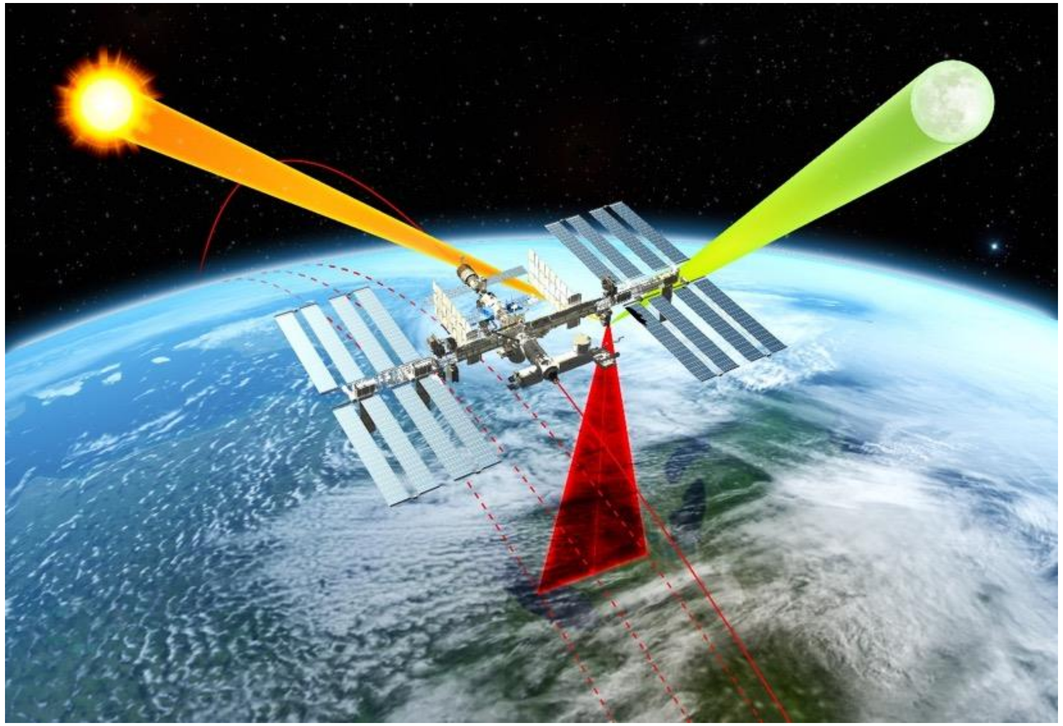
- **NASA demonstration mission to show a factor of 5 improvement in calibration accuracy across the entire reflected solar spectrum. 0.3% (k=1) SI traceable absolute accuracy (Kopp et. al. 2017, Wielicki et al. 2013)**

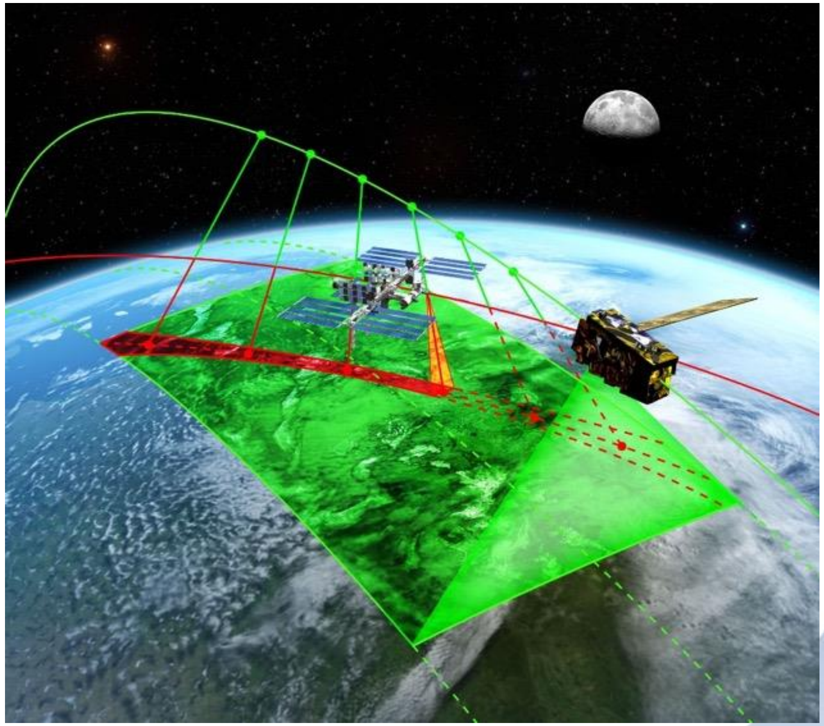
- **The ability to inter-calibrate CERES and VIIRS to higher accuracy and stability by matching angle/time/space/spectral response across the entire range of spectral channels and scan swath**
  - 3 nm contiguous spectral sampling 350 nm to 2300 nm.
  - 0.5 km fields of view, 70km wide swath at nadir
  - 0.3% (k=1) inter calibration capability. (Wielicki et. al. 2013, Lukashin et al. 2013). Can also calibrate geostationary imagers, land imagers, ocean imagers.
  - Launch to International Space Station in 2022

# CLARREO Pathfinder:
## Baseline Mission Objectives

***Demonstrate high accuracy SI-Traceable Calibration***

***Demonstrate Reference Inter-Calibration Capabilities***





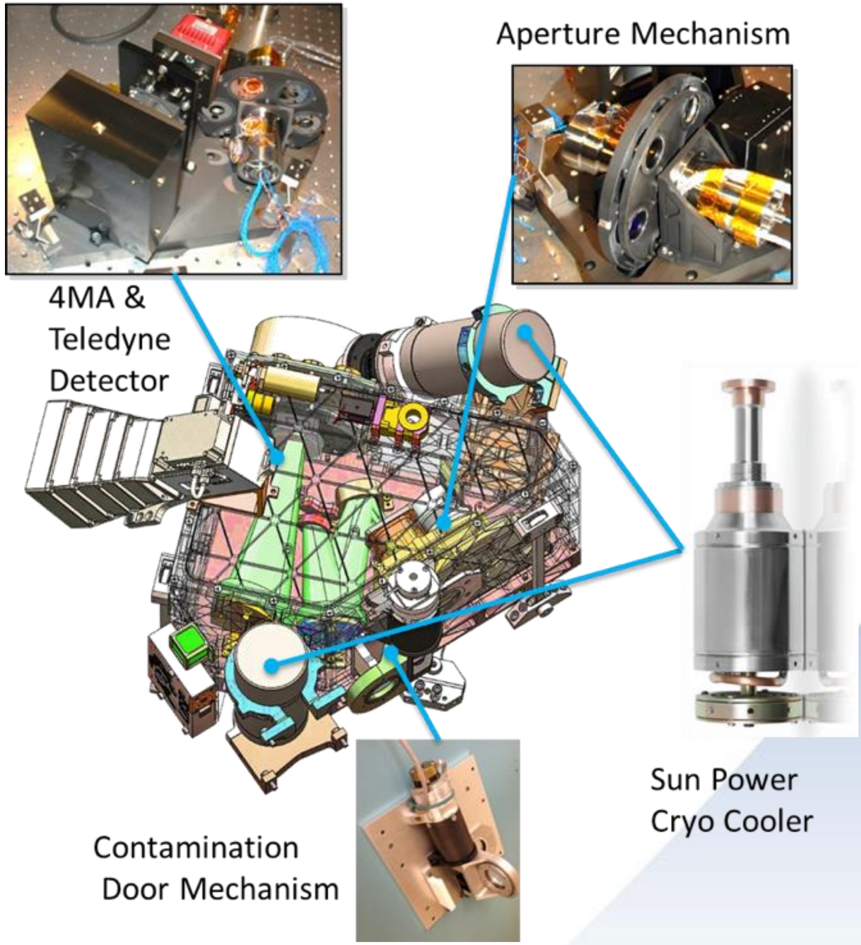
Objective #1: Demonstrate the ability to conduct, on orbit, SI-Traceable calibration of measured scene spectral reflectance with an advanced accuracy over current on-orbit sensors using a reflected solar spectrometer flying on the International Space Station.

Objective #2: Demonstrate the ability to use that improved accuracy to serve as an in orbit reference spectrometer for advanced intercalibration of other key satellite sensors across the reflected solar spectrum (350-2300 nm).

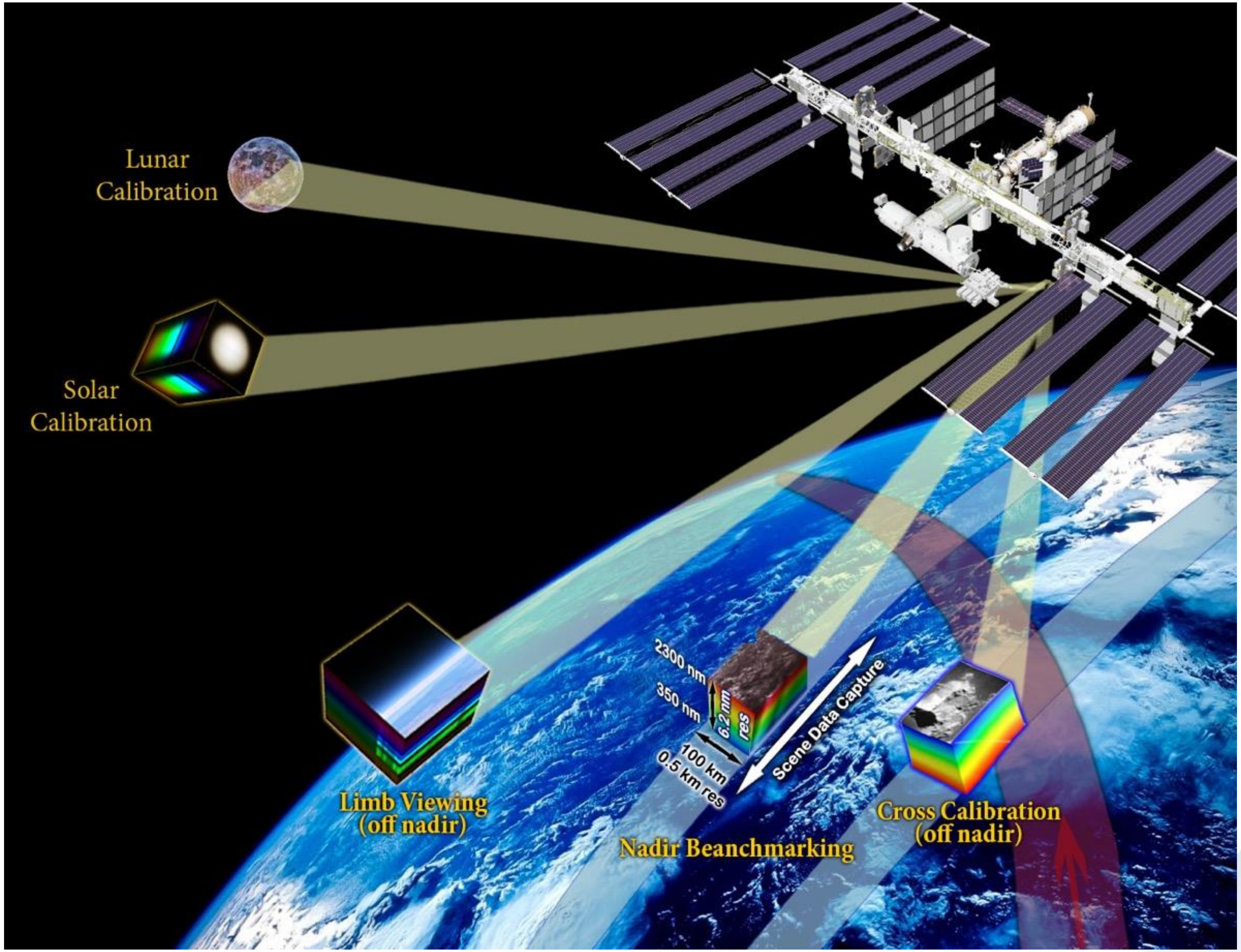
# CLARREO Pathfinder
# Reflected Solar (RS) Spectrometer Description

- **Based on Hyper-Spectral Imager for Climate Science (HySICS) instrument**
  - Developed by the ***University of Colorado Laboratory for Atmospheric and Space Physics (LASP)*** under NASA Earth Science Technology Office (ESTO) Instrument Incubator Program (IIP)
  - IIP Awards in 2007 and 2010
- **Push-broom Spectrometer**
  - 350-2300 nm contiguous spectral coverage
  - 3 nm spectral sampling, 6 nm resolution
  - 70 km cross-track swath width
  - 0.5 km earth viewing pixels
  - Balloon flights demonstrated accuracies approaching CLARREO requirements for climate data records
- **Two-Axis Pointing System enables solar / lunar / Earth viewing**
  - Active stabilization for use on ISS
  - Leverages significant design heritage from past programs – TSIS, GLORY, TIMED

***HySICS instrument has been previously flown on two high altitude balloon flights (37 km altitude)***



# Viewing Modes



# Level 1 Requirements Summary

| | Measurement Uncertainty | |
|---|---|---|
| **Demonstration Parameter** | **Baseline Objective*** | **Threshold Requirement**** |
| **Spectrally-Resolved Earth Reflectance (350 – 2300 nm):** SI-Traceable, referenced to spectral solar irradiance | ≤ 0.3% (k = 1) | ≤ 0.6% (k = 1) |
| **Spectrally-Integrated Earth Reflectance (350 – 2300 nm):** SI-traceable broadband (350 - 2300 nm) spectrally-integrated Earth reflectance with spectral accuracy weighted using global average Earth spectrally reflected energy | ≤ 0.3% (k = 1) | ≤ 0.6% (k = 1) |
| **On-Orbit Inter-Calibration:** Demonstrate the ability to Inter-Calibrate with CERES/RBI short wave channel and VIIRS reflectance bands | ≤ 0.3% (k = 1) | ≤ 0.6% (k = 1) |

**Baseline Objective is within a factor of 2 of full CLARREO Tier-1 Decadal Survey Mission Requirements*

***Threshold requirement is a factor of 2 (CERES) to 4 (VIIRS) better than current capabilities.*

# Summary

- The world still lacks a designed and committed climate change observing system
- The recent 2017 Decadal Survey does not change this: NASA lacks the funding, as do ESA, Japan, China, and the rest of the world
- We continue to focus on short term process observations as the “answer” but lack evidence that process observations alone can reduce uncertainty in cloud feedback: we must find a way to obtain highly accurate long term climate change observations (cloud properties and radiative fluxes)
- We need to act as a climate research community and stress the serious shortcomings, but point out the large economic value of overcoming them. Its a critical responsibility to society, and the climate science community is the only group with the relevant information.
- This is not a process observation vs long term observation vs modelling vs emerging constraints: we critically need all of the above
- The CLARREO Pathfinder is a significant first step in the right direction

# Status of CLARREO Infrared Observations

- **The CLARREO Mission, defined in the U. S. National Academy Decadal Survey of 2007, also included an extremely accurate infrared spectrometer**
- **NASA Langley was the lead center for development of this instrument and the CLARREO mission**
- **In 2011, the CLARREO mission was removed from the NASA budget**
- **In 2015, the CLARREO Pathfinder was proposed in the NASA budget**
  - The proposed budget was sufficient to cover only 1 instrument, not both RS and IR
- **CLARREO Infrared instrument continued in "pre-formulation" until Sept. 2018**
- **The 2017 Decadal Survey recognized the importance of the IR, but did not prioritize its measurement – Development of the IR instrument has ended**

**FORUM is now the best/only chance to obtain an accurate far-IR record in the 2020-2030 time period**

# Further Information:
# Google "CLARREO NASA"

- Mission Overview: Wielicki et al. 2013, BAMS cover article
- Economic value of higher accuracy climate obs: Cooke et al., J. Environ. Systems and Decisions, 2014; Cooke et al. Climate Policy, 2015, Weatherhead et al. AGU Earth's Future, 2017
- CLARREO Web site: http://clarreo.larc.nasa.gov
- CLARREO Science Team Report (~200 page summary of mission science, instruments, orbits, options, costs), CLARREO Pathfinder mission summary: http://clarreo.larc.nasa.gov
- CLARREO related/funded journal papers: 130 papers, 1100 citations, list can be found at: http://clarreo.larc.nasa.gov
- CLARREO Science Team Meeting Presentations: http://clarreo.larc.nasa.gov
- CLARREO conference presentations: a wide range of venues, U.S. & international

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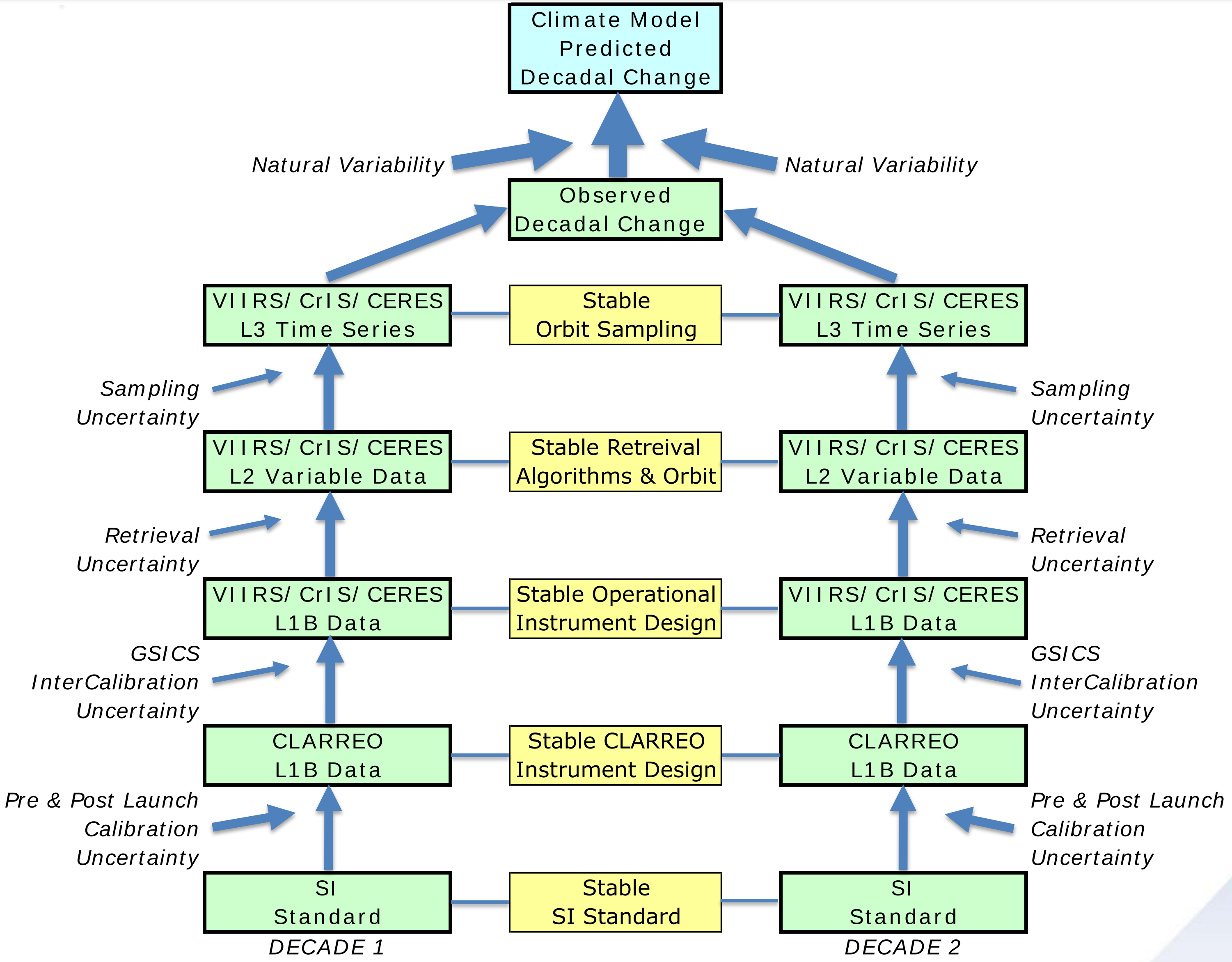
# Backup Slides

# Accuracy of Climate Change Observations & Predictions




*Trenbrerth et al. 2013*

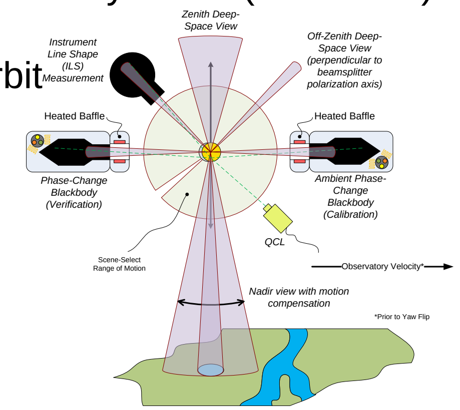
# Climate Absolute Radiance & Refractivity Observatory (CLARREO)

## 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% science @ 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, ISRO, IITM
- WMO GSICS

# The Cloud Feedback Challenge

- **Why is this?**
- **Why is the climate science community seemingly satisfied with business as usual?**
- **Why are we not strongly arguing the huge economic value of what we can offer if investments are increased?**
    - Are we afraid it sounds too self serving?
    - Are we too focused on short term research goals and budgets?
    - Are we afraid the politics won't support it?
    - Are we afraid we don't understand enough economics?  Even a factor of 5 uncertainty in the economic calculations does not change the result

- **Why aren't we pointing out to the world the need and the economic benefit.  They can choose to ignore it.**
- **We are the only ones who have the information to offer them the choice.  We remain quiet and speechless.**

# The Cloud Feedback Challenge

- Long term broadband cloud radiative effect observations are now in jeopardy
- Cost over-runs in building the CERES follow-on broadband instrument (recent RBI cancellation) mean that no broadband instrument will fly on JPSS-2 (~2022).
- A new instrument competition is being held to try to get an instrument on JPSS-3 (~ 2027), but is cost capped below the previous attempt
- If this fails, a gap is assured by 2028 with current mission plans. If it succeeds and the new instrument flies on JPSS-3, the gap risk still exceeds 30% by 2028, and grows to 50% by 2033. A follow on after JPSS-3 is “TBD”
- This is symptomatic of many if not most long term climate change focused observations. There is no follow on plan for long term climate change observations from cloud lidar (cloud fraction/height) following CALIPSO and EarthCare. The Decadal Survey aerosol lidar may or may not be able to fulfill this role: its primary mission goals are driven for aerosol and cloud processes.

# The Cloud Feedback Challenge

- The recent 2017 Decadal Survey chose to prioritize critical short term cloud process observations (e.g. lidar/radar/polarimeter) over long term change observations (e.g. reference calibration spectrometers to provide factor of 5 to 10 higher calibration accuracy to CERES and MODIS/VIIRS radiation/cloud instruments
- The Climate Panel of the report prioritized long term accurate observations over process observations, but the steering committee prioritized process observations. The steering committee takes precedence in the Decadal Survey process. Funding, not science is the issue.
- We still have no climate observing system designed to climate change requirements (Trenberth et al. 2013, NRC Continuity Report 2015, WMO/WCRP/CEOS/CGMS report 2012, Weatherhead et al. 2017). We have no plans to create one.

# The Cloud Feedback Challenge – A Significant First Step

- **The CLARREO Pathfinder Mission**
- **NASA demonstration mission to show a factor of 5 improvement in calibration accuracy across the entire reflected solar spectrum. 0.3% (k=1) SI traceable absolute accuracy (Kopp et. al. 2017, Wielicki et al. 2013). ~ $100 million Class D mission**
- **The ability to inter-calibrate CERES and VIIRS to higher accuracy and stability by matching angle/time/space/spectral response across the entire range of spectral channels and scan swath**
    - 3 nm contiguous spectral sampling 350 nm to 2300 nm.
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    - Launch to International Space Station in 2022
    - The bad news: only 1 year of operations on orbit is planned to demonstrate the capability: no current plan for longer term observations even if the instrument is successful and continues to operate on ISS.