Earth's Radiation Budget Observations from Space: Progress on and Risks to Continuity

(and an update on CLARREO Pathfinder if time permits)

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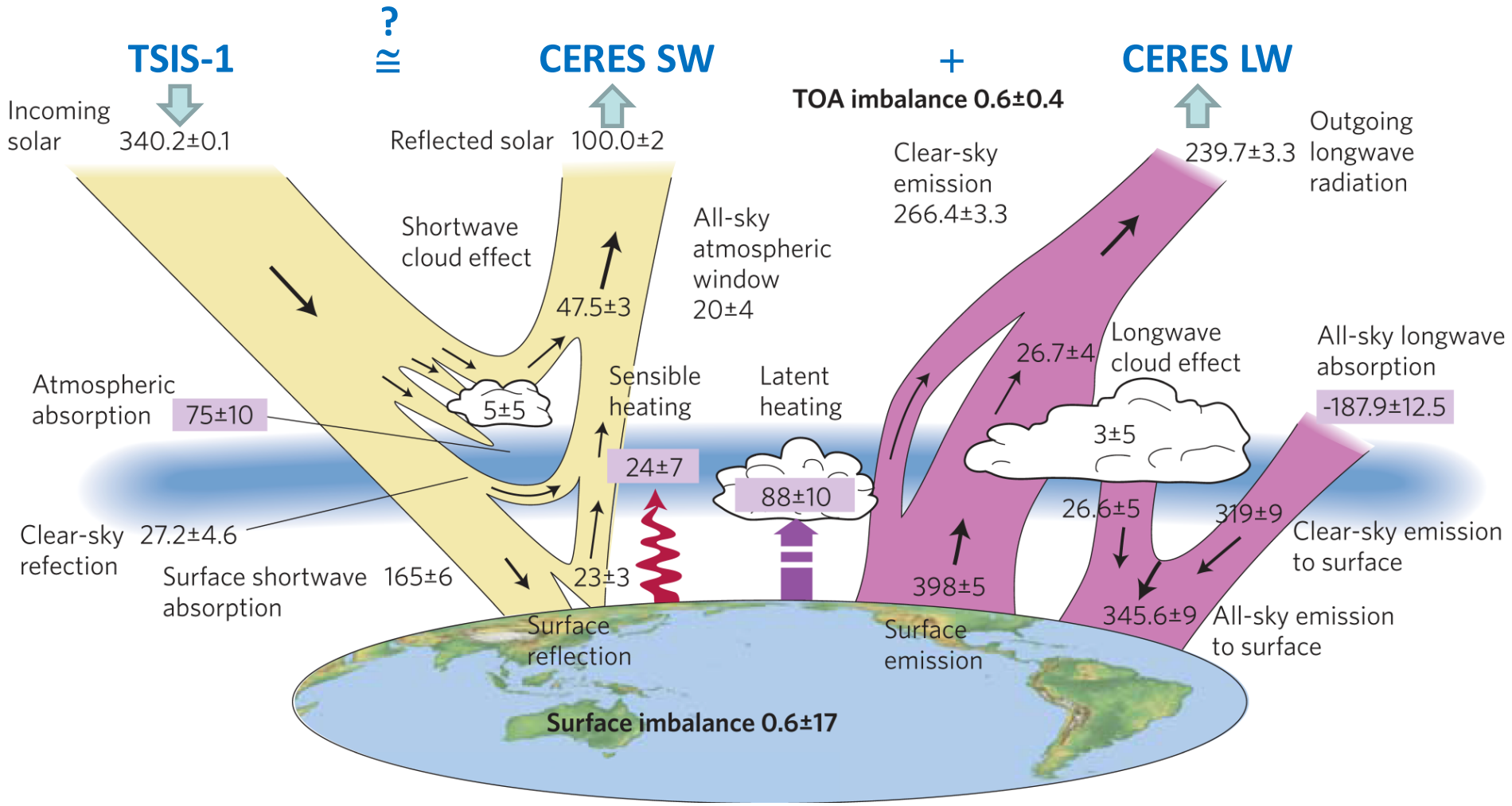
The Global Radiative Energy Budget

Current Measurements

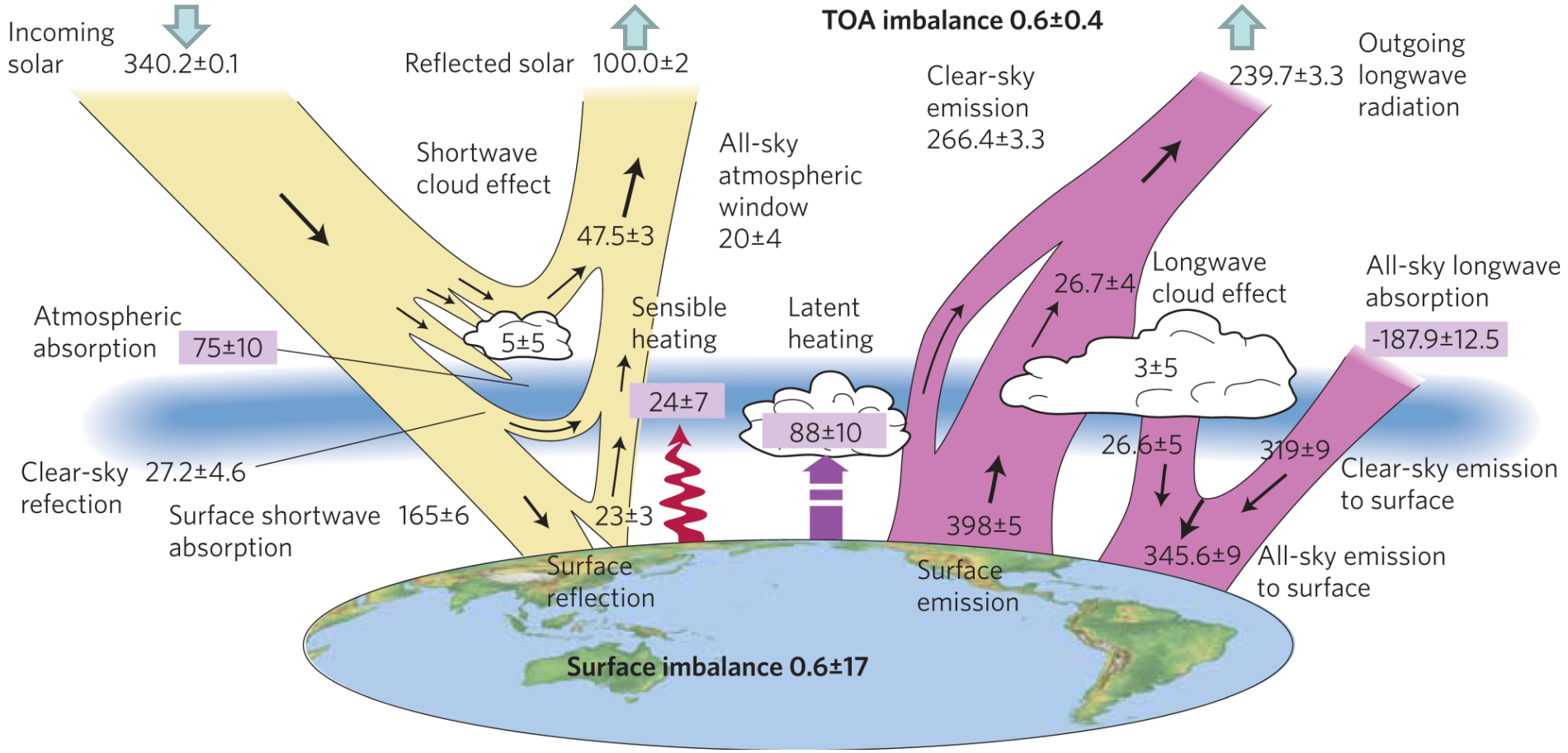


Stephens et al., Nature Geo., 2012

The Global Radiative Energy Budget

Near-term Measurement Continuity

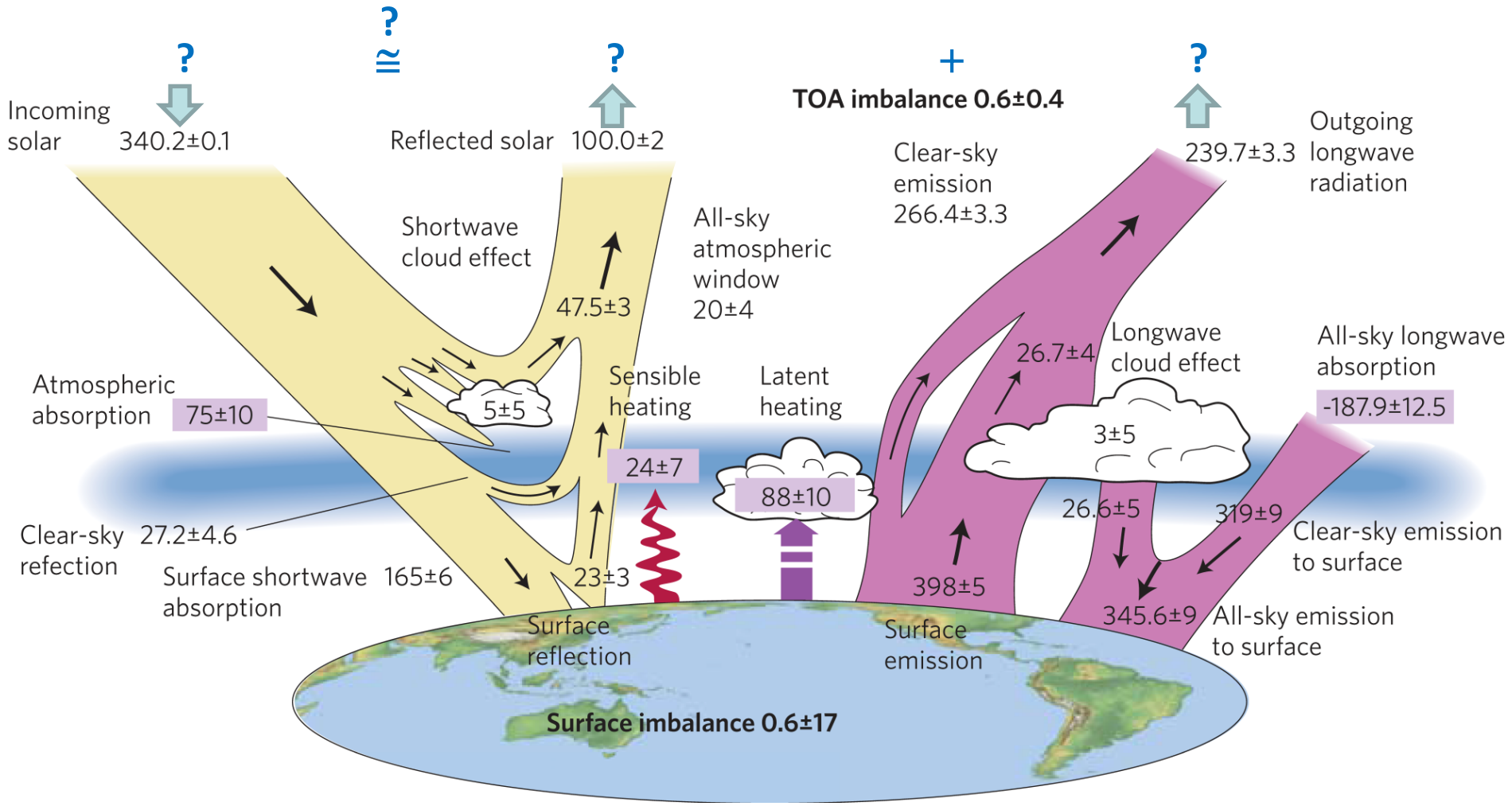
TSIS-2 ? ≅ ***Libera* SW & Split SW** + ***Libera* LW**



Stephens et al., Nature Geo., 2012

The Global Radiative Energy Budget

Longer-term Measurement Continuity

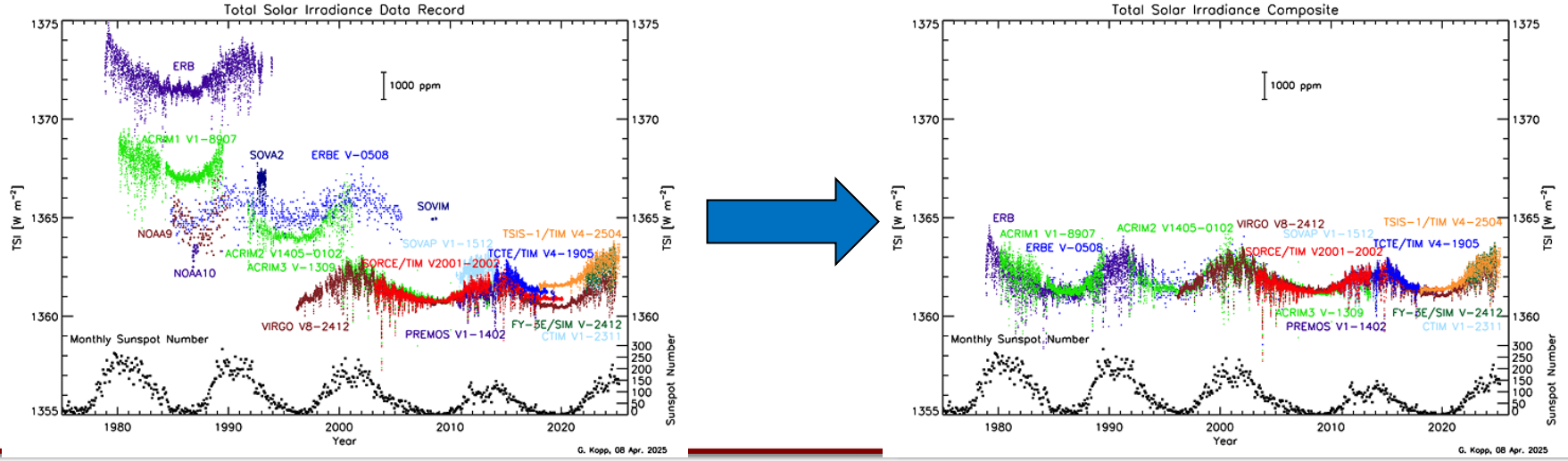


Stephens et al., Nature Geo., 2012

ERB Continuity

- Understanding how changes in the ERB impact the Earth system require accurate, precise, and stable ERB data products maintained over a period sufficient to detect trends.
- These trends are sufficiently small such that measurements must be maintained over multiple generations of instruments in such a way that:
  - ➢ discontinuities or gaps are not introduced into the data products
  - ➢ pre-flight and in-flight calibration and validation procedures are established to mitigate drifts in data records
- The data record requires continuity and overlap between ERB sensors.
  - ➢ Gap-filling methods using imagery data have uncertainty on the order of current decadal trends, 0.4 Wm^{-2}.

Example from the 48-year total solar irradiance record. With continuity and overlap, measurements from 13 instruments are put on a common calibration scale.



Near-term ERB Continuity: TSIS-2 and *Libera*

TSIS-2 Solar Measurements

Expect 12 months of operational overlap with TSIS-1 in 2027/28 time period

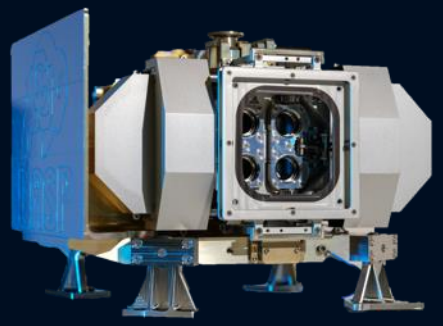
Current Status

Will continue the TSI & SSI measurements with similar performance to the TSIS-1 measurements

- Planning at least 1 year of observational overlap with the TSIS-1 measurements in SC25 declining phase.
- ***Only a 3-year prime mission, with potential extension beyond end of the decade.***

Instruments integrated to S/C and preparing for Observatory TVAC testing

Current LRD in early 2027

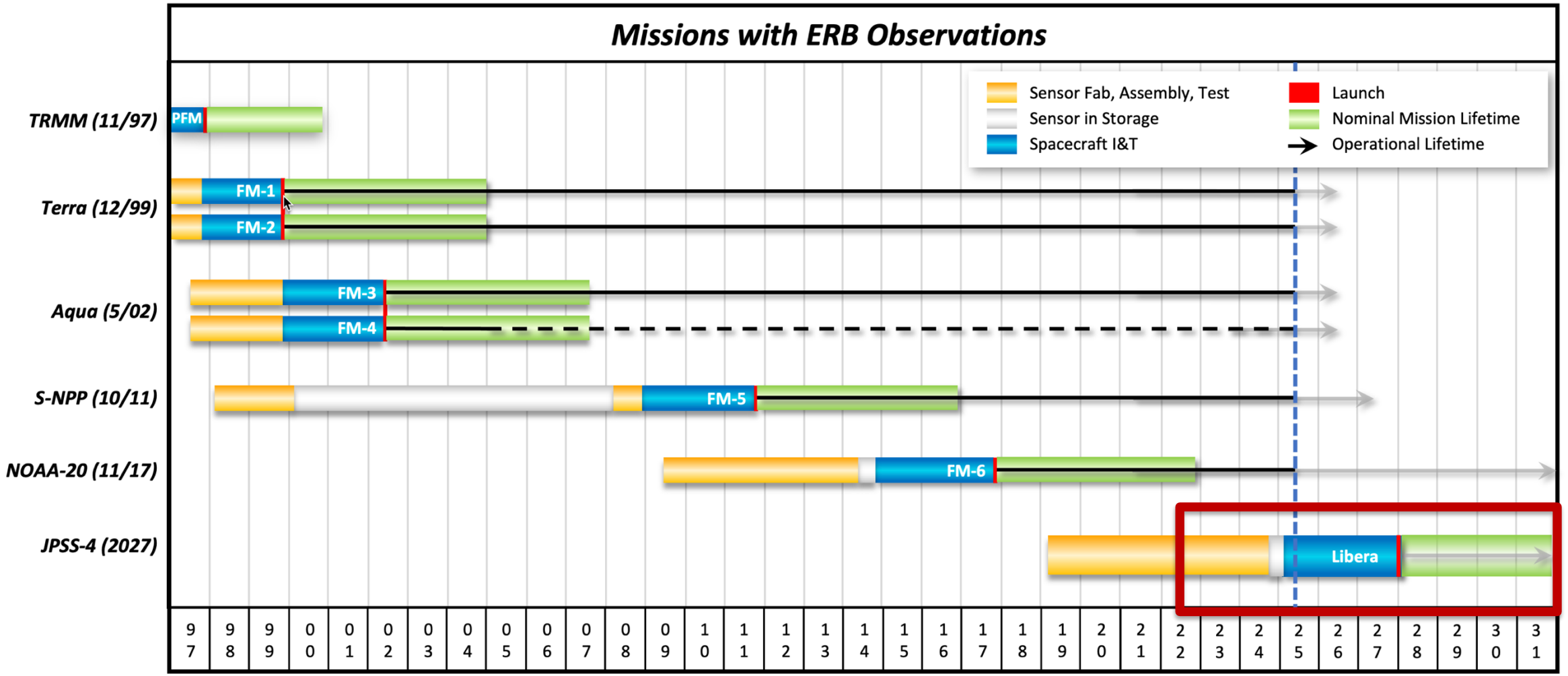


Total Irradiance Monitor (TIM)

Spectral Irradiance Monitor (SIM)

Total and Spectral Solar Irradiance Sensors -2

Near-term Earth Radiation Measurement Continuity



- *Currently, 6 CERES instruments fly on 4 satellites: Terra (L1999), Aqua (L2002), SNPP (L2011), NOAA-20(L2017)*
- *Libera scheduled for launch in 2027 on JPSS-4*

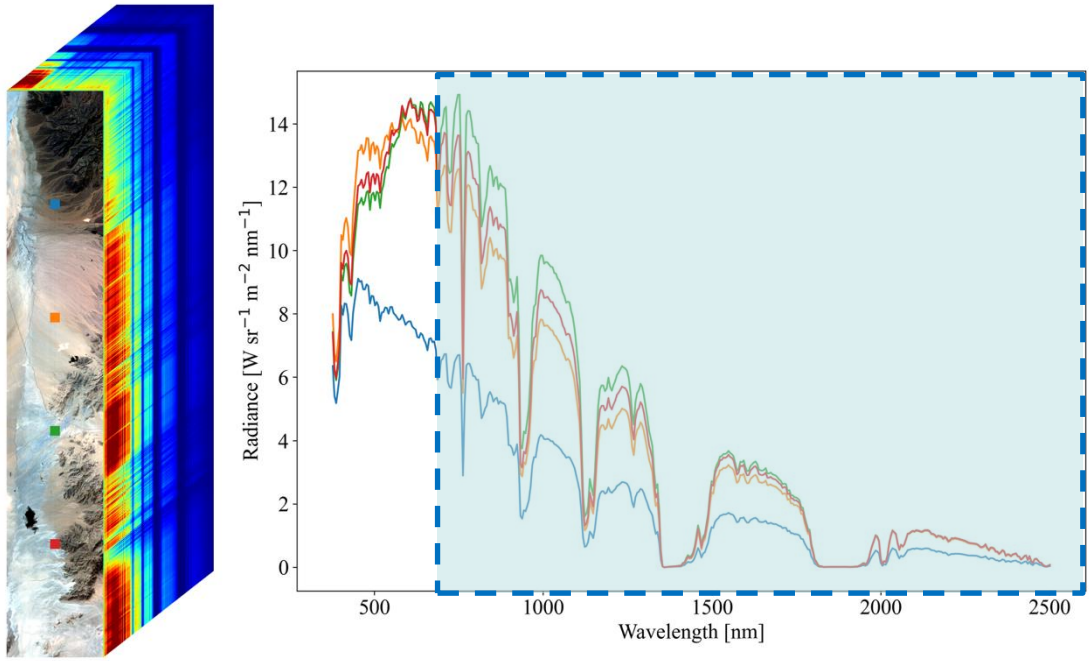
Libera, NASA Earth Venture Continuity-1 Mission

'Li-be-ra, named for the daughter of Ceres in ancient Roman mythology

Provides continuity of the Clouds and the Earth's Radiant Energy System (CERES) Earth radiation budget

- ***Measures integrated shortwave (0.3–5 µm), longwave (5–50 µm), total (0.3–100+ µm) and (new) split-shortwave (0.7–5 µm) radiance over 24 km nadir footprint; uncertainty ~ 0.2%***
- ***Includes a wide FOV camera for scene context and rapid split-SW ADM generation; explores pathway for future free-flyer ERB observing system***
- ***Electrical substitution radiometers (ESRs) using vertically-aligned carbon nanotube (VACNT) detectors***
- ***Primary operational modes: Cross-track and azimuthal scanning; on-board calibrators; solar and lunar viewing.***
- ***Partners: LASP, BAE, NIST Boulder, Space Dynamics Lab***
- ***Science Team: CU, JPL, CSU, UA, UM, LBL***

The *Libera* Split-Shortwave Channel

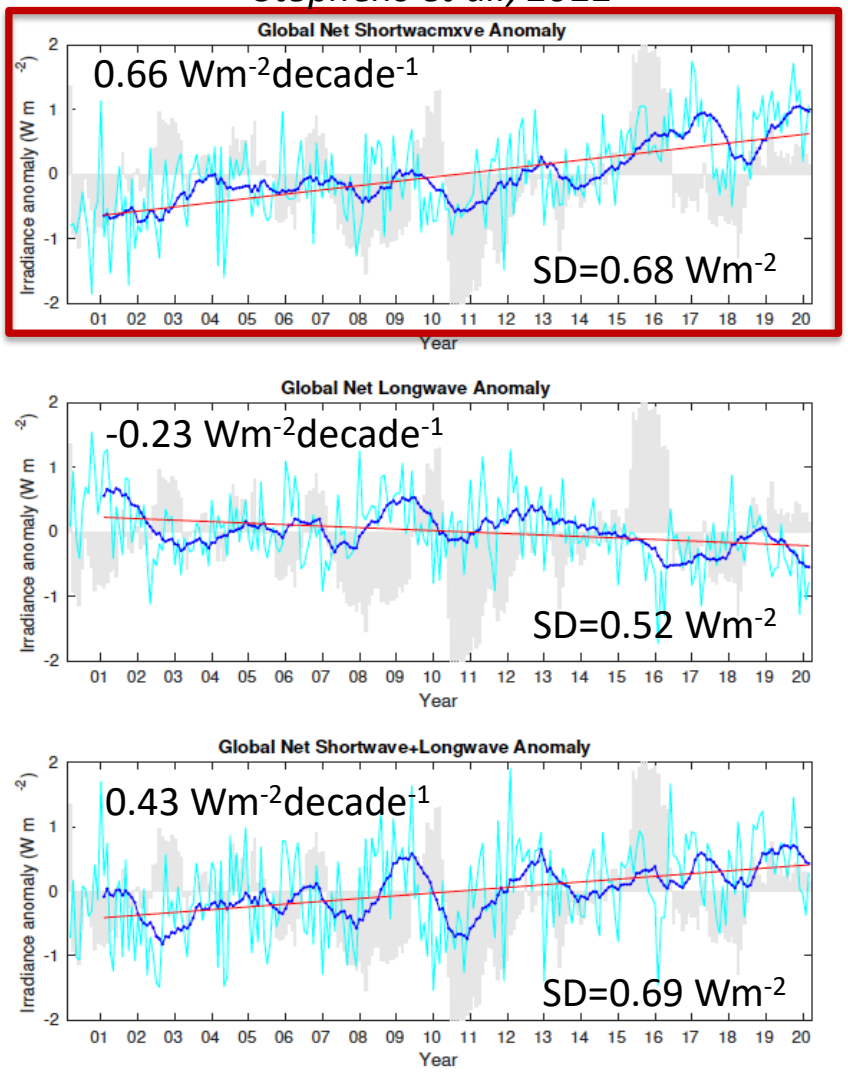


EMIT Level 1b at-sensor radiance in a sample area in the Southwest United States

NIR & VIS signature of processes controlling the absorption of solar radiation & climate feedbacks.

- *In the CERES record, a positive trend in ASR is the driving the increase in EEI*
- *Climate models suggest that warming is sustained by the increase in ASR on decadal to centennial time scales (positive SW feedbacks)*

Stephens et al., 2022



Libera Integrated on JPSS-4

Libera Major Reviews and Key Milestones

Milestone	Acronym	Date	Convening Authority
Authorization to Proceed	**ATP**	**6 Jul 20**	**-**
System Requirements Review	**SRR**	**22 Feb 21**	**SRB**
Key Decision Point - B	**KDP-B**	**30 Apr 21**	**SMD PMC**
Preliminary Design Review	**PDR**	**8-10 Feb 22**	**SRB**
Key Decision Point - C	**KDP-C**	**Apr 22**	**SMD PMC**
Critical Design Review	**CDR**	**27-29 Jun 23**	**SRB**
Scan-Mode dPMC		**22 Mar 24**	**ESD**
Libera Accommodations Review	**LAR**	**15-16 May 24**	**JPSS**
Re-plan DPMC		**13 May 25**	**SMD**
Instrument Build Complete		**Jun 25**	
Pre-Environmental Review	**PER**	**Sep 25**	**SRB**
Pre-Ship Review	**PSR**	**27 Jan 26**	**SRB**
Delivery to Spacecraft		**23 Feb 26**	**-**
Delta-Spacecraft PER	**ΔS/C PER**	**19 May 26**	
Launch Readiness		Sep 2027	-
Key Decision Point E	KDP-E	2027	SMD PMC
Post Launch Assessment Review	PLAR	L+90d	SRB
Operational Transition Review	OTR	PLAR + 9mo	TBD

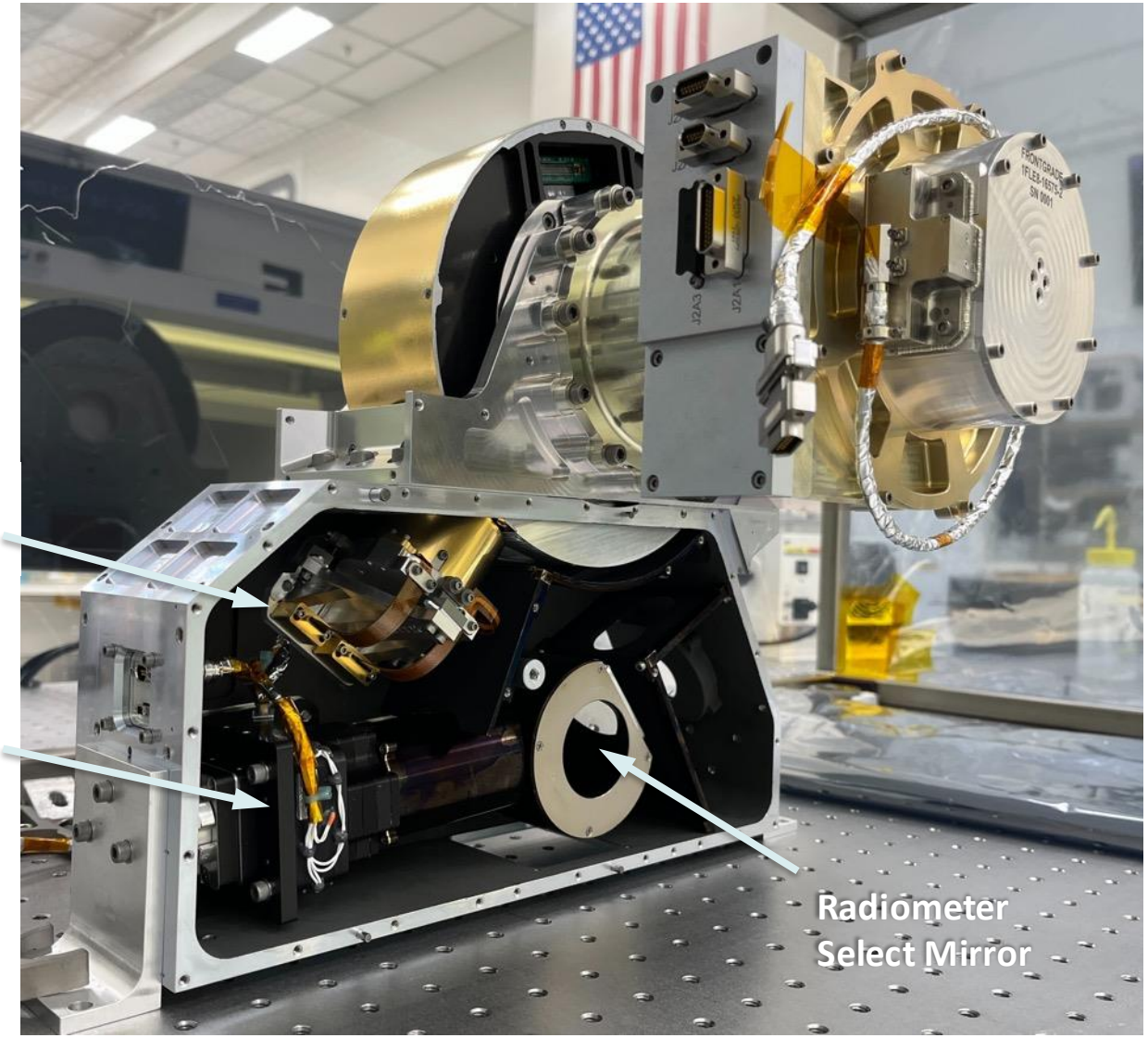
Libera Level-1 Requirements

Requirement	Baseline Value	Threshold Value
Design Lifetime	5 years	5 years
Spectral Ranges	0.3 μm - 5 μm 0.7 μm - 5 μm 5 μm - 50 μm 0.3 μm – 100+ μm	0.3 μm - 5 μm 5 μm - 35 μm 0.3 μm – 100+ μm
Channel Accuracies (k=1)	SW: 0.17% Split SW: 0.17% LW: 0.24% Total: 0.22%	SW: 1% LW: 0.5% Total: 0.5%
Channel Precisions	0.11 $W/m^2/sr$ for all channels	SW: 0.2 $W/m^2/sr$ LW: 0.45 $W/m^2/sr$ Total: 0.3 $W/m^2/sr$
Channel Stability	0.1%/decade	0.3%/decade
Channel Linearity	0.1% deviation over dynamic range for all channels	0.15% deviation over dynamic range for all channels
Channel Dynamic Range	0 - 500 $W/m^2/sr$	0 - 500 $W/m^2/sr$
WFOV Imaging	wavelength 555 nm 20 nm bandwith 140° FOV 1 km horiz. Resolution at nadir 1.5% uniformity 5% radiometric accuracy 0.2 - 600 $W/m^2/sr/\mu m$ dynamic range 0.33 Hz frame acquisition	No requirement

Libera On-Orbit Calibration and Validation

- Onboard calibration targets (daily)
  - Shortwave calibrator using LED sources (365, 405, 520, 635, 840, 1550 nm) and transmissive diffuser; stability tracked via a SW calibration radiometer
  - Longwave calibrator: flat-plate blackbody (310-335K) with VANTABLACK®S-IR coating, SI-traceable PRTs to NIST standards
- Solar calibrations (bi-monthly)
  - Spectralon reflective diffuser, three separate faces

  viewed bi-monthly/monthly/semi-annually for degradation tracking
- Lunar calibrations (~ 12-16 per year)

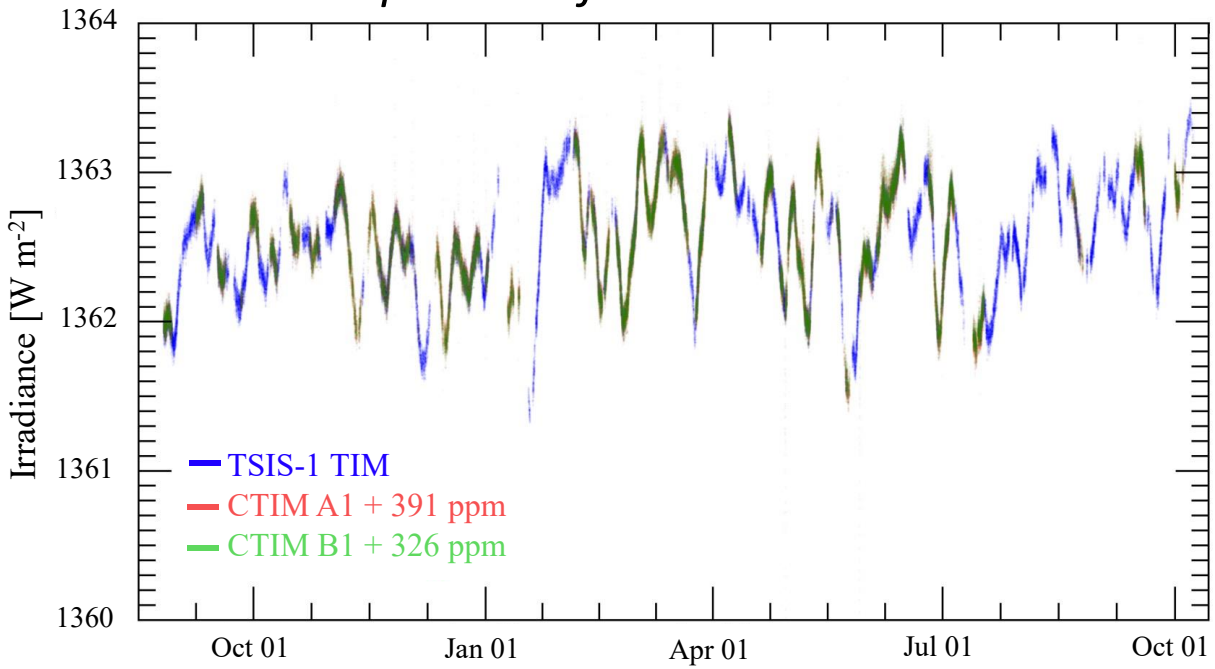


Beyond Near-term Continuity

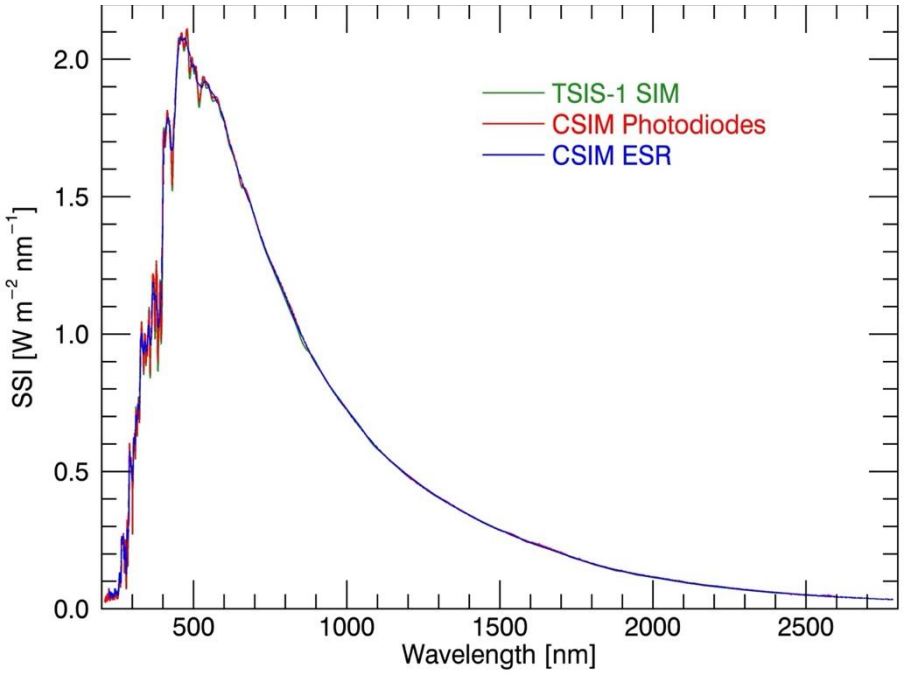
Beyond Near-term Continuity: Solar Irradiance

Solar irradiance is easier. Compact total and spectral irradiance monitors (CTIM and CSIM) have been demonstrated on CubeSats, obtaining climate-quality measurements.

Comparison of CTIM with TSIS-1 TIM



Comparison of CSIM with TSIS-1 SIM

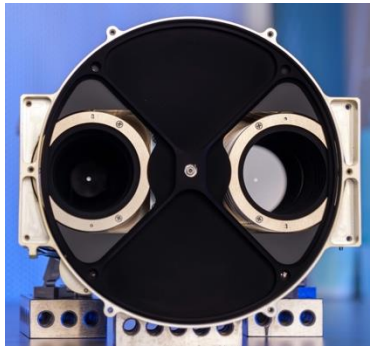


CTSIS concept exists for a multi-year, multi-platform plan to implement solar irradiance continuity on SmallSats/CubeSats at ~ 10% of the current budget for solar irradiance measurements.

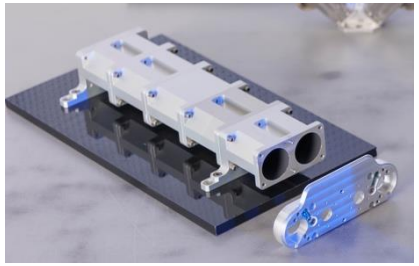
Beyond Near-term Continuity: Earth Radiation

Next generation SmallSat/CubeSat concepts are in development:

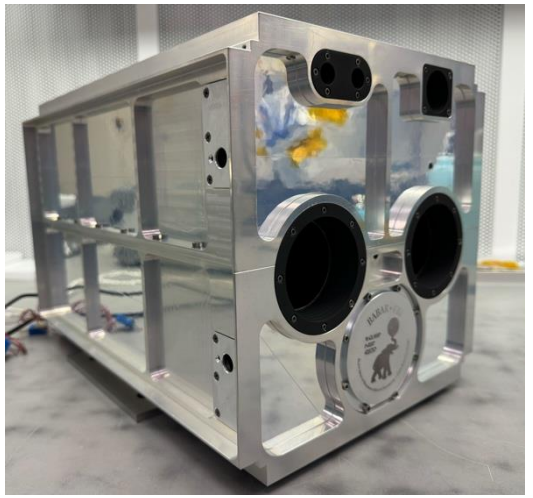
- LASP: Black Array of Broadband Absolute Radiometers – Earth Radiation Imager (BABAR-ERI)
  - 32-element array of micromachined silicon, electrical substitution radiometers with high-efficiency broadband carbon nanotube absorbers



2 Cassegrain Telescopes
Co-registered footprints
Simultaneous Total and Shortwave Imaging
Longwave = Total-Shortwave



Planar Bolometric Radiometer for stability monitoring



BABAR-ERI in 12U form-factor

- NASA Langley: DEMETER

Beyond Near-term Continuity: Earth Radiation

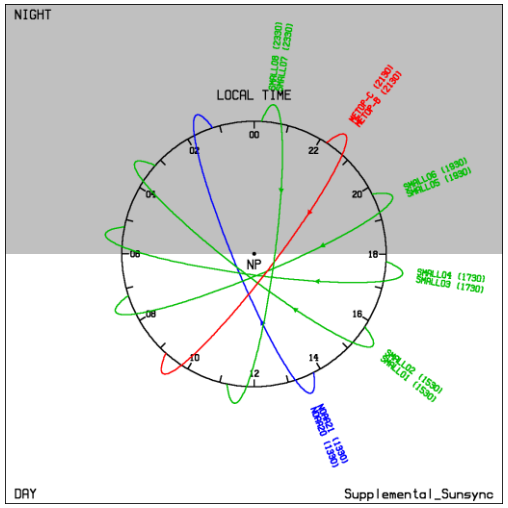
A low-risk option for continuity with Libera:

- Build a *Libera*-2 for integration on JPSS-3 (launch in 2032/33)
- JPSS-3 will fly an RBI mass model - sufficient to accommodate a *Libera* rebuild
- Provides time for technology demonstration flights of next-generation ERB sensors

Other Related Concepts

- Direct radiometric measurement of EEI (ECO and others)
- Radiation pressure (Space Balls)
- Adding the spectral dimension to more traditional approaches
- CLARREO-like benchmarking and spectral fingerprinting

Longer-term Continuity is Uncertain



Kidder et al., (2022)

- What is planned for Earth radiation beyond CERES/Libera?
  - Nothing identified
  - Libera has a 2027 launch with a 5-year prime mission lifetime
  - ***Need to be planning now for ERB continuity into the next decade***
  - GEWEX has encouraged the development of a concept from Tom Vonderhaar to establish an *International Earth Radiation Budget Consortium* (IERBC) modeled after the International Satellite Cloud Climatology Program to "design, implement and analyze the 7th Era of ERB observations".
    - One proposed concept: Sun-synchronous constellation with 6 orbital planes to address diurnal variability
    - Published in the GEWEX Quarterly; full paper published in JEMS
- What is planned for solar irradiance beyond TSIS-2?
  - Nothing identified
  - TSIS-2 has a 2027 launch with a 3-year mission lifetime
  - ***Need to be planning now for solar irradiance continuity into the next decade***
  - LASP has developed a CubeSat/MicroSat approach that lowers risk and cost of long-term solar irradiance continuity

A proposal …

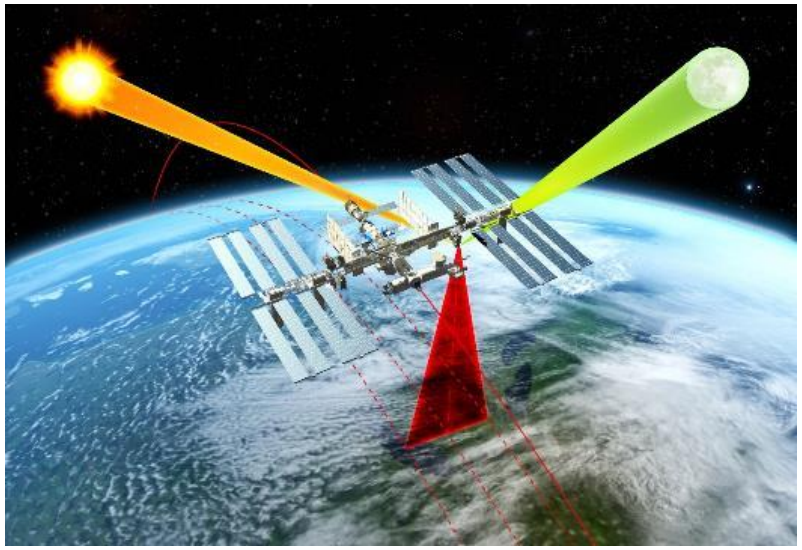
International GEWEX Earth Energy Imbalance Project
WCRP/WMO/IRC/ISC

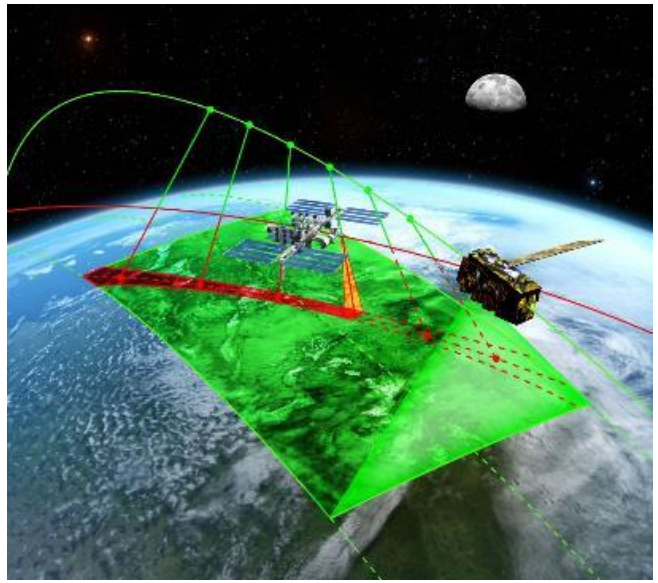
Purpose. *The International GEWEX Earth Energy Imbalance Project shall serve as the coordinating and oversight group for the nations and organizations cooperating in the observation and understanding of all details of Earth's energy exchange with the Sun and Space.*

This Implementation Plan Draft is to be modeled after the successful World Climate Research Programme, GEWEX 45-year International Satellite Cloud Climatology Programme (ISCCP) that began in coordination with international scientists, engineers and program leaders in the early 1980s. (Rossow, 2022; doi:10.13021/gewex.isccp)

CLARREO Pathfinder

- Measures shortwave reflectance and reflected radiance
- Spectral Range: 350 – 2300 nm
- Spatial Resolution: 0.5 km
- Spectral Resolution: 6 nm; Sampling Resolution: 3 nm
- ***Reflectance Uncertainty: 0.3%*** (1-σ)
- Polarization Sensitivity: 1-2%
  - ➢ Less than 1% (350-1800 nm), less than 2% (1800-2300 nm)
- Swath width: 70 km
- Operations from the International Space Station for one year
  - ➢ May 2026 launch to International Space Station
- Objective 1: Demonstrate high-accuracy SI-traceable, on-orbit calibration of measured scene spectral reflectance
- Objective 2: Transfer high accuracy via inter-calibration of other satellite sensors across spectral range



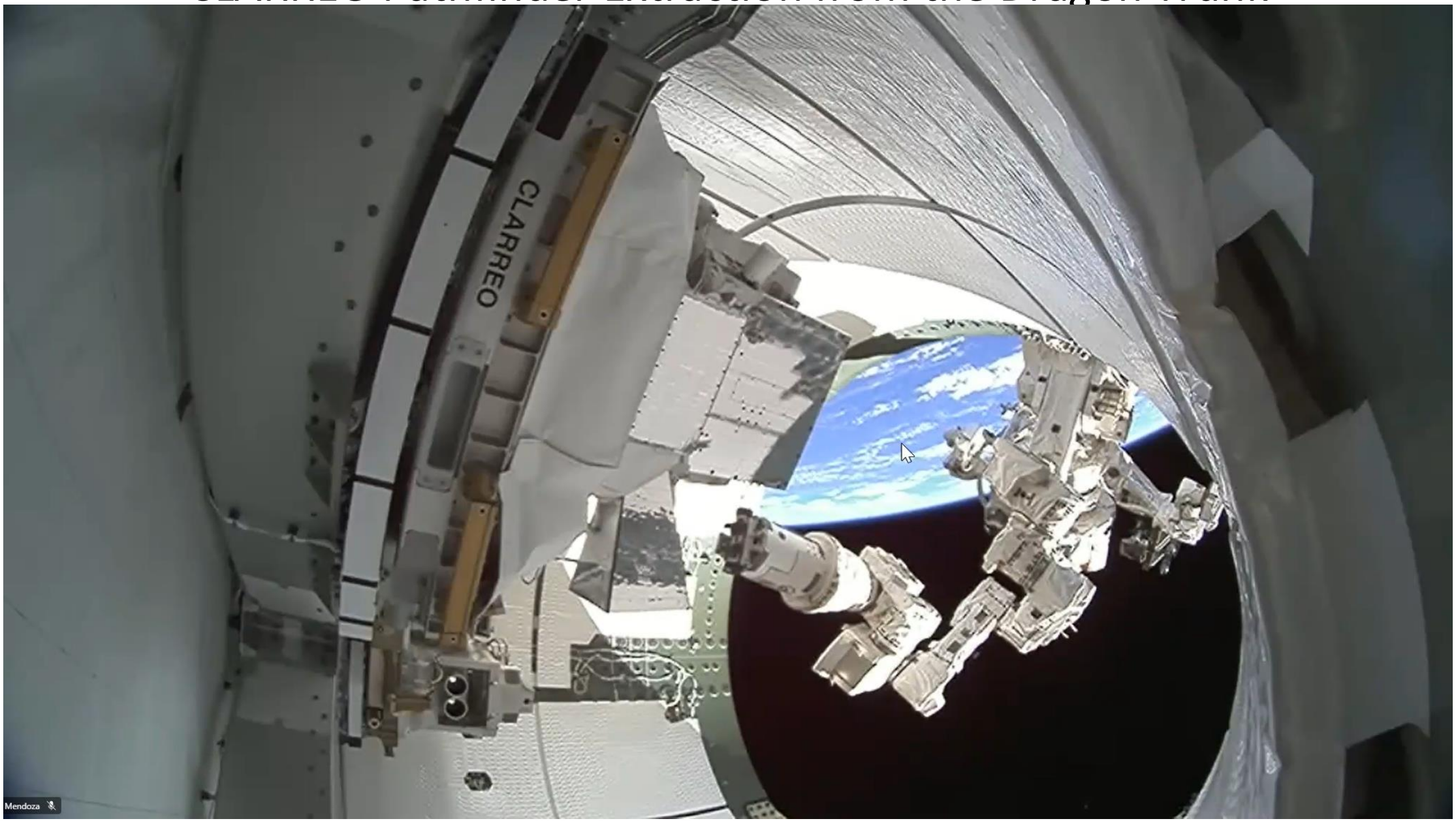


CLARREO Pathfinder Launch to ISS on 15 May

Schedule

- 15 May: Launch to the International Space Station
- 20 May: ROBO trunk extraction & translation to ELC1 Site 3
- 22 May: ELC Installation start
- 22 May: Initial payload activation
- 23 May: ROBO survey, HPS Launch Lock release followed by HPS range of motion.
- 1 Jun: HySICS venting & contamination door open
- 4 Jun: HySICS cryocooler enabled, start of cooldown
- Jun. 2026 – Aug. 2026: Commissioning
- Sep. 2026 – Aug. 2027: Phase E science operations
- EOC+ ? mos.: First data release

CLARREO Pathfinder Extraction from the Dragon Trunk



Initial Range of Motion Activations