

Earth's Radiation Budget Observations from Space:
Progress on and Risks to Continuity
(and an update on CLARREO Pathfinder if time permits)

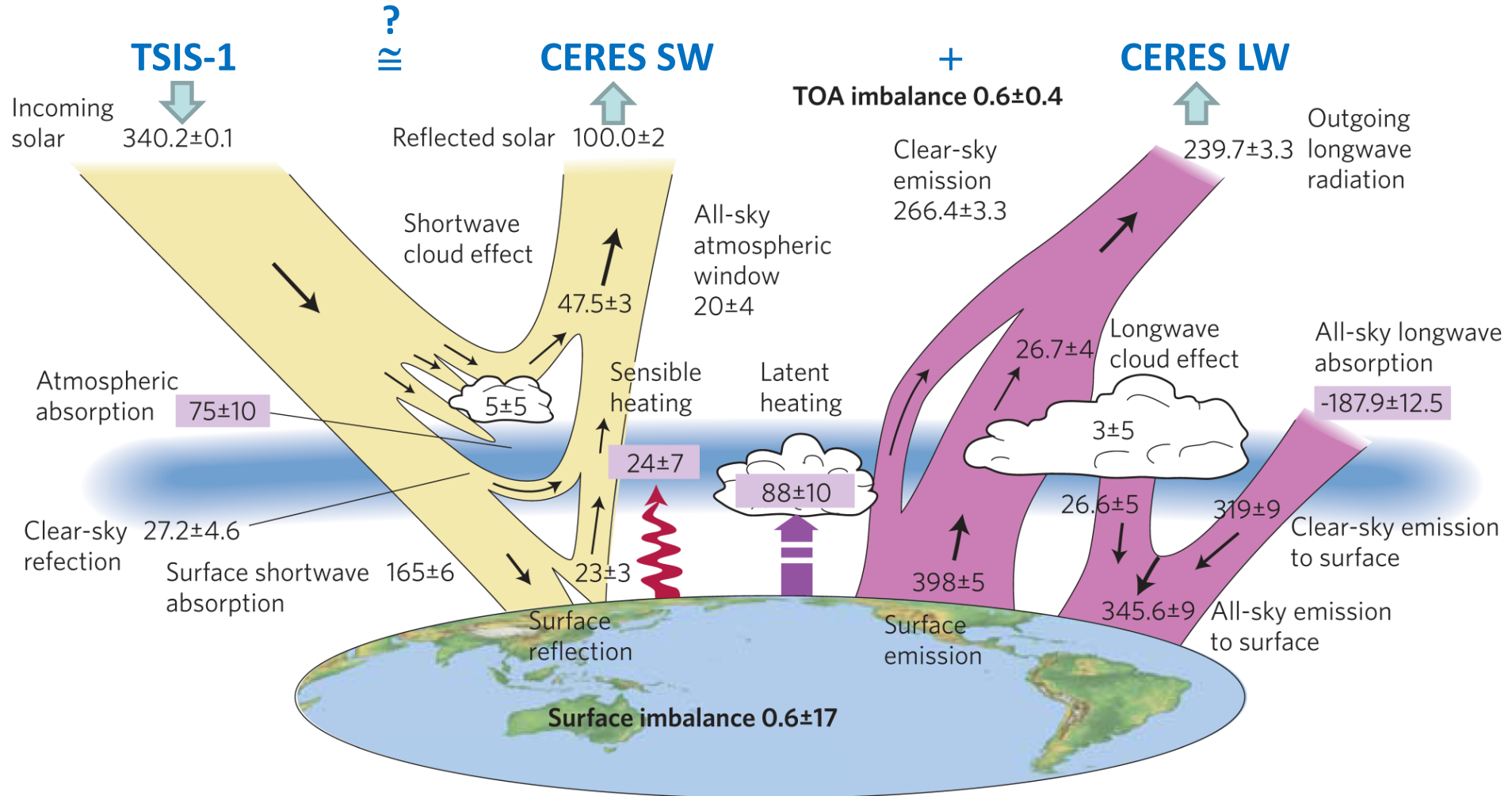
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The Global Radiative Energy Budget

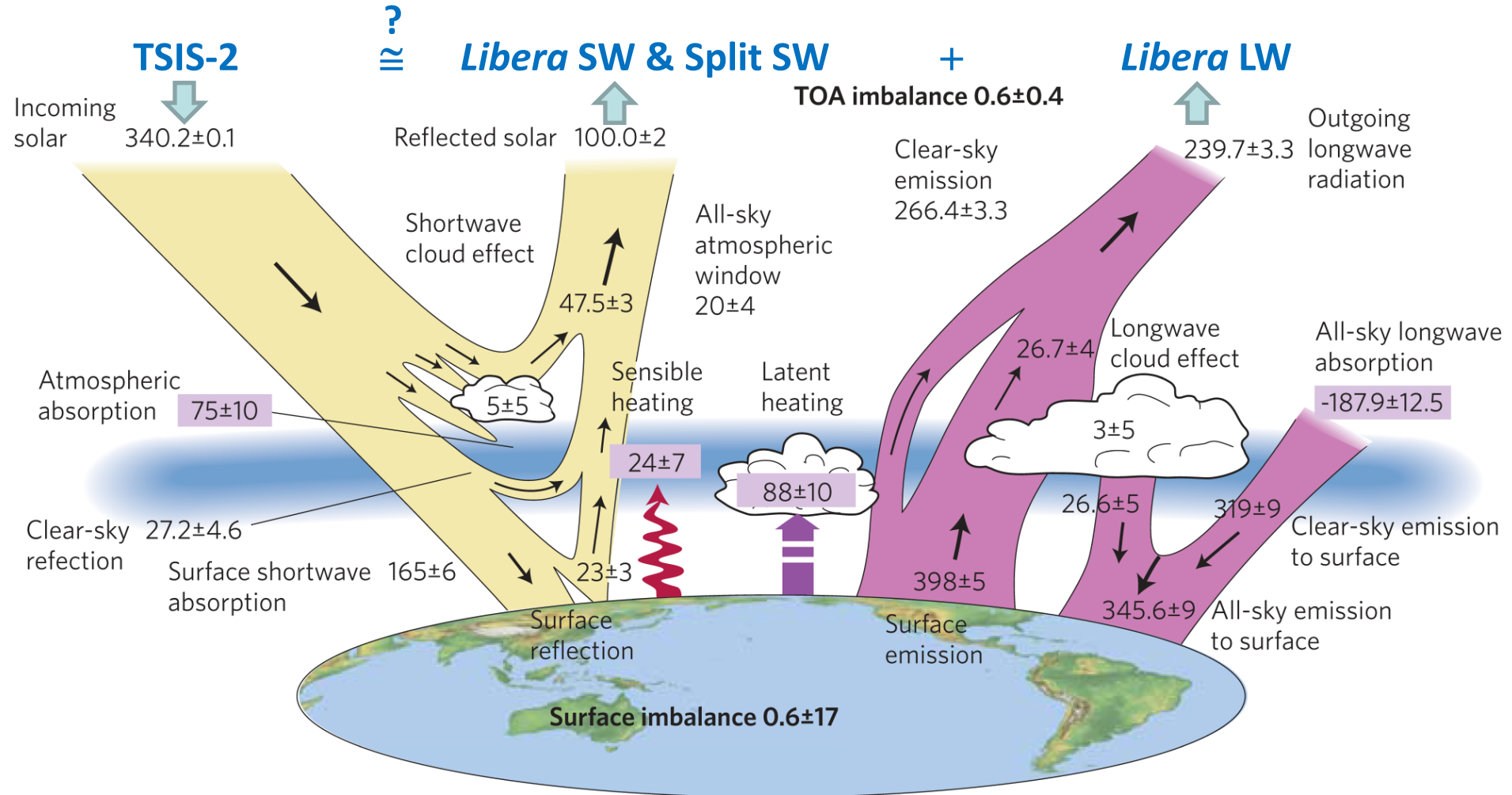
Current Measurements



Stephens et al., Nature Geo., 2012

The Global Radiative Energy Budget

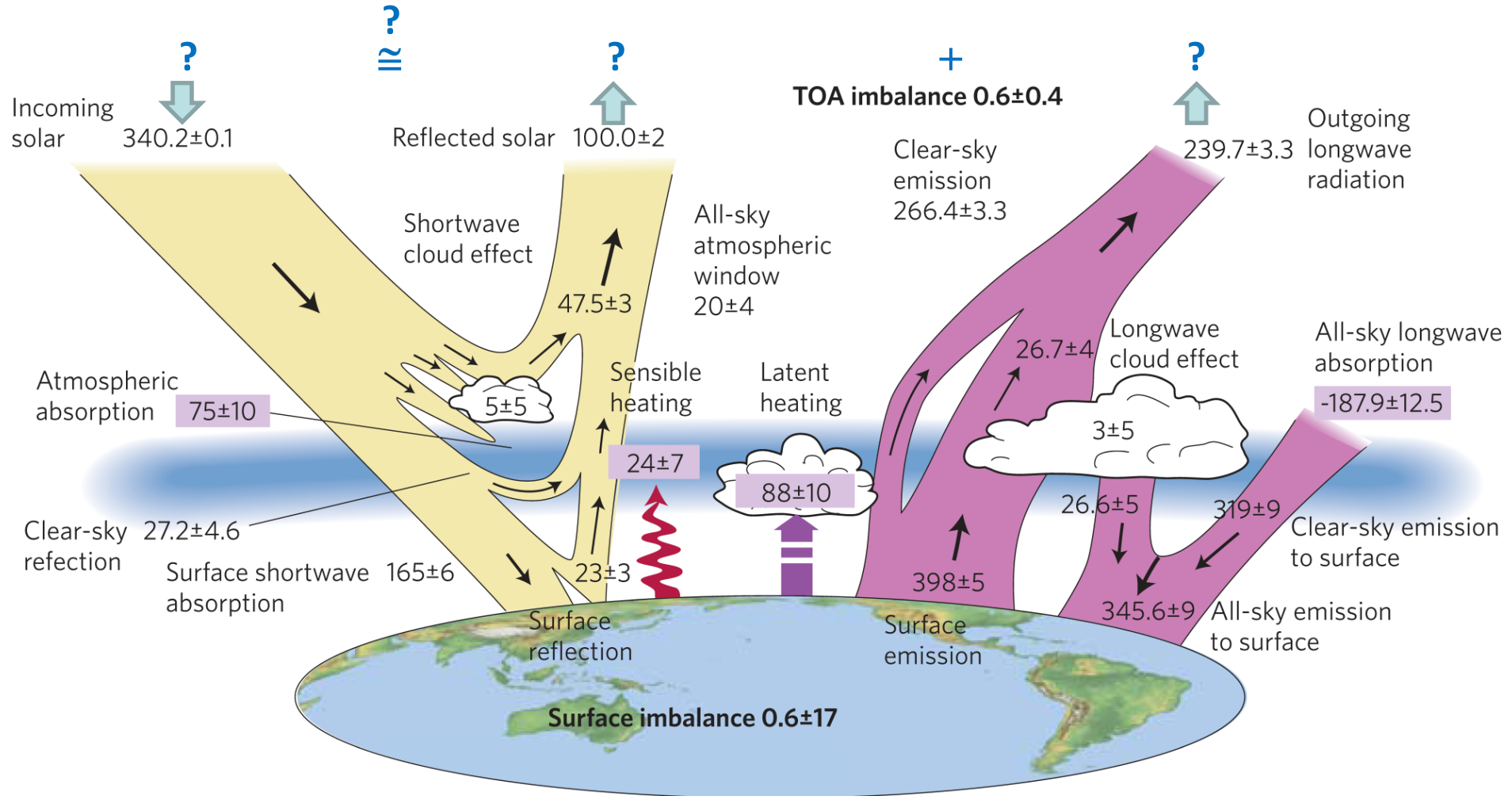
Near-term Measurement Continuity



Stephens et al., Nature Geo., 2012

The Global Radiative Energy Budget

Longer-term Measurement Continuity

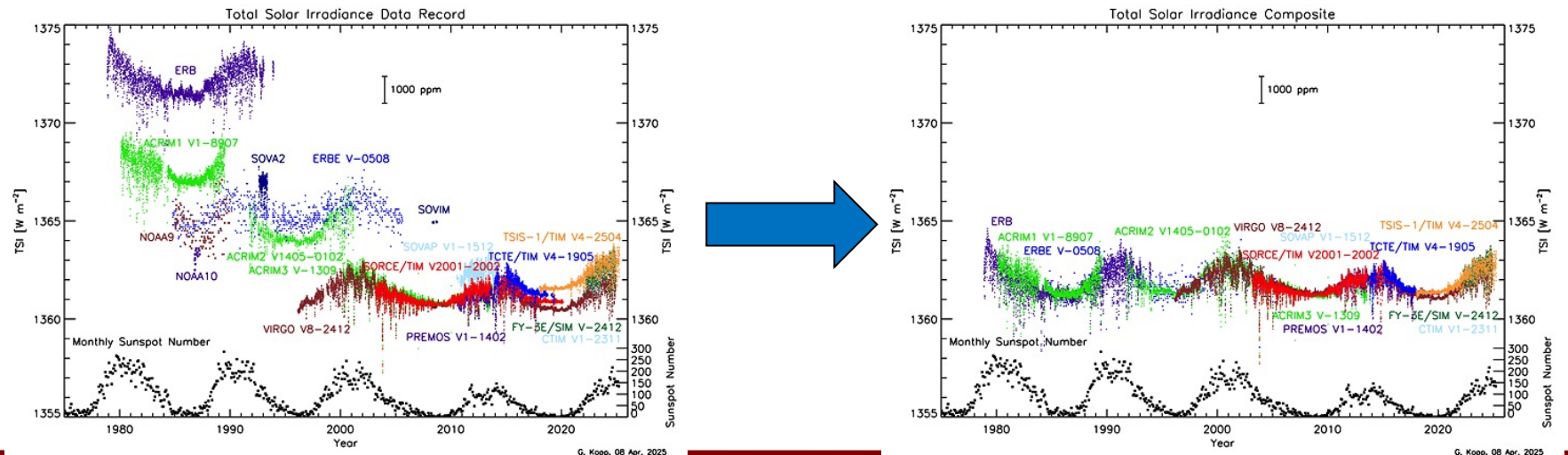


Stephens et al., Nature Geo., 2012

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

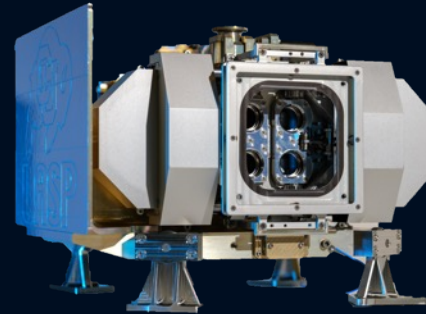
Current Status

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

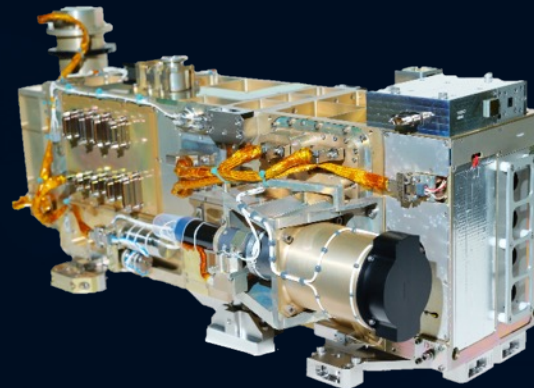
- Planning at least 1 year of observational overlap with the TSIS-1 measurements in SC25 declining phase.
- **Only a 3-year prime mission, with potential extension beyond end of the decade.**

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

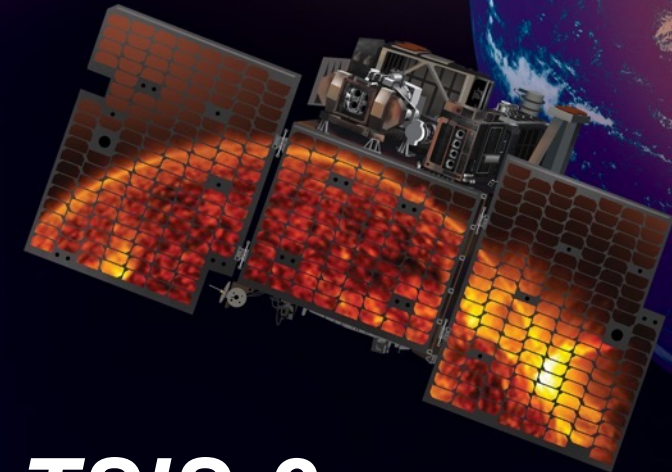
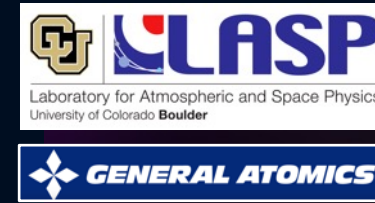
Current LRD in early 2027



Total Irradiance Monitor (TIM)



Spectral Irradiance Monitor (SIM)



TSIS-2

Total and Spectral Solar Irradiance Sensors -2

Libera, NASA Earth Venture Continuity-1 Mission

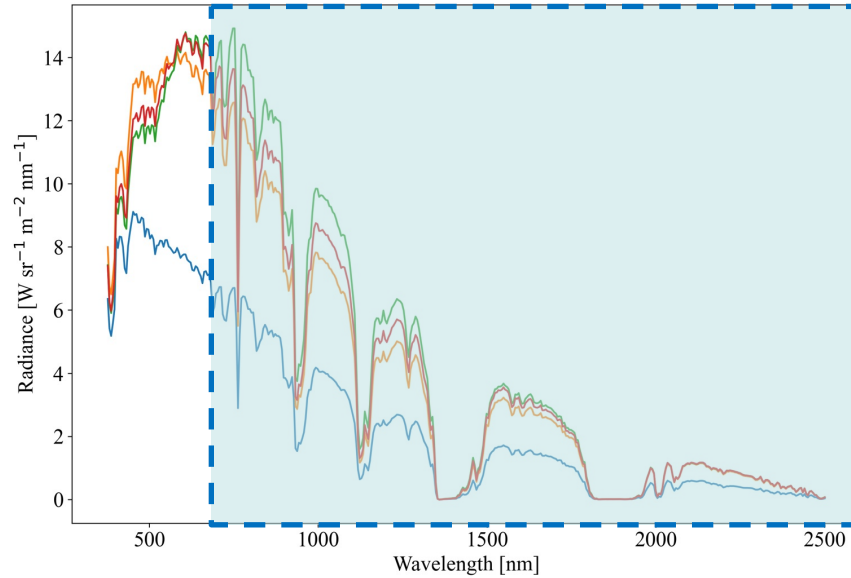
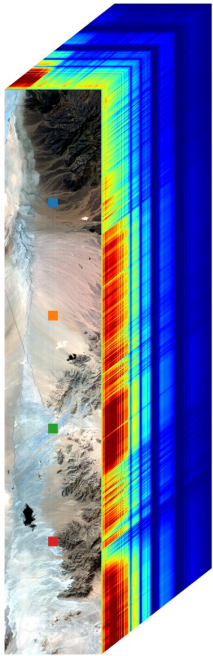
'Li-be-ra, named for the daughter of Ceres in ancient Roman mythology



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 \sim 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***

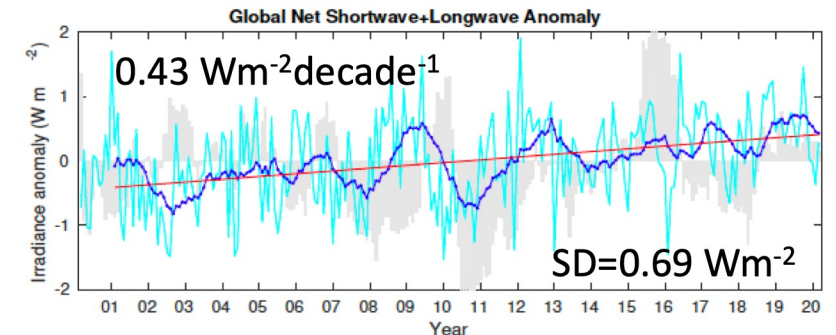
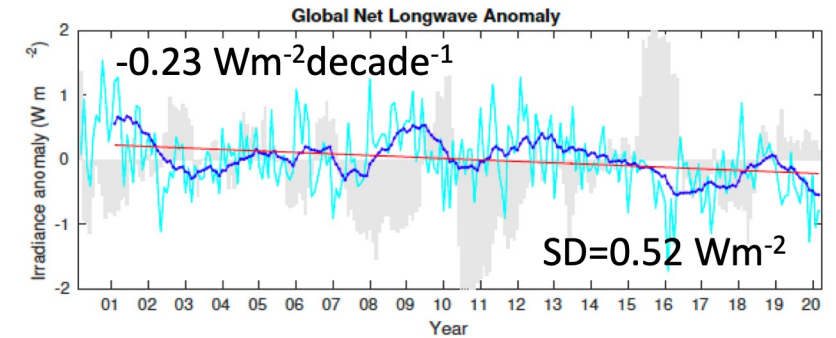
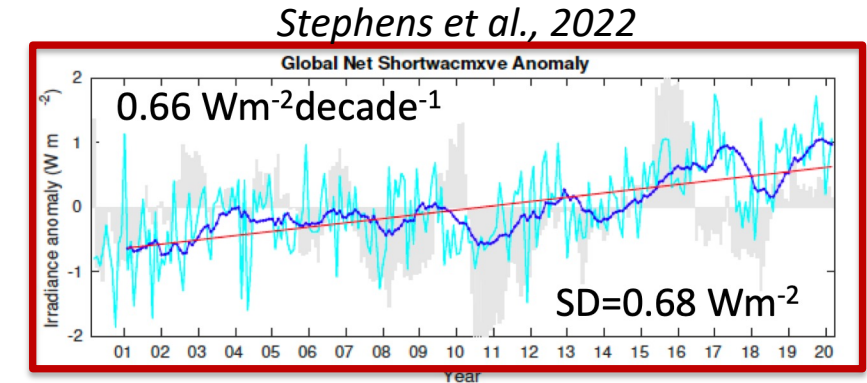
The *Libera* Split-Shortwave Channel



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)*



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	Δ S/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 bandwidth 140° FOV 1 km horiz. Resolution at nadir 1.5% uniformity 5% radiometric accuracy 0.2 - 600 W/m ² /sr/ μm 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)

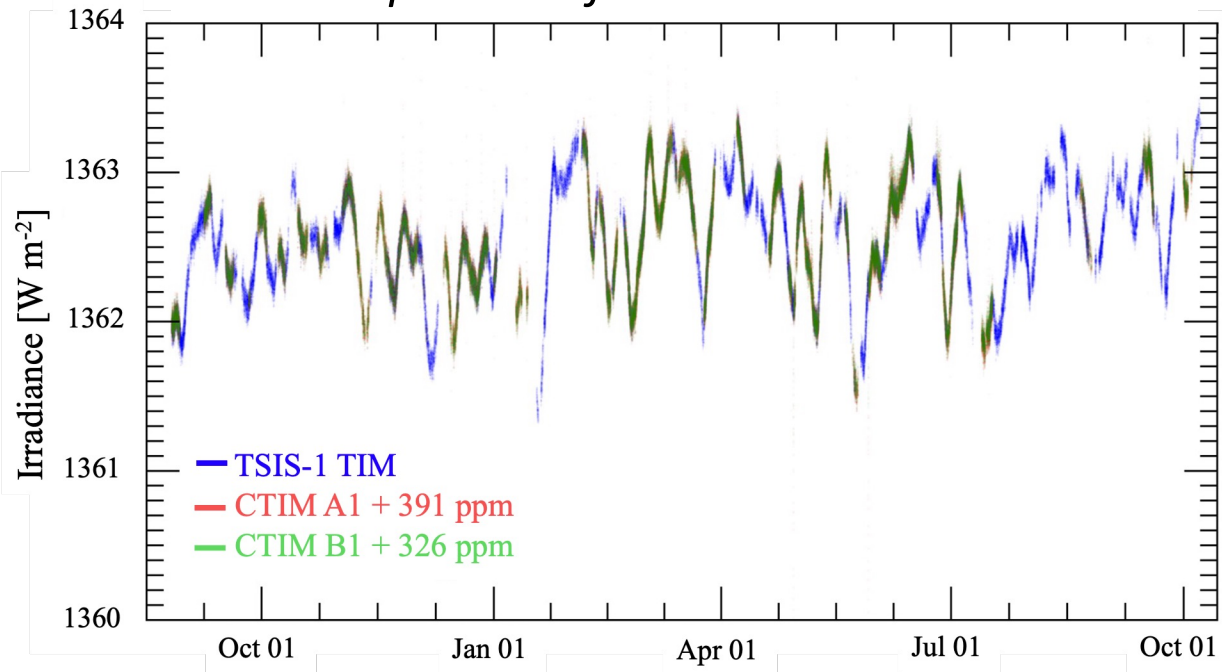


Beyond Near-term Continuity

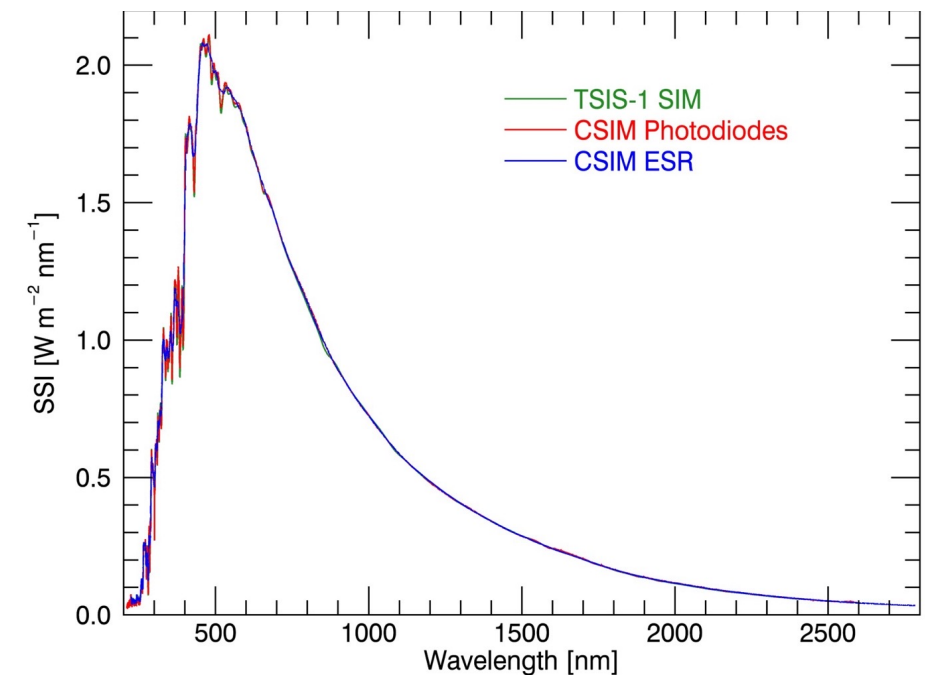
Beyond Near-term Continuity: Solar Irradiance

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

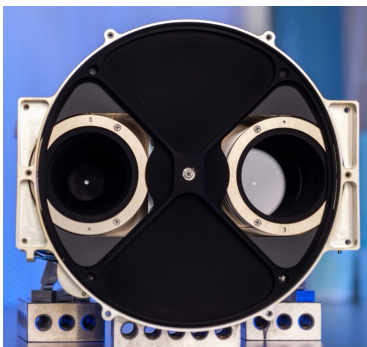


CTIS concept exists for a multi-year, multi-platform plan to implement solar irradiance continuity on SmallSats/CubeSats at ~ 10% of the current budget for solar irradiance measurements.

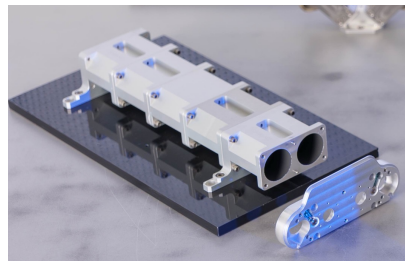
Beyond Near-term Continuity: Earth Radiation

Next generation SmallSat/CubeSat concepts are in development:

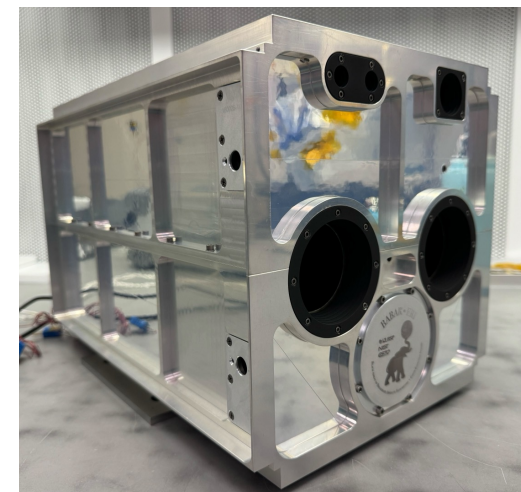
- LASP: Black Array of Broadband Absolute Radiometers – Earth Radiation Imager (BABAR-ERI)
 - 32-element array of micromachined silicon, electrical substitution radiometers with high-efficiency broadband carbon nanotube absorbers



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



*Planar Bolometric Radiometer
for stability monitoring*



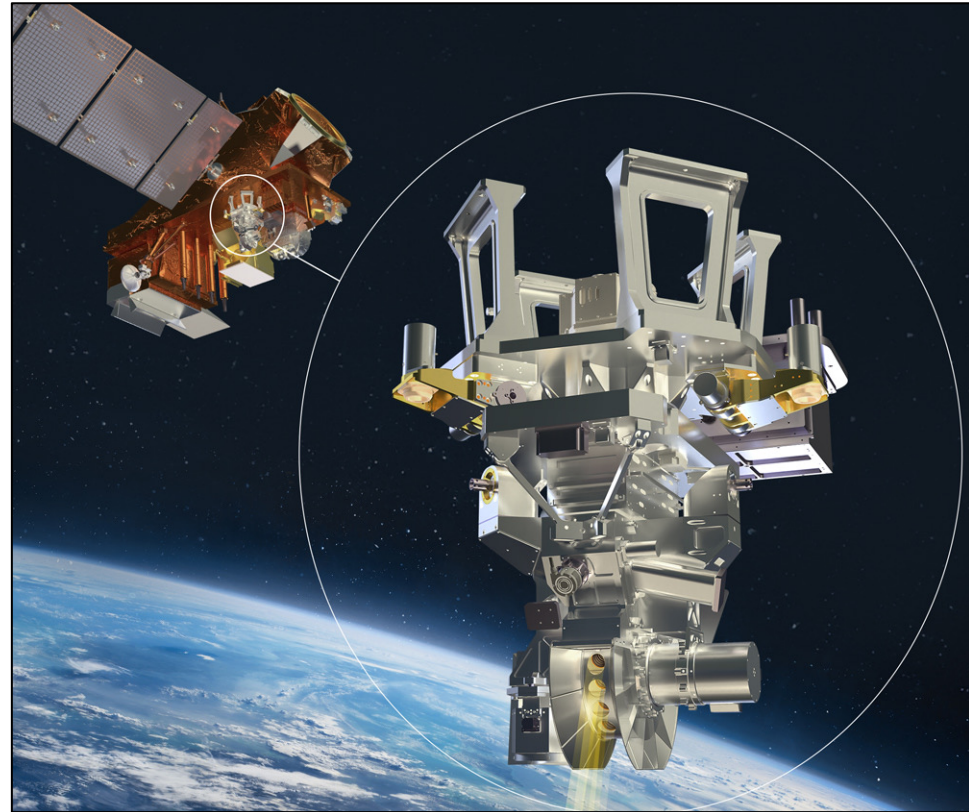
BABAR-ERI in 12U form-factor

- 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



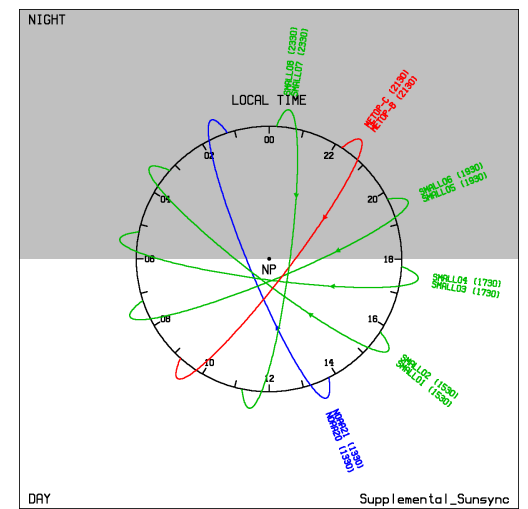
Other Related Concepts

- 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

- 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



Kidder et al., (2022)

- 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)