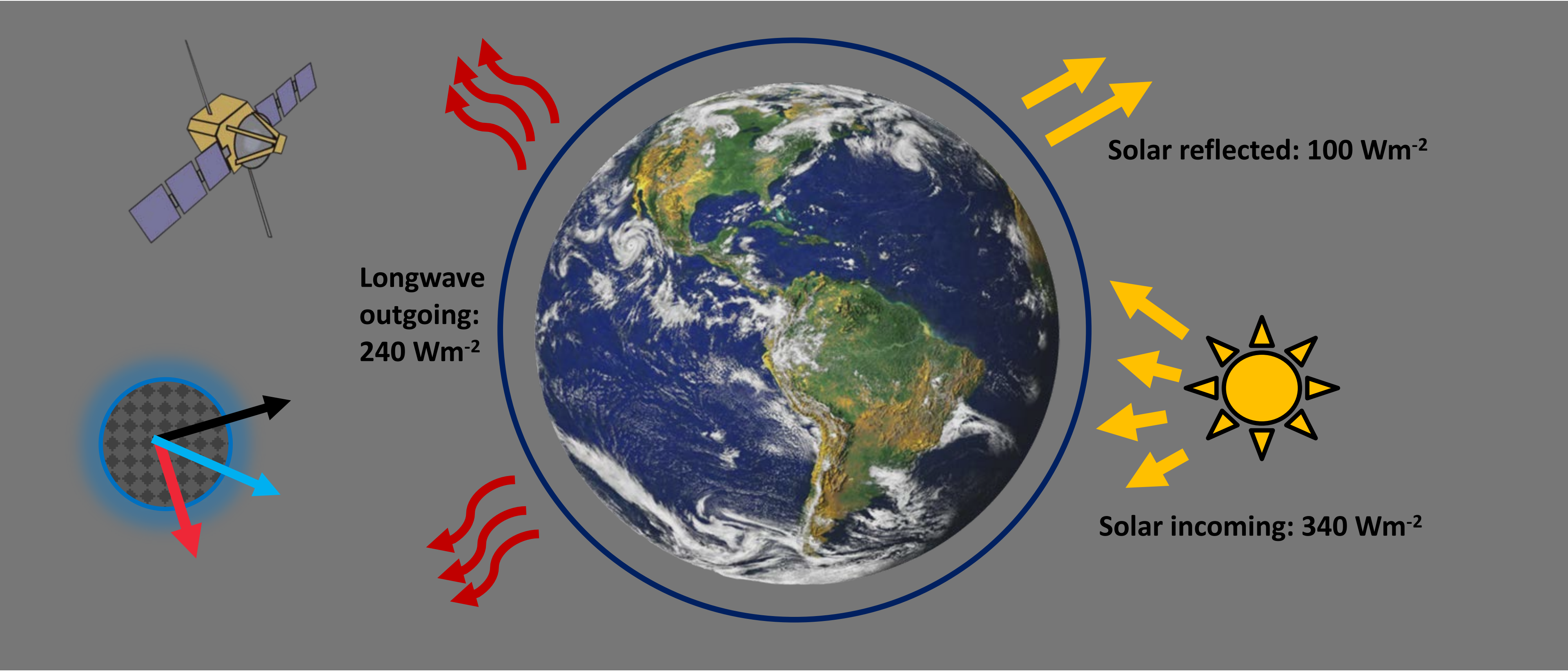
Maria Zita Hakuba

Born in Poland; raised in Germany; 10 years Zurich; 5.5 years in Pasadena, LA

- Bachelor degree from ETH Zurich in Environmental Sciences (2008)
- Internship at Mauna Loa Observatory (2009)
- Master Thesis on Orographic height feedbacks of Greenland ice sheet (2011)
- PhD *Towards improved estimates of atmospheric shortwave absorption*; BSRN database and clear-sky retrievals; teaching assistant (2015)
- Postdoc with Colorado State Univ. (but at JPL): Energy budget and water cycle studies; mission concepts (2016-2020)
- Research Scientist II at Jet Propulsion Laboratory (since July 2020):
  - Deputy Principle Investigator for *Libera*
  - *Mission concepts; Science & measurement strategies*
  - *Research: Sea level, energy budget, clouds*
  - *New Researchers' Support Group; International Radiation Commission; Co-organizer of AGU sessions, GEWEX GDAP workshop on Ocean Heat Uptake*







Earth’s Energy Budget measured from Space

Maria Hakuba, Libera DPI

AOPC Panel meeting April 19

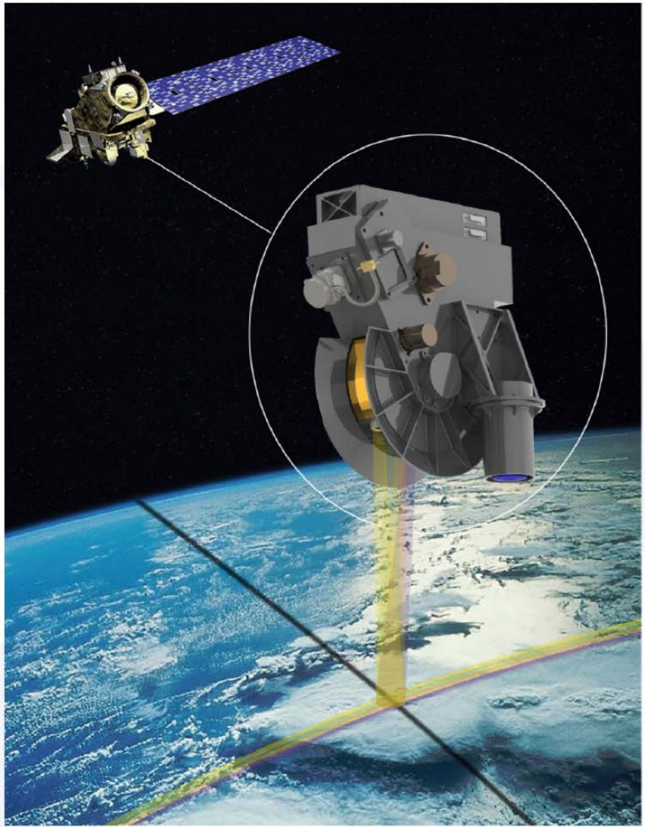
Jet Propulsion Laboratory
California Institute of Technology

Outline

1) Libera – Continuity ERB mission
2) Space Balls – Direct measurement of Earth's Energy Imbalance

Libera, NASA's first *Earth Venture* ***Continuity*** 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 (ERB).

- 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.
- Includes a wide FOV camera for scene ID and simple ADM generation to pave way for future free-flyer ERB observing system.

Innovative technology: Electrical Substitution Radiometers using VACNT detectors

Flight: JPSS-3, 2027 launch; 5-year mission

Partners: LASP, Ball Aerospace, NIST Boulder, Space Dynamics Lab; CU, JPL, CSU, UA, UM, LBL

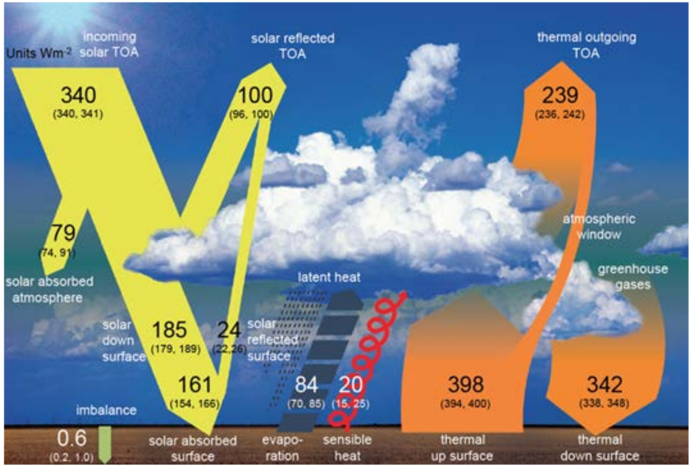
Principle Investigator: Peter Pilewskie, Laboratory for Atmospheric and Space Physics (LASP) at University of Colorado

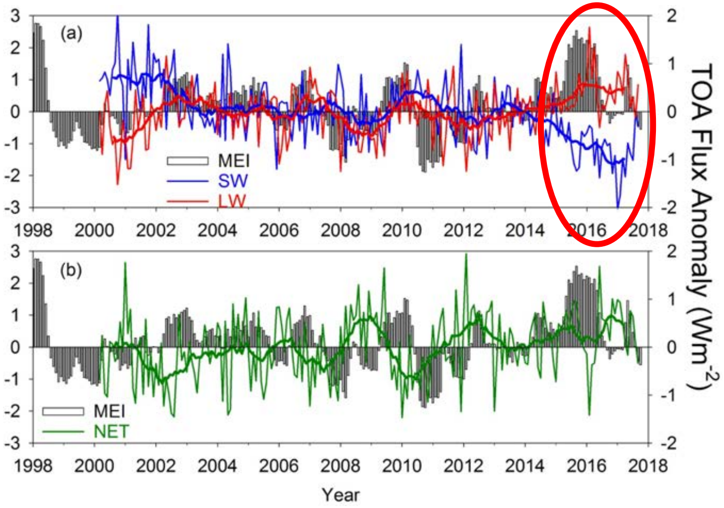
Libera Overarching Science Goals

Meet EVC-1 specific objectives on Earth Radiation Budget (ERB) continuity, innovation, and affordability.

OG1: Provide seamless continuity of CERES ERB Climate data record (CDR).

- Measurement of TOT, SW and LW radiances with same characteristics as CERES.
- **Science objective 1**: Use extended CDR to identify and quantify processes responsible for ERB variability on instantaneous to decadal times scales.





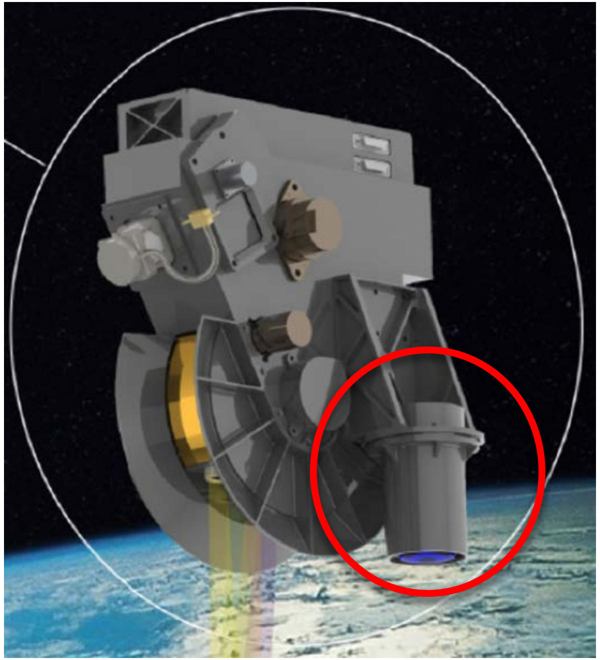
Libera Overarching Science Goals

Meet EVC-1 specific objectives on Earth Radiation Budget (ERB) continuity, innovation, and affordability.

OG2: Advance the development of a self-contained, innovative & affordable observing system.

Science objective 2:

- Explore utility of scene identification from a small and cost-effective field-of-view camera.
- Develop angular distribution models (ADM) to facilitate shortwave near-IR and visible radiance-to-flux conversion.
- **Demonstrate feasibility of separating Libera from complex spectral imagers**



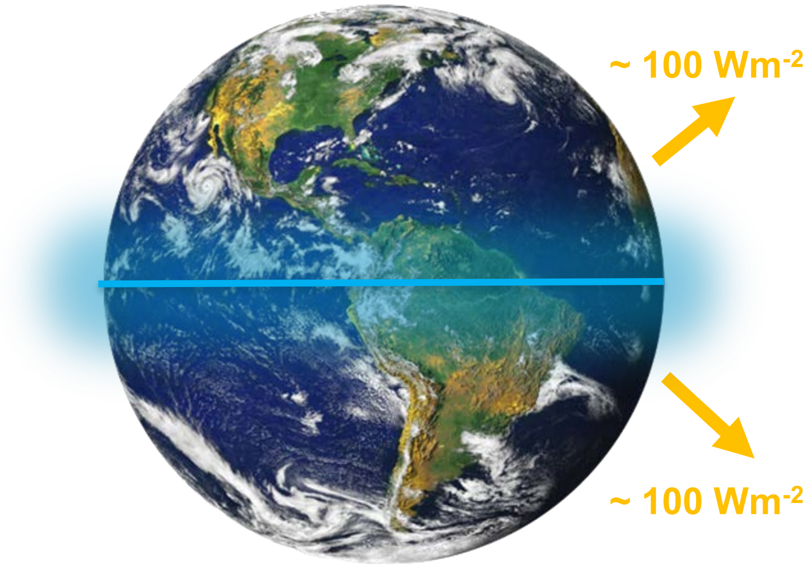
Monochromatic (865 nm) wide field of view (WFOV, 140º) camera provides images at 1 km pixel resolution.

Libera Overarching Science Goals

Meet EVC-1 specific objectives on Earth Radiation Budget (ERB) continuity, innovation, and affordability.

OG3: Provide new and enhanced capabilities that support extending ERB science goals

- **Science objective 3**:
    - Employ Split-Shortwave channel to quantify SW energy deposition (split at 700 nm).
    - Retrieval of NIR and VIS fluxes at TOA and surface.
    - Characterize NIR & VIS signatures of processes that control the absorption of solar radiation, SW climate feedbacks, and the **hemispheric symmetry of planetary albedo.**

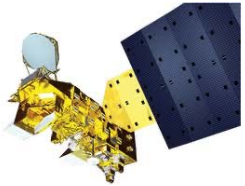


SW reflection may be symmetrical, but spectral "fingerprint" is not!

Models do not represent this symmetry well resulting in errors in circulation & precipitation patterns.

What is Earth's Energy Imbalance and why do we need to know EEI?

EEI = Global mean Net radiative flux at TOA



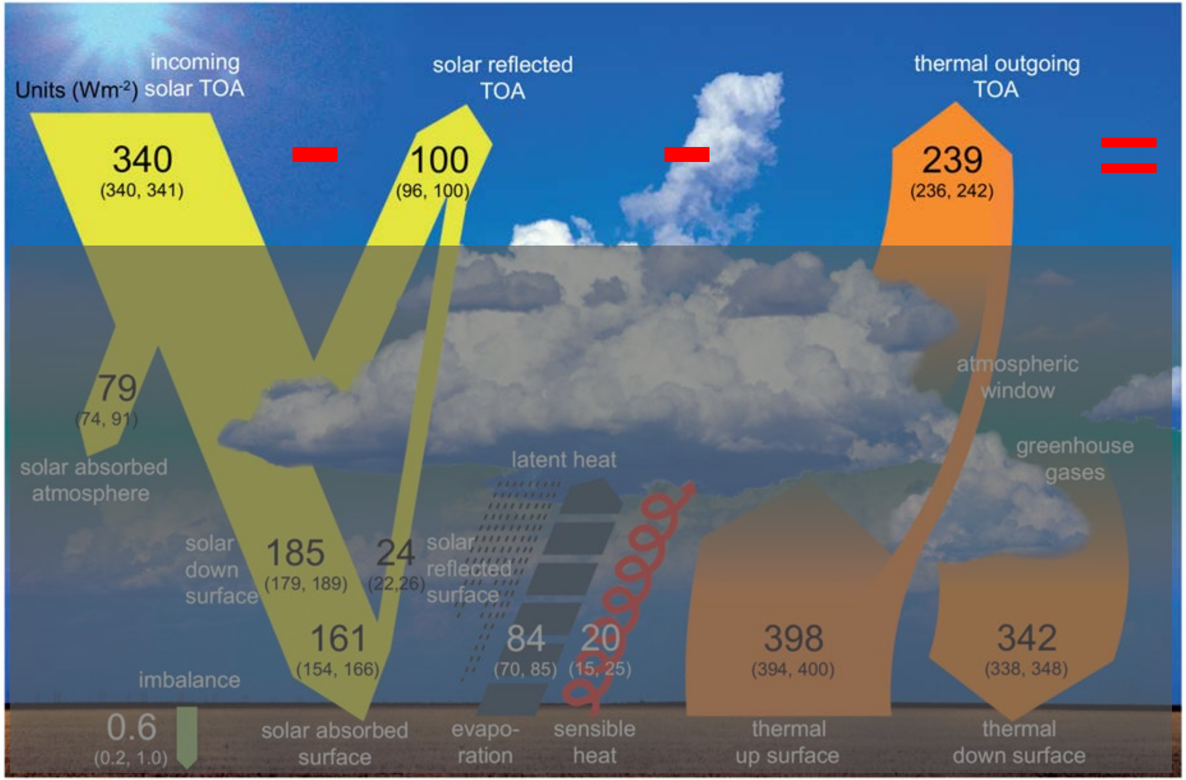
CERES EBAF & Libera

Clouds and Earth's Radiant Energy System

SORCE & TSIS

Solar Radiation and Climate Experiment

Total and Spectral *Solar* Irradiance Sensor



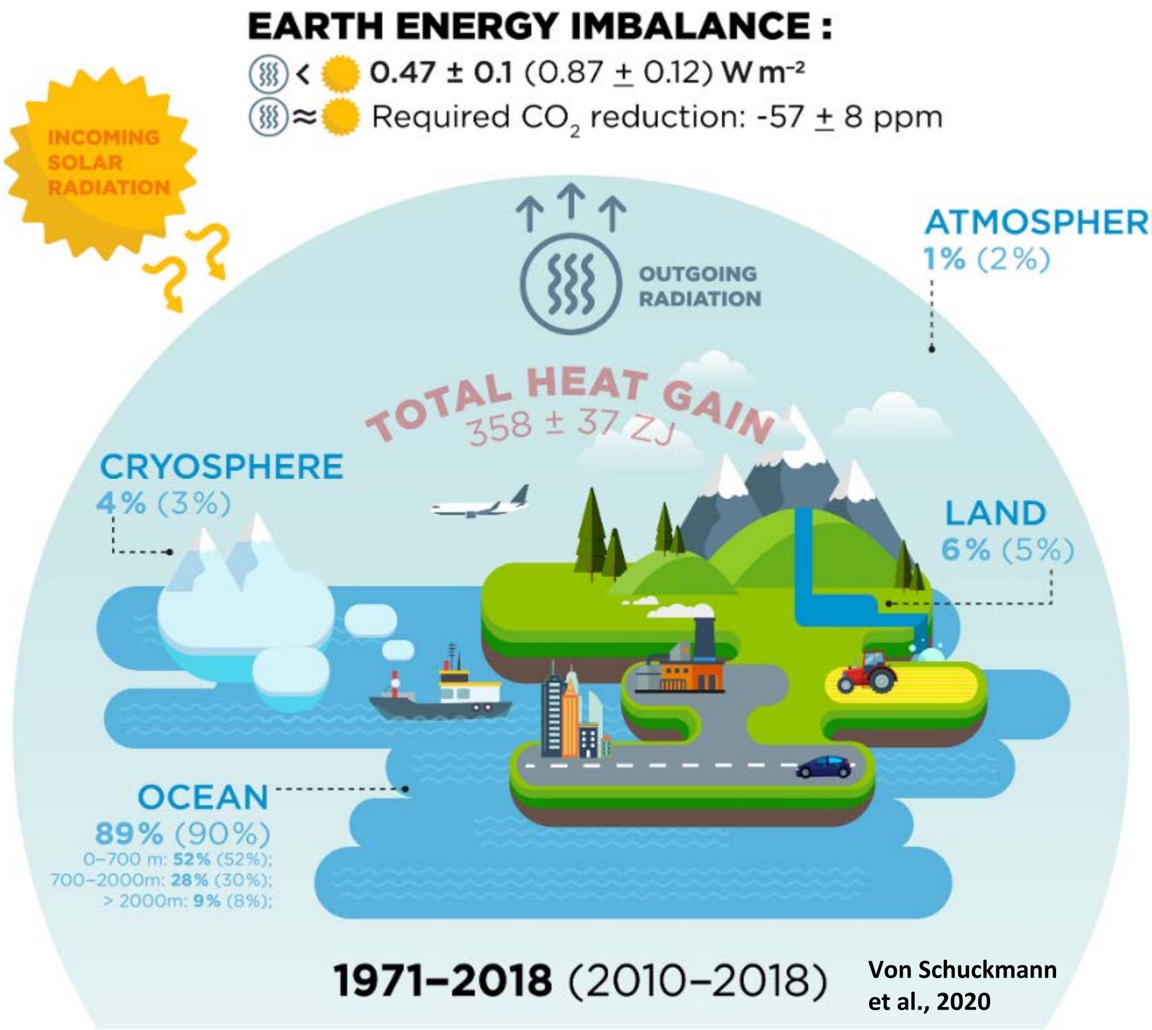
Updated from IPCC AR5 / Wild et al. 2013, 2015 Climate Dynamics

~0.7 Wm^{-2}

(Johnson et al., 2016)

Spoiler: this number does not come from TOA radiation data!

EEI = rate of heat uptake by Earth, …

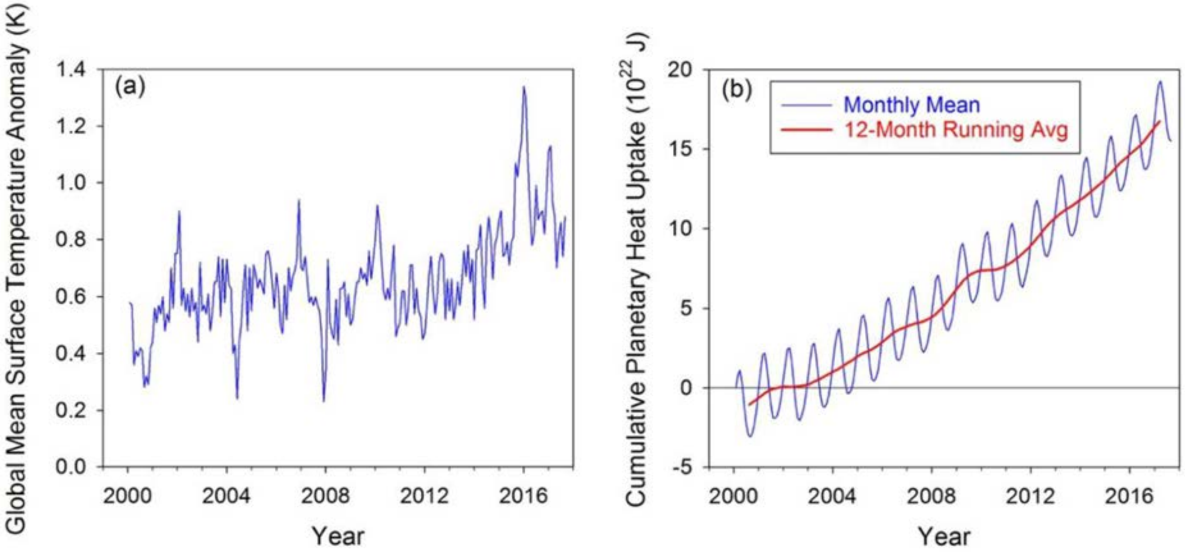


Von Schuckmann et al., 2020

… heat that melts ice, expands ocean, warms the atmosphere and the land

jpl.nasa.gov

EEI is the *true* rate of global warming

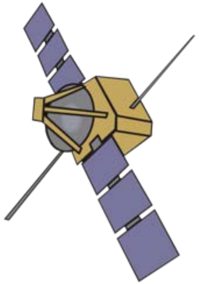


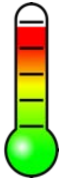
(**a**) NASA Goddard Institute for Space Studies Surface Temperature Analysis (GISTEMP) global mean surface air temperature anomaly relative to 1951–1980 climatology and (**b**) Clouds and the Earth's Radiant Energy System (CERES) cumulative planetary heat uptake for March 2000–September 2017.

What else… Model tuning, anchoring of ERB mission datasets (CERES, Libera), constrain modeled climate sensitivity…

Loeb et al., 2018

It is difficult to measure EEI directly

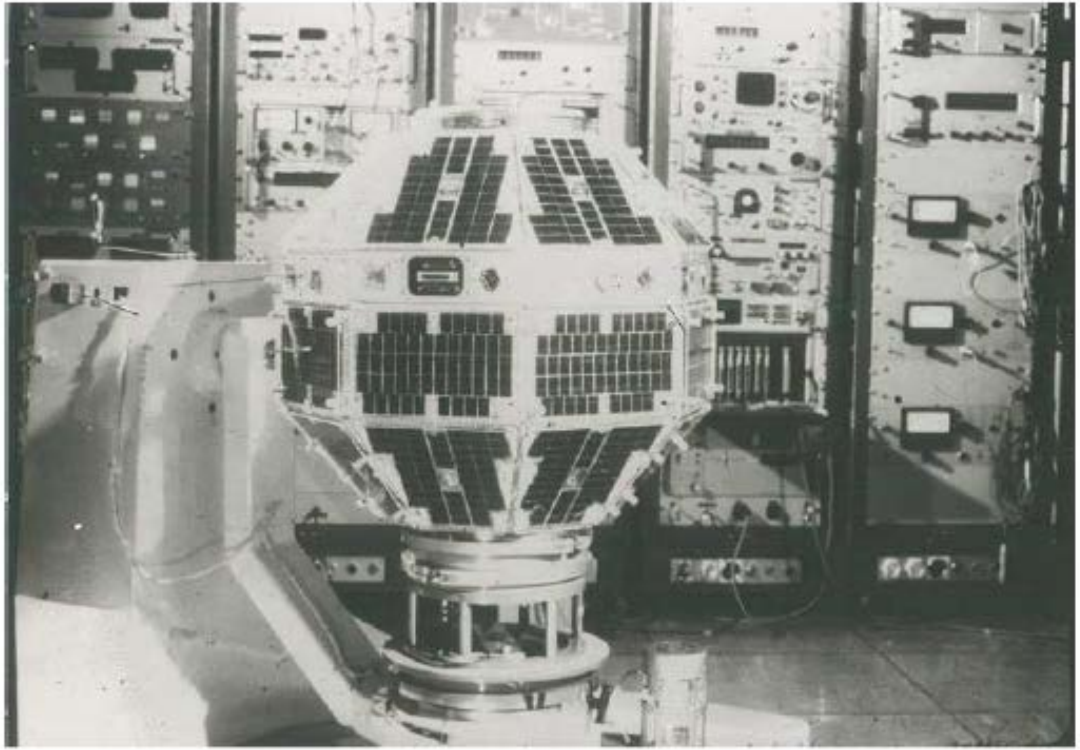




- TOA radiometry: Clouds and Earth's Radiant Energy system (CERES)
  - Uncertainty (calibration, radiation flux retrieval) >> 1 Wm^{-2}
  - Un-anchored, EEI as residual of TOA fluxes would be 4 Wm^{-2}
  - **We cannot estimate EEI directly from the TOA radiation budget**

- Taking Earth's heat inventory (e.g. von Schuckmann et al., 2020)
  - In the global annual mean: $Net\ heat\ flux = heat\ storage + heat\ \cancel{transport}$
  - The world's oceans are the largest sink of heat (90%), followed by the land (5%), ice melt (3%), atmosphere (1%)

- EEI measurement from Space?
  - Sea level budget using geodetic observations (indirect)
  - Radiation pressure acting on LEO satellites (direct)

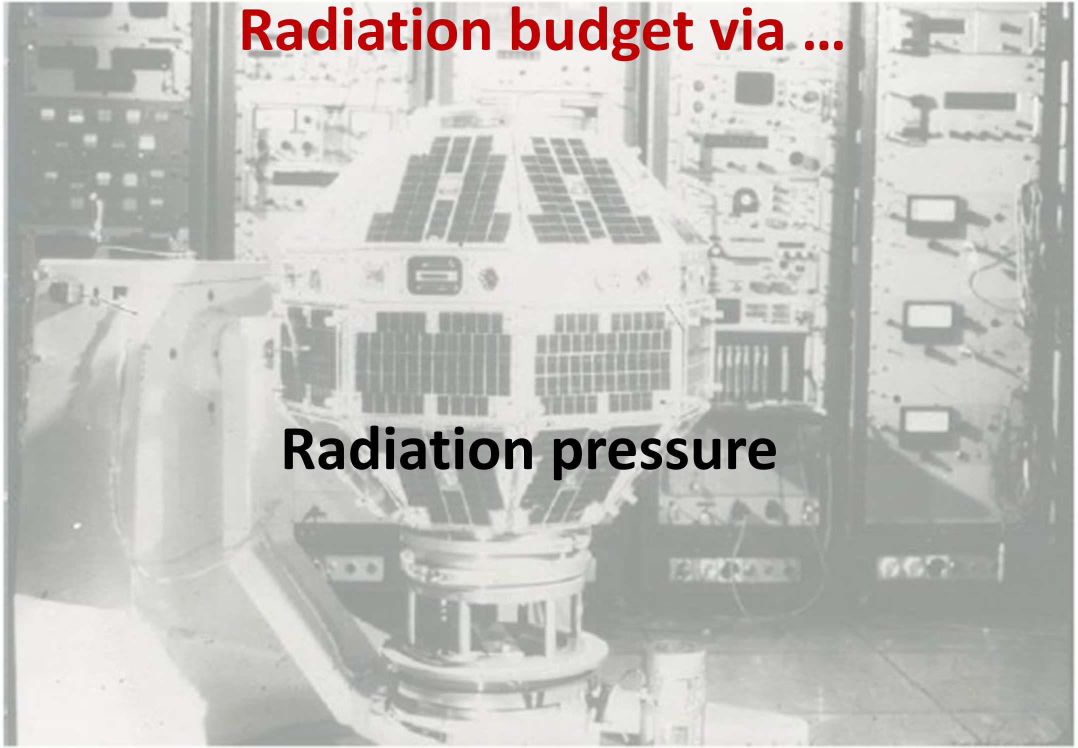


CASTOR D5B Satellite

CNES, 1975

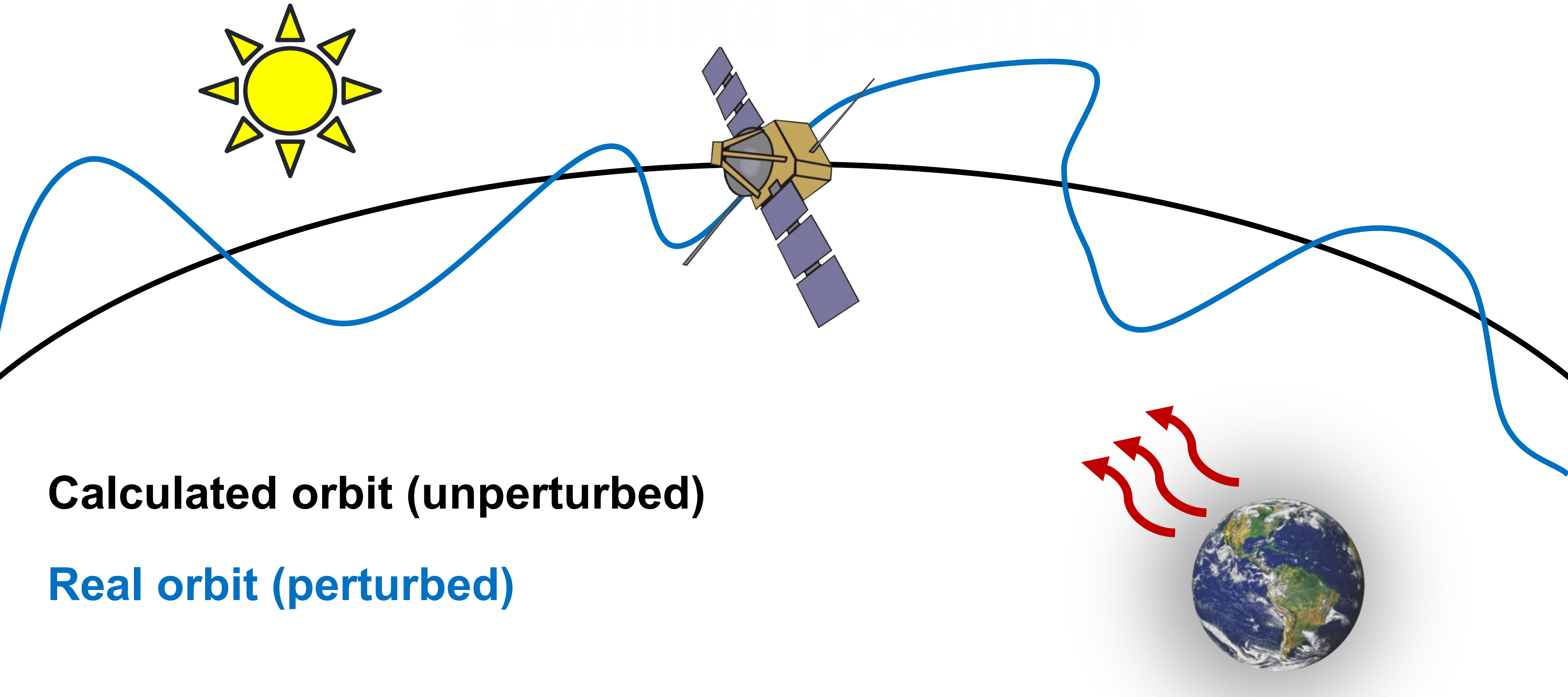
radius: 0.8 m, mass: 76 kg

Radiation budget via …



CASTOR D5B Satellite

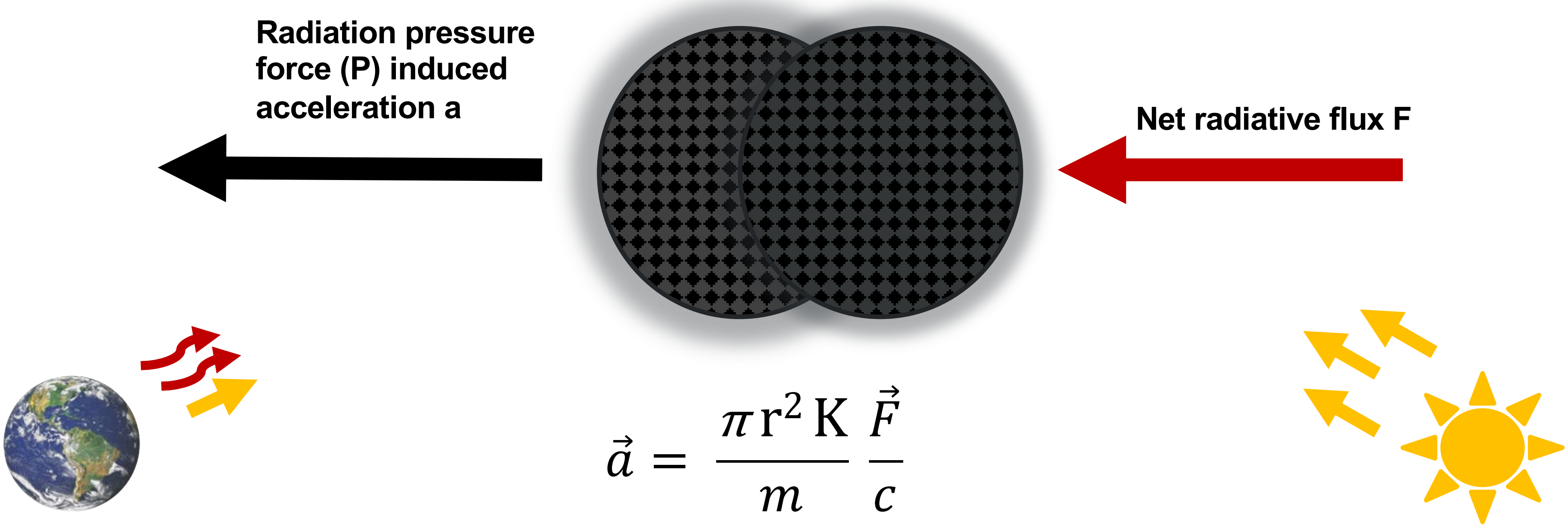
Radiation pressure affects satellite position



Induced acceleration is co-linear and proportional to incident net radiative flux if spacecraft is spherical and fully absorbing across solar and terrestrial spectra

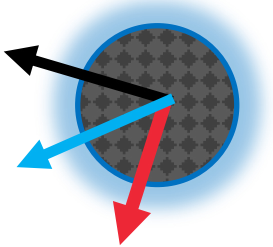
Radial acceleration ~ net radiative flux through the TOA at satellite position

Acceleration measured with accelerometer at center of mass



$$\vec{a} = \frac{\pi r^2 K}{m} \frac{\vec{F}}{c}$$

Conclusions and take-away



- **Earth's energy imbalance represents the *true* rate of global climate change**
- **EEI has never been and is not directly measured from space**
- 90% of EEI goes into the ocean; best estimates rely on in-situ ocean profiling of temperature change
- *Space Balls* could serve to measure EEI comprehensively and most directly at TOA via radiation pressure effects
- What stops us from observing EEI – one of the most important quantities of global climate change - accurately with a dedicated mission?

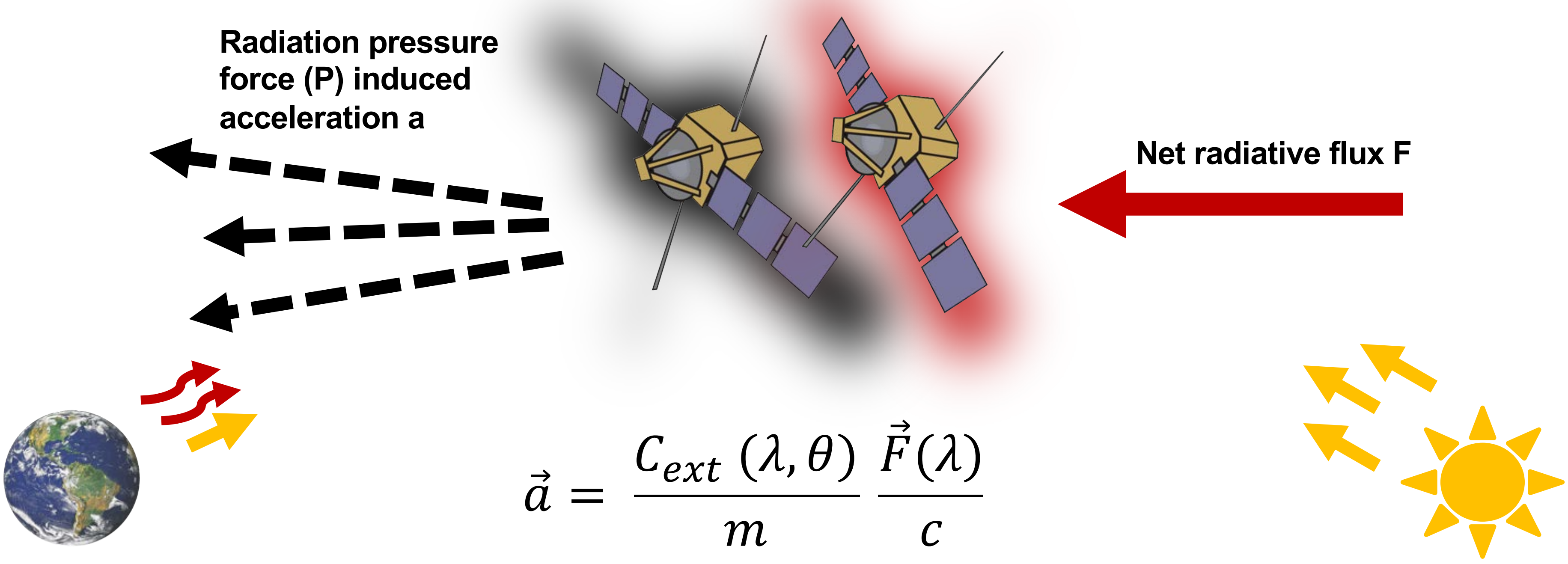
Back-up

Goal

Direct measurement of the net radiative flux (EEI) at TOA

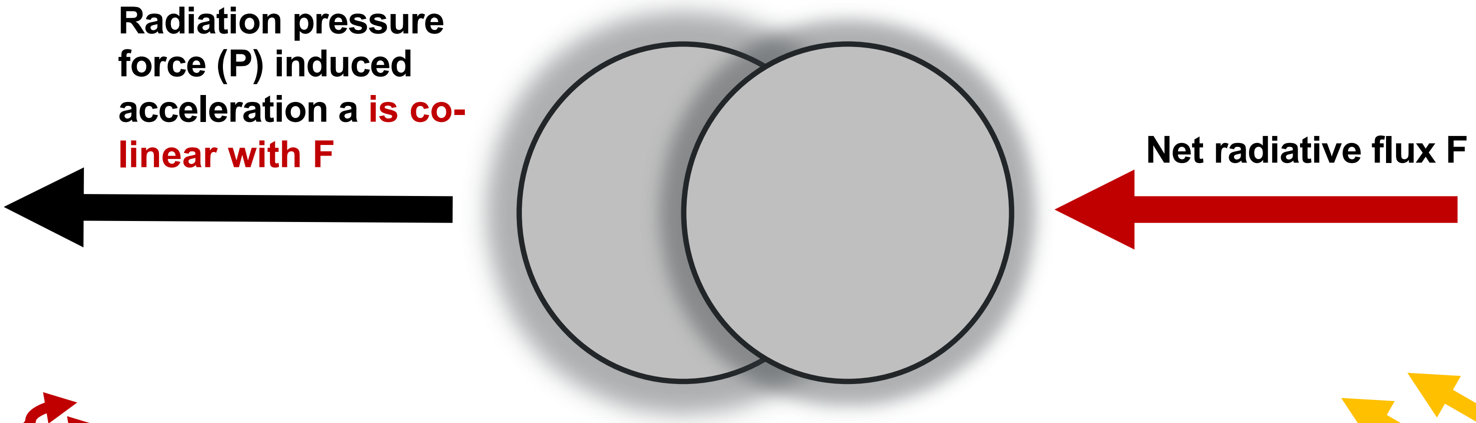
- No residual of component (radiometry)
- No incomplete coverage (in-situ ocean heat)
- No combination of different data products (geodetic ocean heat)

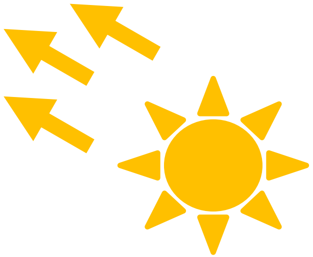
$$\vec{P} = m\vec{a} = \frac{1}{c} C_{ext}(\lambda, \theta) \vec{F}(\lambda)$$



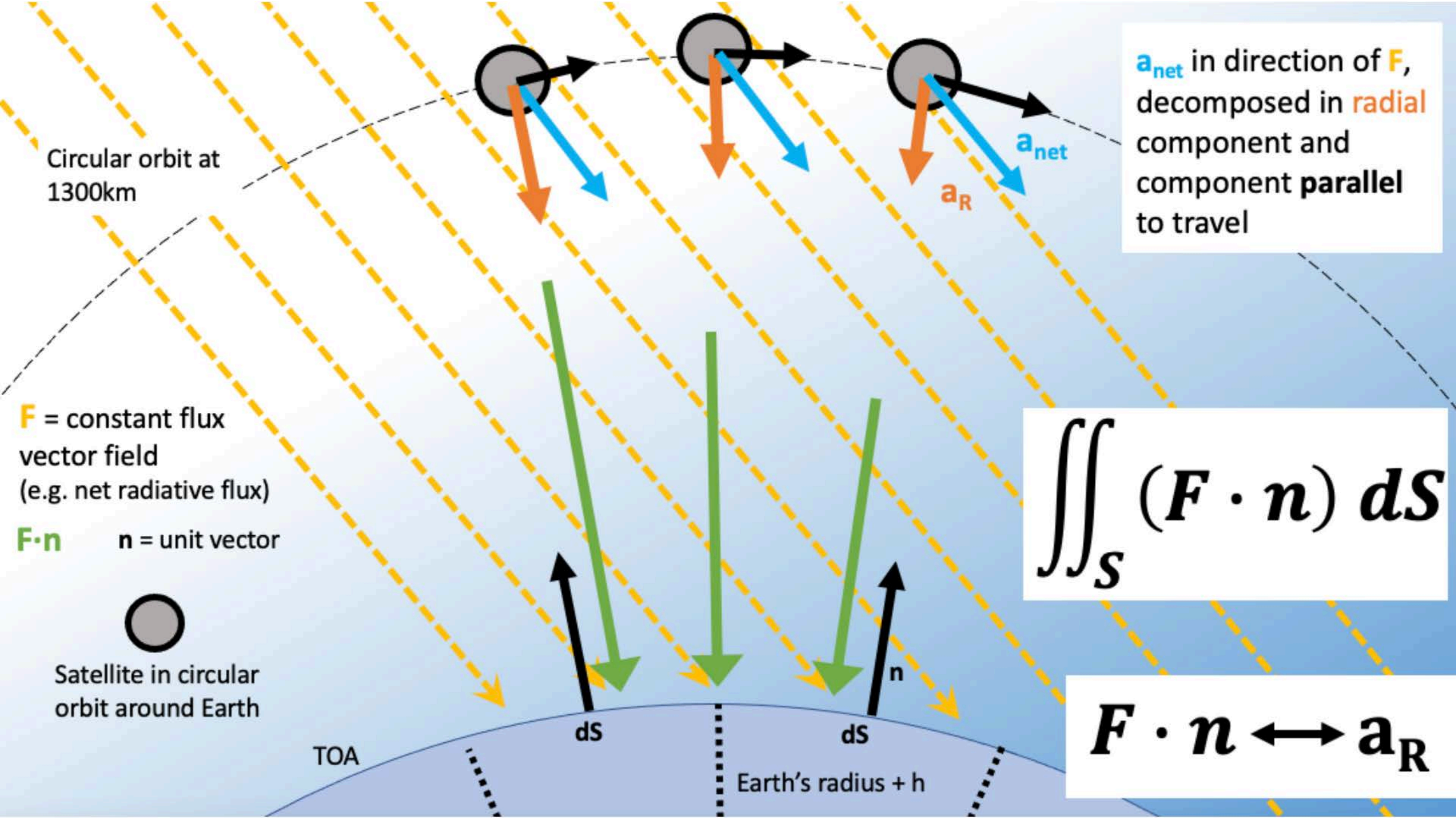
$$\vec{a} = \frac{C_{ext}(\lambda, \theta)}{m} \frac{\vec{F}(\lambda)}{c}$$

$$\vec{P} = m\vec{a} = \frac{1}{c}\pi r^2 K(\lambda)\,\vec{F}(\lambda)$$





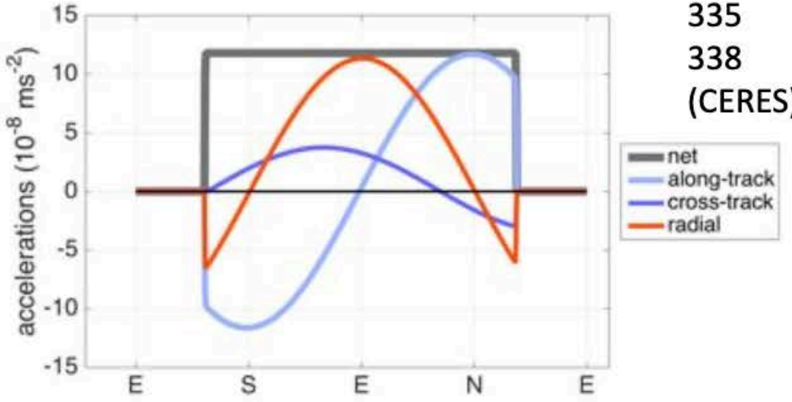
$$\vec{a} = \frac{\pi r^2 K(\lambda)}{m}\,\frac{\vec{F}(\lambda)}{c}$$



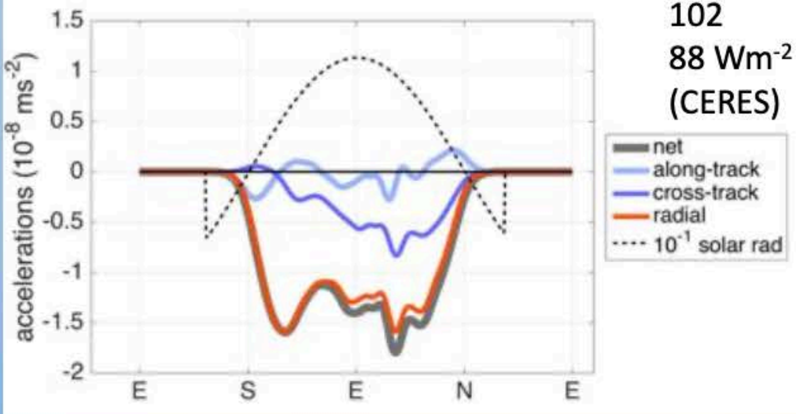
a_{net} in direction of F, decomposed in radial component and component **parallel** to travel
Circular orbit at 1300km
a_{net}
a_R
F = constant flux vector field (e.g. net radiative flux)
F·n
n = unit vector
Satellite in circular orbit around Earth
$$\iint_S (F \cdot n)\, dS$$
n
dS
dS
TOA
Earth's radius + h
$$F \cdot n \longleftrightarrow a_R$$

Solar & Earth albedo

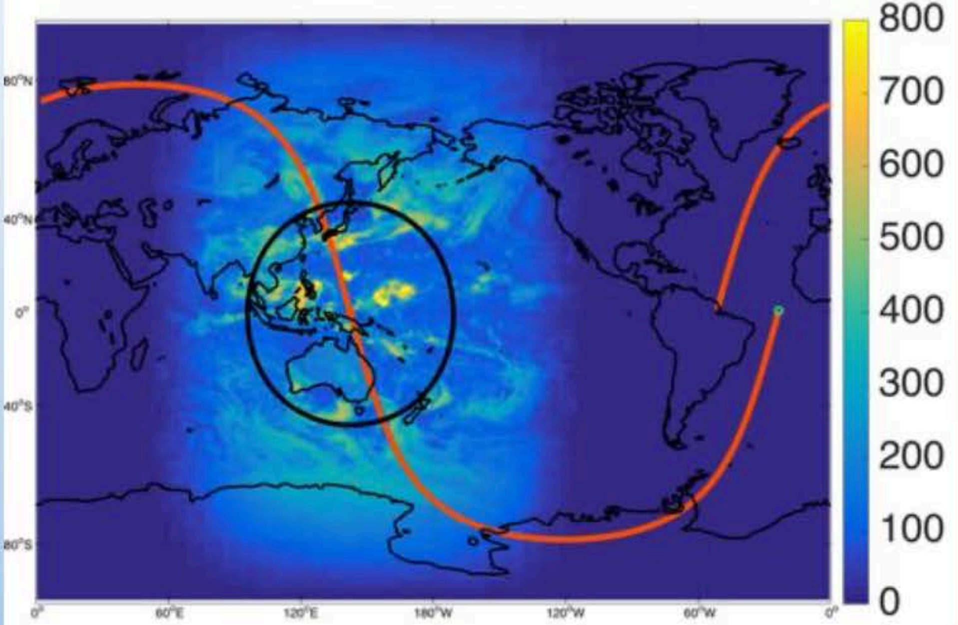
Sun-synchronous, 1300km, equinox (22 Sept, 2017, 1-2am, equator crossing at noon and midnight, FOV ~9%, SORCE solar irradiance, CERES SYN1deg hourly data



335
338
(CERES)



102
88 Wm^{-2}
(CERES)



Solar & Earth albedo

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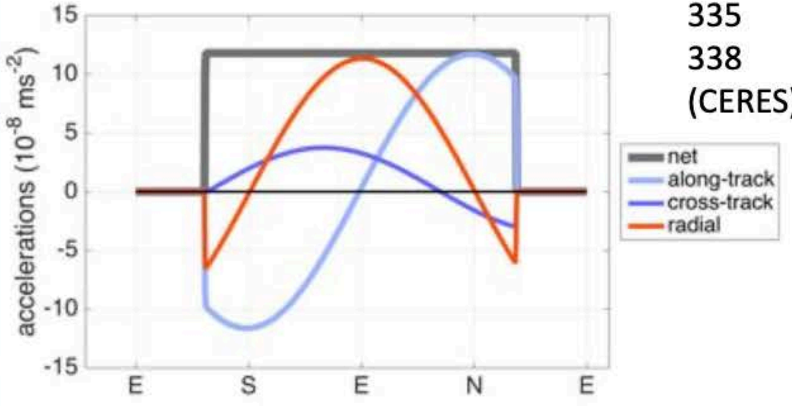
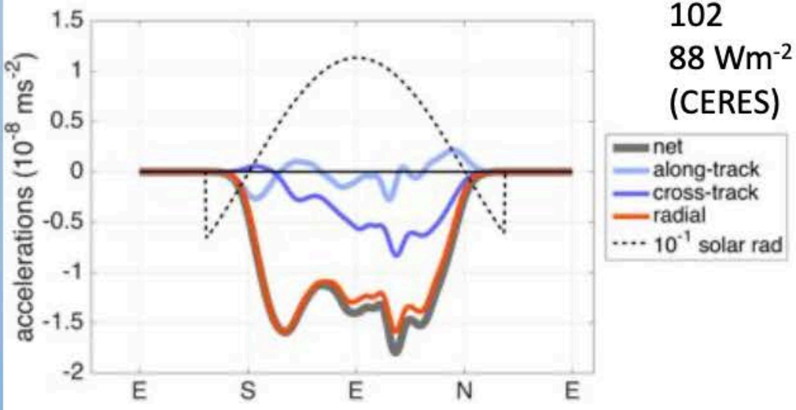


335
338
(CERES)



102
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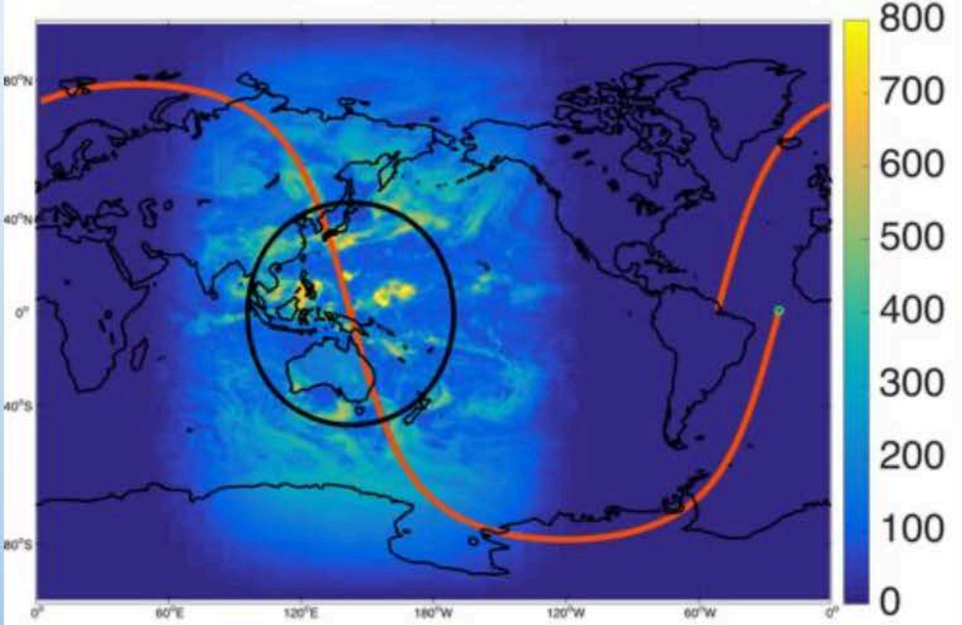


Some requirements

- Sphere needs be fully absorbing (or reflecting); coating properties constant across sphere (K)
- Sphere cannot carry fuel that alters (center of) mass; requires solar paneling
- **Radial acceleration is proportional to net radiative flux through the TOA**, and is orthogonal to some confounding effects acting on sphere (e.g., drag)
- Accelerometer performance itself outperforms radiometric accuracy
- Acceleration induced by total radiation flux intercepted by satellite cross section and represents a WFOV measurement

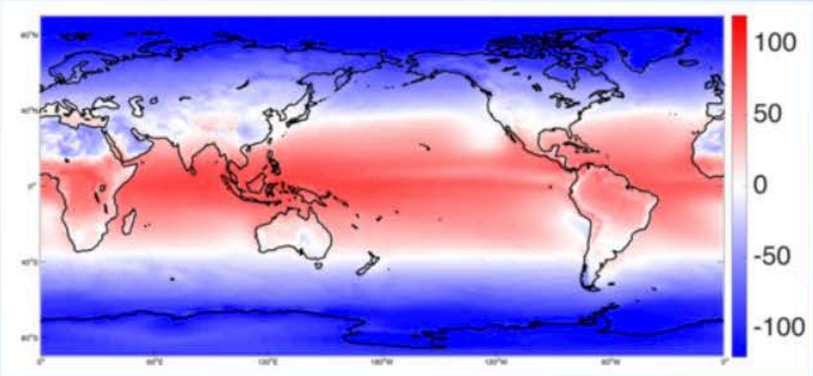
Next steps

“OSSE” studies to inform instrument, spacecraft, and mission proposal development

- Simulate non-gravitational accelerations for different design and meteor. conditions
- Error budget of confounding effects
- Geometrical and optical considerations
- Sampling: How well can 1-? satellites sample global mean EEI?

Deliverables & requirements

- **5-year long-term global mean** at $\pm$ **0.1 – 0.3 Wm^{-2}**
- Annual global means at $\pm$ **0.3 Wm^{-2}**
- Annual zonal means > $\pm$ **10 Wm^{-2}**
- Monthly global means > $\pm$ **5 Wm^{-2}**
- Monthly zonal means
- Mean diurnal cycle



- SW & LW are possible to separate, but focus is on **EEI & some aspects of spatial & temporal variability**
- Needed accuracy $\pm 10^{-11}$ ms^{-2} or $\pm$ 0.3 Wm^{-2} (depends on S/C)
- Instrument measurement accuracy at << 0.3 Wm^{-2} (random error ~ $\pm 10^{-13}$ ms^{-2})