Measuring Earth's Energy Imbalance via radiation pressure accelerations experienced by near-spherical LEO satellites

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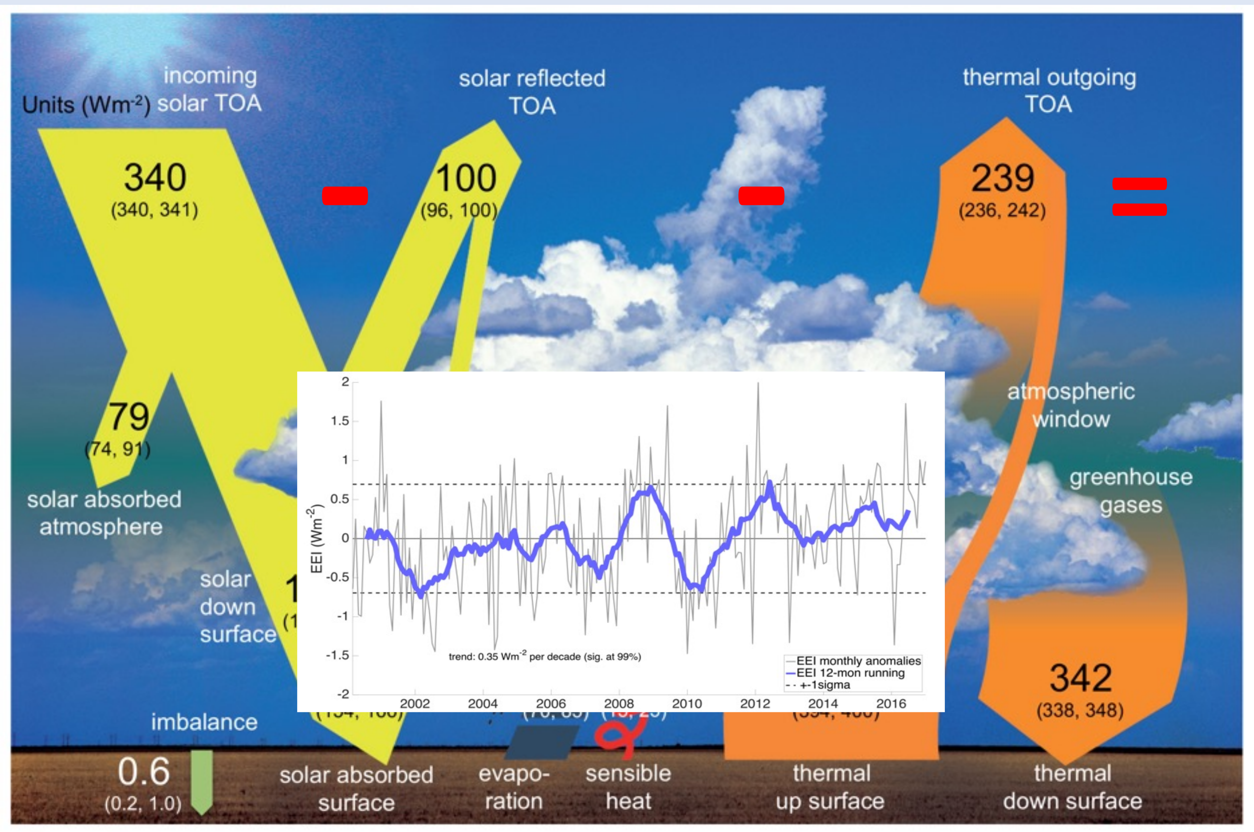
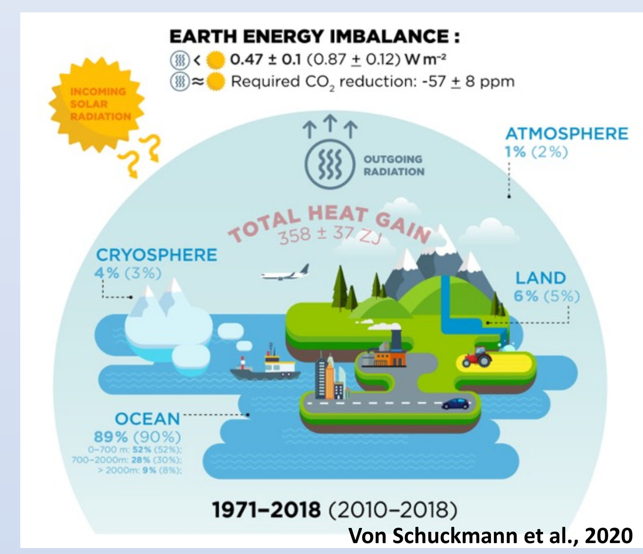
The scientific EEI challenge

Earth's (radiative) Energy Imbalance (EEI) quantifies the rate of global heating in response to radiative forcings & feedbacks and drives climatic changes and impacts. EEI is considered a reliable metric for quantifying global warming and does not "miss" any heat sink in the climate system, while other metrics such as surface temperature change do.





A direct high-accuracy EEI measurement does not exist. Indirectly, EEI is estimated through tracking global heat content change. Its time variability is well-captured by CERES net radiation?

Measuring EEI directly at high accuracy and precision from space would allow us to:

1. Quantify the global long-term (~ 1yr) accumulation of heat in the Earth system
2. Constrain estimates of radiative forcings + responses & climate sensitivity with observations
3. Anchor data products (i.e. CERES EBAF) and 'tune' global climate models that lack energy balance closure
4. Track climate change mitigation efforts through their direct impact on EEI

The radiometric accuracy of Earth radiation budget (ERB) measurements by CERES and Libera is insufficient to derive EEI from TOA net irradiances.

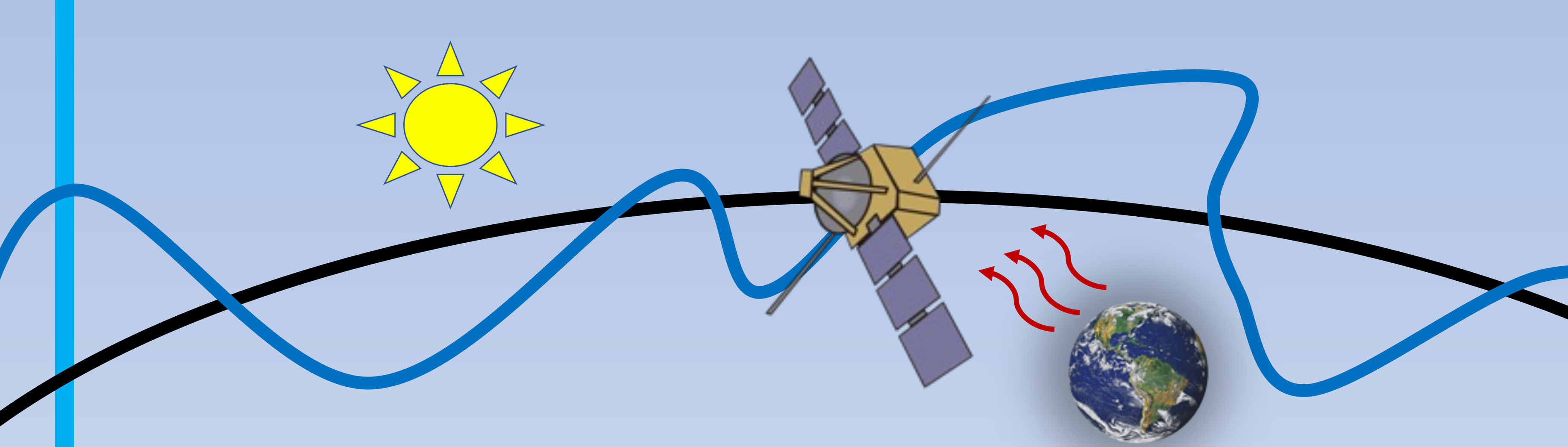
- Unless energy balanced, CERES radiation budget data suggest EEI = -2 to 6 Wm^{-2}. Largest source of error: **absolute calibration** + radiance-to-irradiance conversion + diurnal filling + …
- Although Libera radiometric accuracy is unprecedented, it is still too large for EEI absolute measurements: $\pm 1.5\ Wm^{-2}$

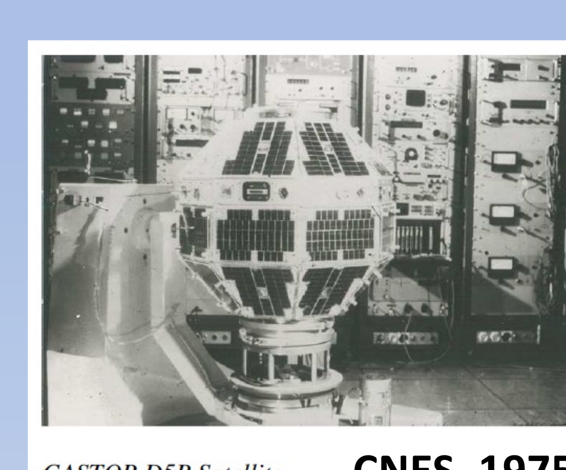
Parameters	Performance	Predicted Performance
Radiometer	CERES	Libera
Field of view	25 km at nadir	24 km at nadir
Cross-track width	Limb-to-Limb	Limb-to-Limb
Spectral range	**LW**: 5-50 µm **SW**: 0.3-5 µm **TOT**: 0.3->100 µm	**LW**: 5-50 µm **SW**: 0.3-5 µm **TOT**: 0.3->100 µm
Radiometric Accuracy	**LW**: 0.5%, **SW**: 1% **TOT**: 0.5%	**LW**: 0.24%, **SW**: 0.17%, **TOT**: 0.22%
Radiom. stability	0.3% / decade	<0.1% / decade
Radiometric Precision	**LW**: <0.45 $Wm^{-2}sr^{-1}$ **SW**: <0.2 $Wm^{-2}sr^{-1}$ **TOT**: <0.3 $Wm^{-2}sr^{-1}$	**LW**: 0.11 $Wm^{-2}sr^{-1}$ **SW**: 0.11 $Wm^{-2}sr^{-1}$ **TOT**: 0.11 $Wm^{-2}sr^{-1}$

A potential solution for direct EEI measurements based on accelerometry: "Space Balls"

Direct measurement of the net radiative flux (EEI) at TOA via radiation pressure accelerations experienced in orbit by LEO satellites

- Not a residual of radiative components (radiometry)
- More complete coverage (as opposed to in-situ heat content)
- State-of-the-art accelerometers allow a measurement of << 0.3Wm^{-2} (10^{-11} ms^{-2})



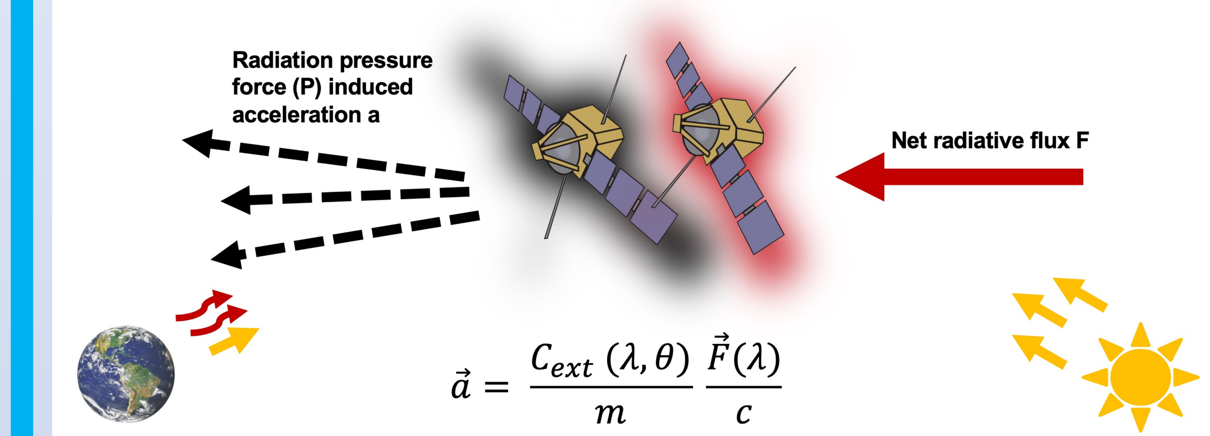


CNES, 1975

The technological EEI challenge

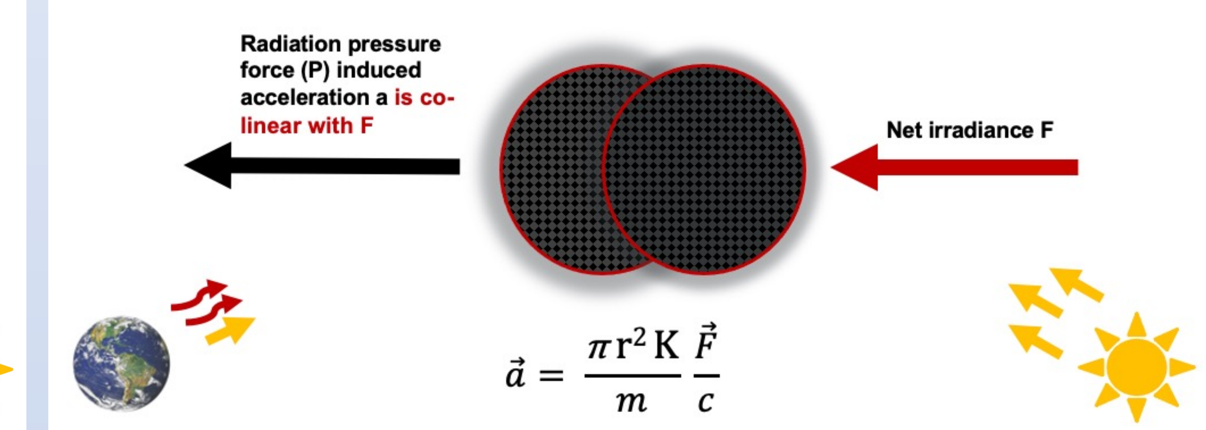
Physical Basis for *Space Balls*

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



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

A perfect black sphere that absorbs across both the solar and terrestrial emission spectra, facilitates a straight forward relationship between incident irradiance and induced acceleration



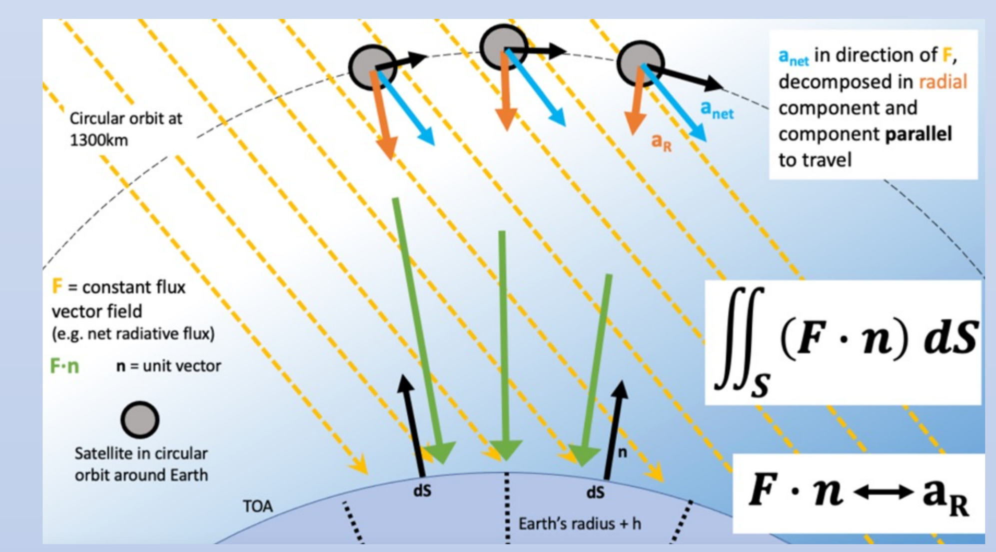
$$\vec{a} = \frac{\pi r^2 K}{m}\frac{\vec{F}}{c}$$

Simulations for Space Balls

Is a high-accuracy measurement of EEI via radial accelerations possible with modern accelerometers and optimal spacecraft design?

Simulations inform instrument, spacecraft, and mission requirements

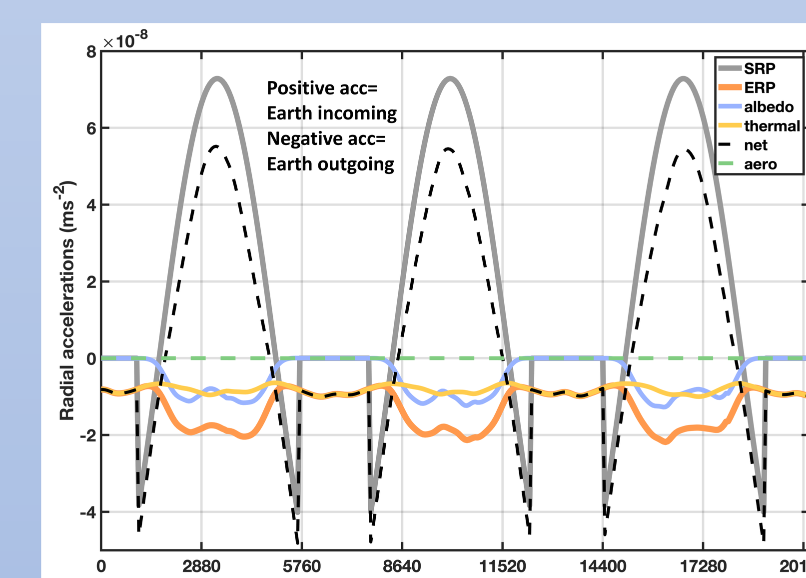
- Non-gravitational **radial** accelerations for different designs
- Influence of parasitic forces such as drag, Yarkovsky …
- Sampling: How well can 1-? satellites sample global mean EEI?

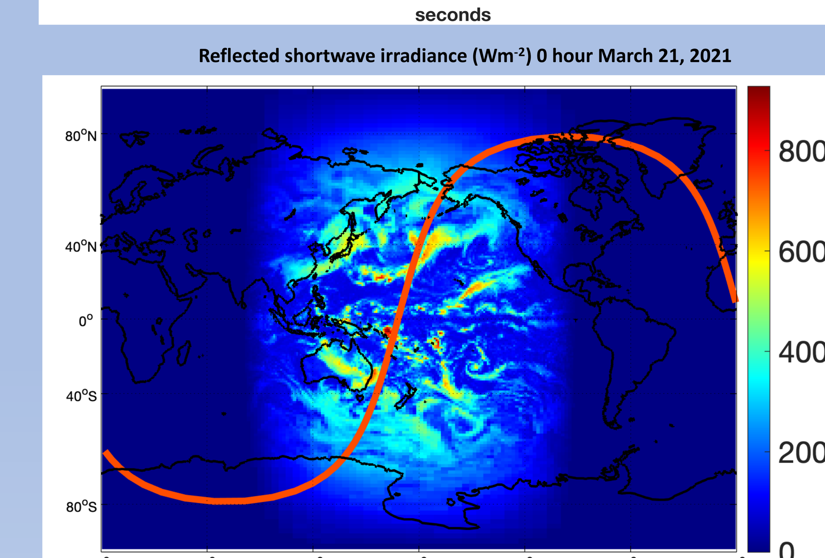


Initial simulations with JPL's mission design software *Monte*

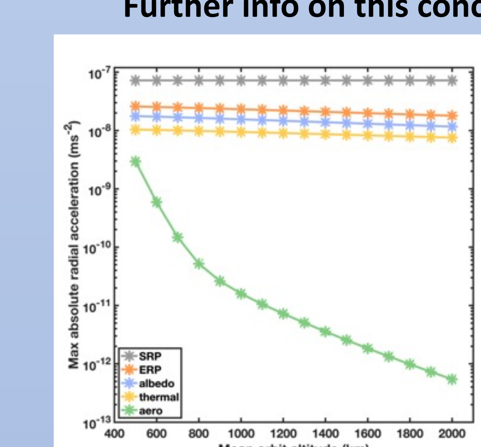
Radial accelerations experienced by spherical space craft (03/21, sun-synchronous, 1300km, m=50kg, r=50cm)

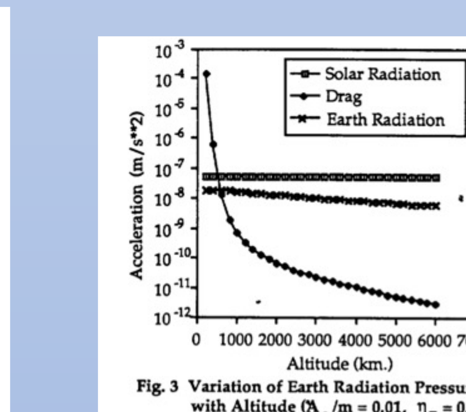
- Radiation pressure model ingests CERES irradiances
- Current work focuses on validation and S/C shape models





Change in radiation pressure and aerodynamic drag with orbit altitude compares well to published LAGEOS analysis. Sensitivity to S/C size is as expected and is under investigation wrt. diffuse reflectivity of spacecraft skin. **Further info on this concept: Hakuba et al., 2019, IEEE**





Design challenges:

1. **Custom built shell** that is as **spherical** as possible, allows integration of faceted **solar panels**, antenna, star tracker…
2. **Skin:** Perfectly absorbing (**UV-FIR**), thermally & optically **stable** black paint?
3. **Spin** to equalize shape and optical/thermal gradients. How to stabilize? Add thermopiles to correct for thermal push?
4. **Fuel**: Alternatives to solar panels? "Solid" fuel?
5. Choice of **accelerometer**?

References:

- M. Z. Hakuba *et al.*, "Earth's Energy Imbalance Measured From Space," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 57, no. 1, pp. 32-45, Jan. 2019, doi: 10.1109/TGRS.2018.2851976.
- *Knocke, P.C., Ries, J.C., & Tapley, B.D. (1988). Earth radiation pressure effects on satellites.*