National Aeronautics and Space Administration

Measuring Earth's Energy Imbalance via radiation pressure acting on spherical LEO satellites (Space Balls): Simulating feasibility, confounding effects, and sampling requirements

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Program: FY22 R&TD Topics
Strategic Focus Area: Climate Science

Objectives

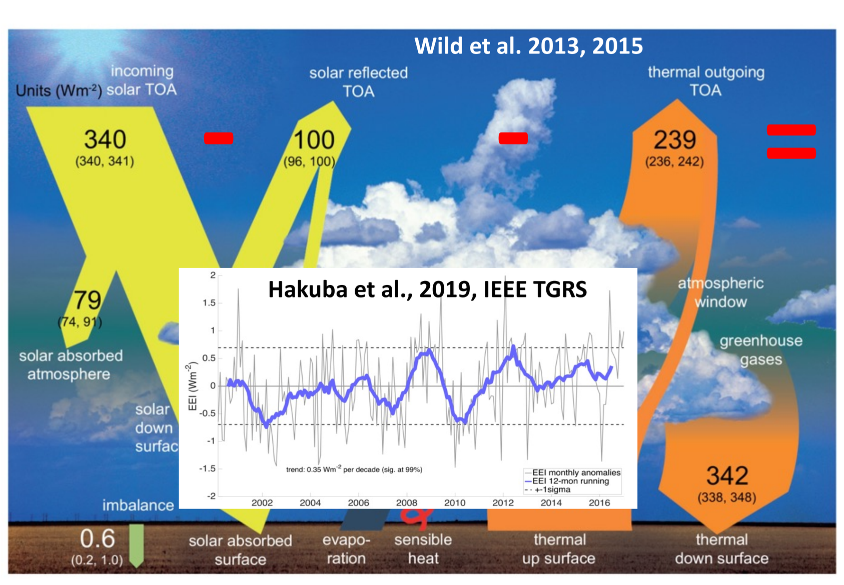
The goal of this research task is to develop a simulation environment for "*Space Ball(s)*", a near-spherical LEO spacecraft equipped with an accelerometer at its center of mass to measure radiation pressure-induced radial accelerations as a way to quantify and track changes in Earth's Energy Imbalance (EEI).

1. Improve upon the Earth radiation pressure model that is part of *Monte's* suite of orbital force models
2. Evaluate the impact of spacecraft characteristics (size/mass, absorptivity/reflectivity, shape, spin) on simulated accelerations.
3. Study the significance of confounding effects such as related to aerodynamic drag, attitude and thermal variations across the spacecraft skin.

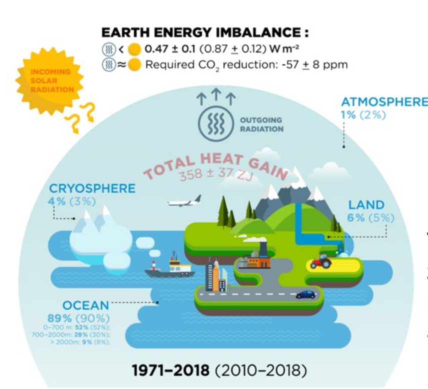
These sensitivity analyses are to inform requirements for spacecraft and mission design to enable a high-accuracy measurement of net radiative flux at the top-of-the-atmosphere (TOA). This work could inform ESTO InVEST or EVM proposals.

Background

Earth's (radiative) Energy Imbalance (EEI) quantifies the rate of global energy accumulation 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 sinks in the climate system, while other metrics such as surface temperature change do.



~0.9 Wm^{-2}



Von Schuckmann et al., 2020

A direct high-accuracy EEI measurement does not exist. Indirectly, EEI is estimated through tracking global heat content change.

Measuring EEI directly from space would allow us to:

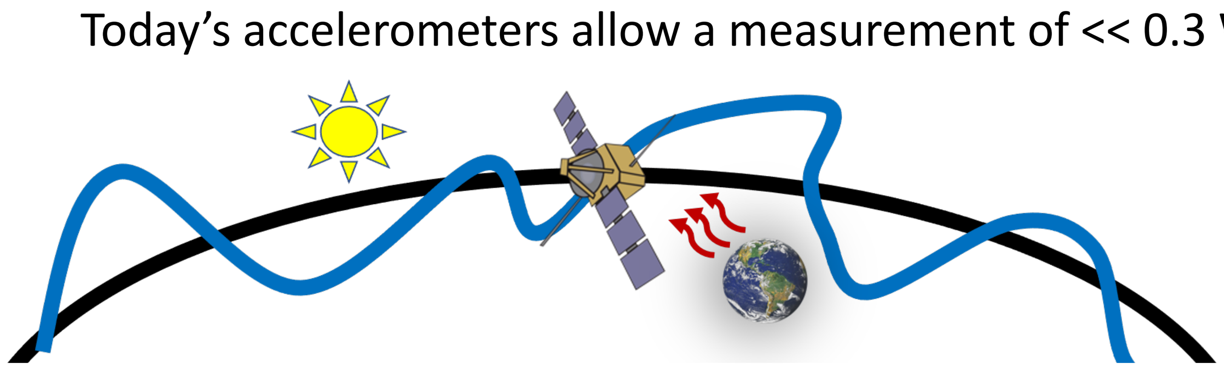
1. Quantify the global long-term (~ 1yr) accumulation of heat in the Earth system
2. Constrain radiative forcings/responses & climate sensitivity with observations
3. Anchor data products (i.e. CERES EBAF) and 'tune' global climate models that lack energy balance closure
4. Track climate change mitigation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

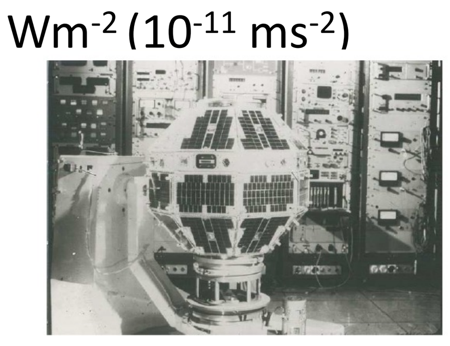
Current (CERES) and future (Libera) radiation budget (ERB) observations lack the absolute accuracy (± 4 Wm^{-2}) to resolve EEI as the ERB components' residual.

A potential solution based on accelerometry: "Space Balls"

Direct measurement of the net radiative flux (EEI) at TOA through sensing radiation pressure accelerations acting on a near-spherical LEO spacecraft

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

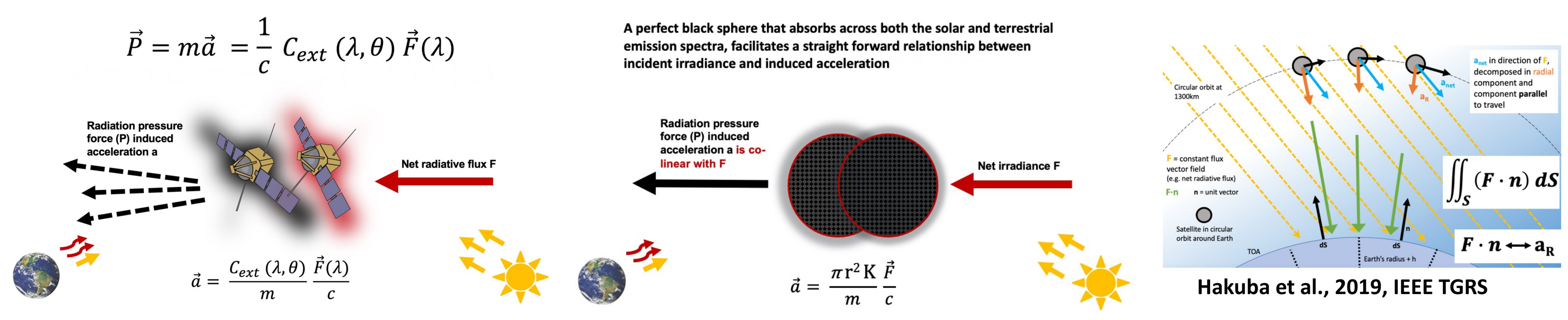




CASTOR D5B Satellite CNES, 1975

Approach and Results

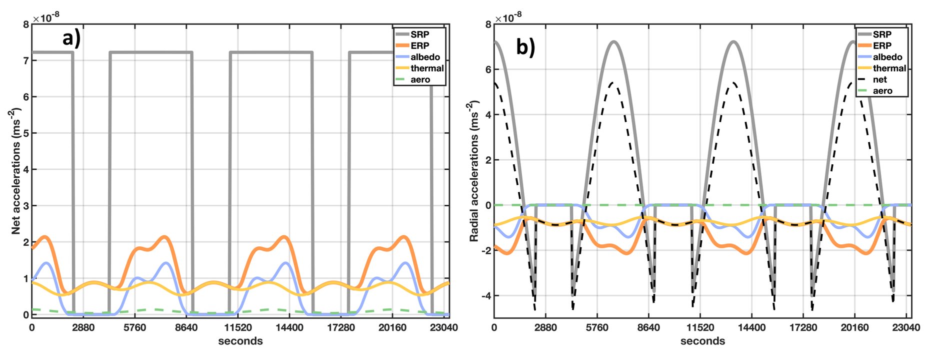
While the accelerometer at the center of the spacecraft senses the non-gravitational orbit perturbations, the absorbing-reflecting S/C skin represents the detector itself, translating the impact of radiation pressure into sensible accelerations.



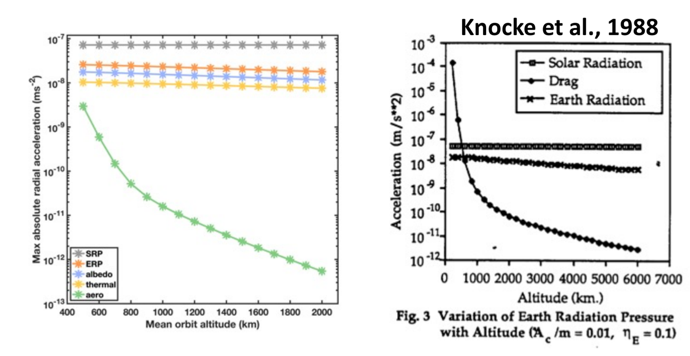
Hakuba et al., 2019, IEEE TGRS

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

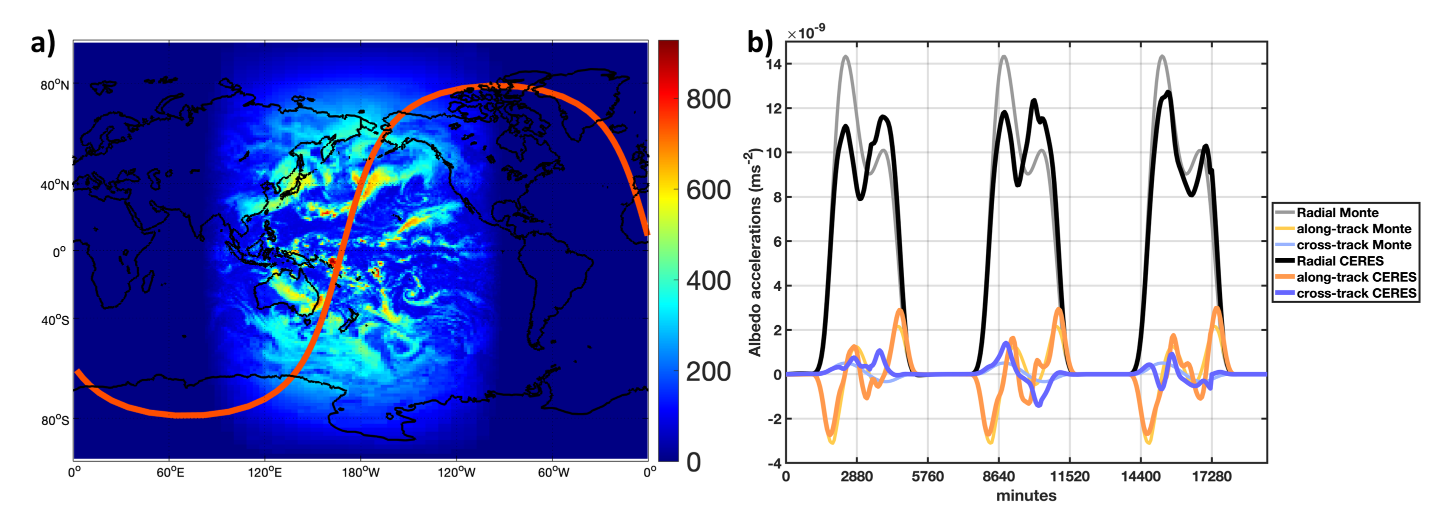
- Radial accelerations experienced by a spherical and perfectly absorbing S/C
- March 21, sun-synchronous orbit at 1300km, m=50kg, r=50cm
- Radiation pressure model ingests CERES SYN1deg irradiances at 1h resolution



Net and radial accelerations due to SRP, ERP, albedo, thermal radiation, and aerodynamic drag. SRP is the dominant force, followed by Earth's albedo, which is absent in shadow, and thermal radiation.



Change in radiation pressure and drag with orbit altitude compares well to published LAGEOS analysis. Drag is negligibly small at >1000 km.



CERES-based albedo accelerations are 3 % lower than those from the *Monte*. Albedo has been declining since 2000 as observed by CERES. Thermal induced accelerations are larger (not shown), which aligns with an observed increase in OLR. The CERES data provide high temporal and spatial resolution, which translates into more pronounced and realistic variability in the simulated accelerations.

Significance/Benefits to JPL and NASA

- EEI reflects the integrated Earth system response to changes in surface and atmospheric properties observed by current and future NASA missions (AOS).
- A dedicated EEI measurement would therefore complement NASA's vision of a space-based Earth System Observatory.
- *Space Balls* could serve as a companion to future and current NASA projects that provide the individual shortwave and longwave fluxes (CERES, *Libera)*.
- Concept represents a concerted effort toward energy cycle closure and heat uptake estimation, and addresses several science questions posed by the ESAS-2017 *Decadal Survey* (C-1b, C-2f, H-1a, H-2b).
- Novel radiation pressure and coverage algorithms for use in *Monte* may support other projects such as GRACE-FO non-gravitational force modeling.

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Publications:

[A] M. Hakuba et al., "Measuring Earth's Energy Imbalance with "Space Balls"," to be submitted to *International Radiation Symposium 2022*, Thessaloniki, Greece, 2022.
[B] M. Hakuba et al., "Measuring Earth's Energy Imbalance via Radiation Pressure Accelerations Experienced in Orbit," to be submitted to *IEEE Aerospace conference*, Big Sky, Montana, 2023.
[C] C. Reynerson et al., "Real-Time Modeling of Albedo Pressure on Spacecraft and Applications for Improving Trajectory Estimation and Earth's Energy Imbalance Measurements", to be submitted to AIAA SciTech Forum, 2023.

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