National Aeronautics and Space Administration

FY25 Strategic University Research Partnership (SURP)

Space Balls Constellation Optimization for Measuring Earth's Energy Imbalance

Principal Investigator: David Wiese (392)**; Co-Investigators:** Maria Hakuba (329), Christopher Mccullough (392), R. Steven Nerem (University of Colorado at Boulder), Peter Pilewskie (University of Colorado at Boulder), Lluc R. Busquets (University of Colorado at Boulder)

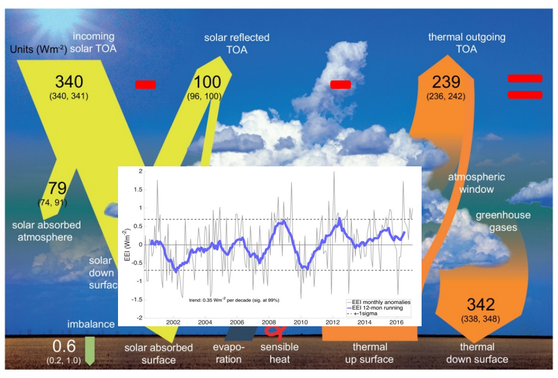
Objectives

The technical objective of this SURP is to advance the development of an Observing System Simulation Experiment (OSSE) and to define requirements and quantify the science return for the Space Balls mission concept, which aims to measure Earth's Energy Imbalance (EEI) via space-based accelerometry. The objectives for Year 1 (which we just completed) have been

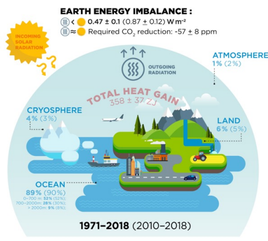
- to establish a dedicated research team at the University of Colorado Boulder,
- to re-visit/refactor an existing preliminary software implementation of a Space Balls OSSE that relies on the MONTE software suite,
- to introduce new features such as allowing for different satellite shapes and time-variable Total Solar Irradiance (TSI), and
- validate results via end-to-end closure of the full simulation process (Fig. 1). This OSSE will eventually morph into the Space Balls Science Data System (SDS).

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.



~1 Wm^{-2}



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:

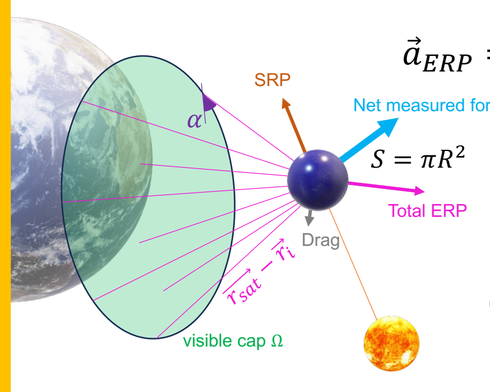
1. Quantify the global long-term (~ 1yr) accumulation of heat in the Earth system
2. Constrain radiative forcings, feedbacks & climate sensitivity with observations
3. Anchor data products (i.e., CERES EBAF) and 'tune' global climate models that lack energy balance closure
4. Track climate change mitigation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

Current Earth Radiation Budget (ERB) observations lack the absolute accuracy (± 4 Wm^{-2}) to resolve EEI as the ERB components' residual.

A 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 spacecrafts:

- 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})



$$\vec{a}_{ERP} = \frac{S \cdot K}{m \cdot c} \sum_{i}^{N} \frac{LW_i + I_i\, SW_i}{\pi} A_i \cos(\alpha_i) \frac{(\overrightarrow{r_{sat}} - \overrightarrow{r_i})}{\|\overrightarrow{r_{sat}} - \overrightarrow{r_i}\|^3} \quad (1)$$

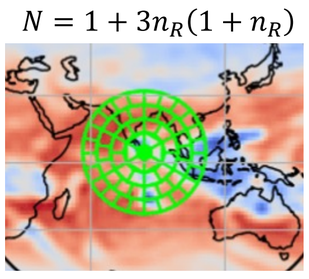
$$\vec{a}_{SRP} = K \frac{S}{m} \frac{TSI}{c} \frac{\left(\overrightarrow{r_{sat}} - \overrightarrow{r_\odot}\right)}{\left\|\overrightarrow{r_{sat}} - \overrightarrow{r_\odot}\right\|} \quad (2)$$

Goal: $$\boxed{EEI \approx -\frac{m \cdot c}{S \cdot K} \frac{1}{T} \int_0^T (\vec{a}_{ERP} + \vec{a}_{SRP}) \cdot \hat{R}\, \mathrm{d}t} \quad (3)$$

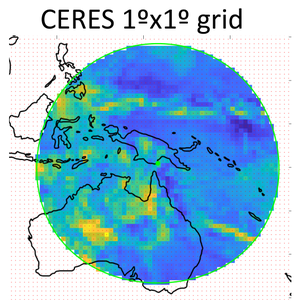
Approach and Results

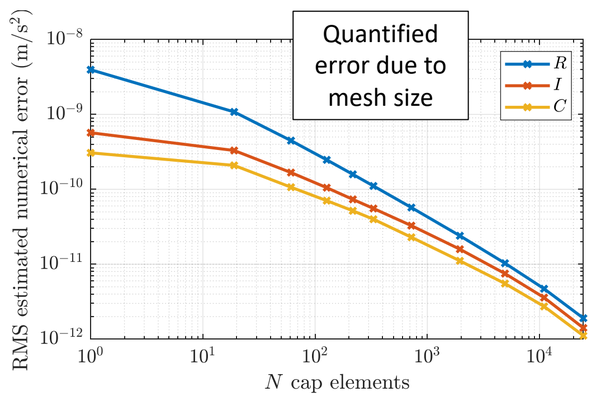
CERES data grid vs. Monte mesh

n_R concentric rings
$N = 1 + 3n_R(1 + n_R)$



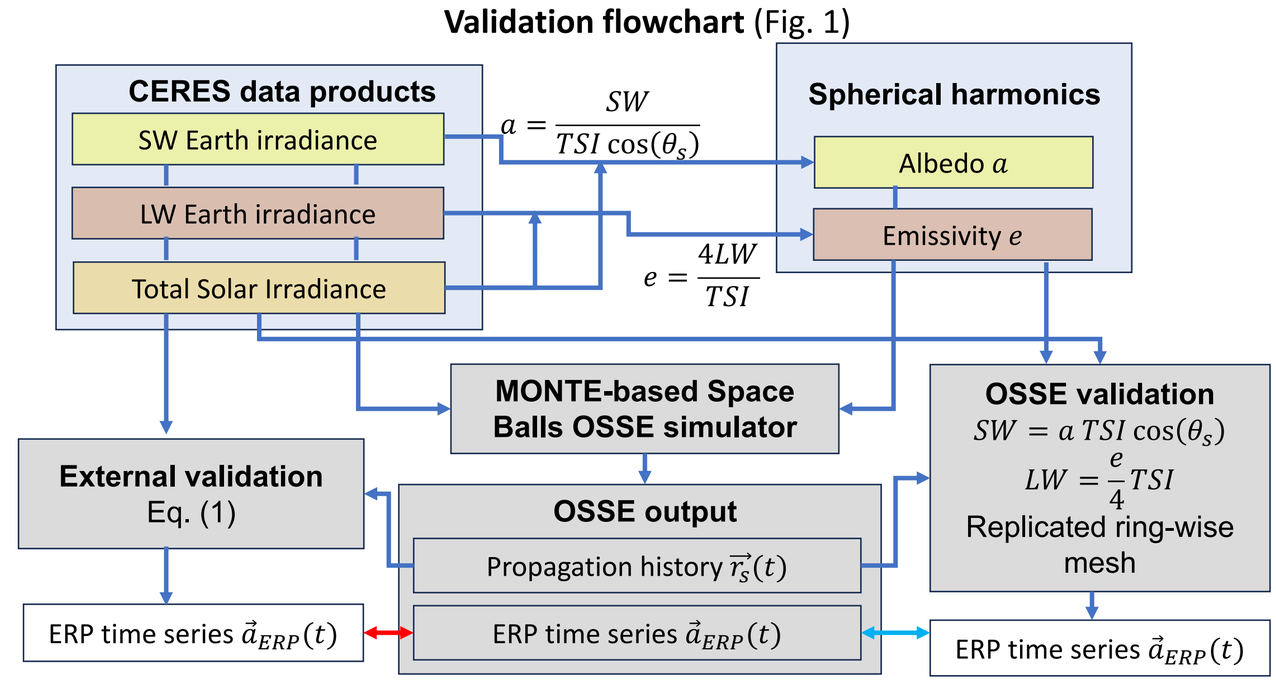
CERES 1ºx1º grid



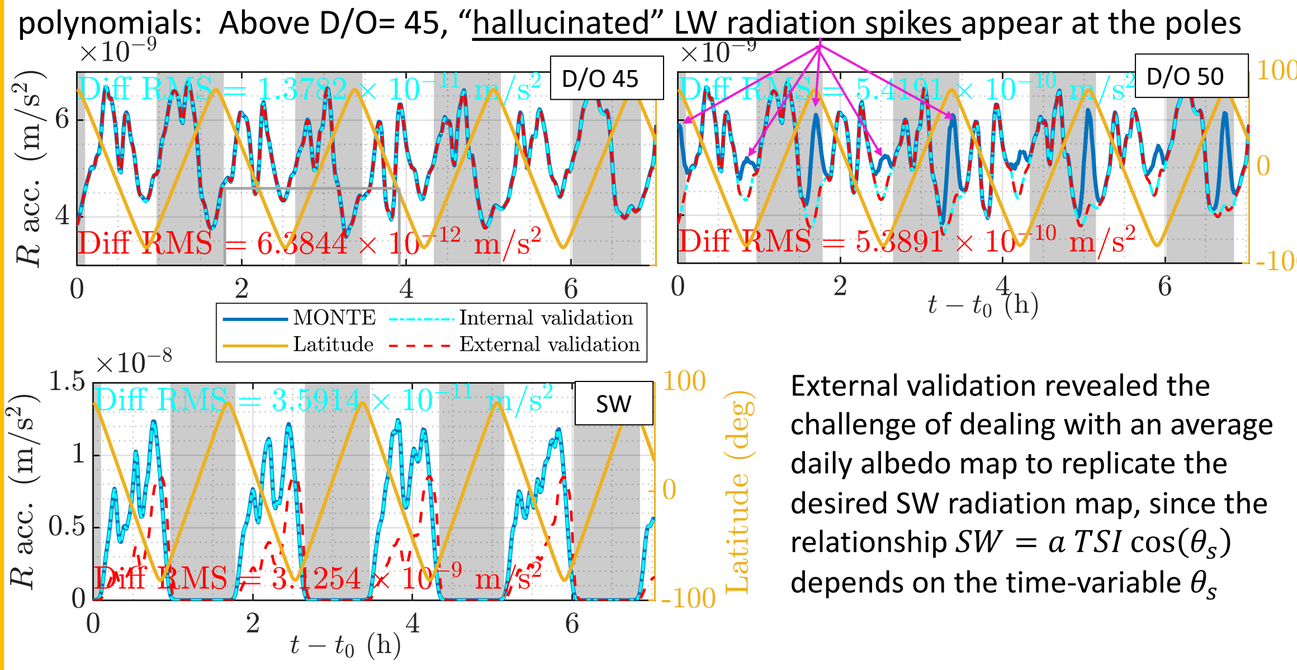


Convergence analysis has evinced the need to use ~25 rings in the orbit integration

Validation flowchart (Fig. 1)



OSSE validation revealed issue with MONTE's computation of **unnormalized** Legendre polynomials: Above D/O= 45, "hallucinated" LW radiation spikes appear at the poles



External validation revealed the challenge of dealing with an average daily albedo map to replicate the desired SW radiation map, since the relationship $SW = a\, TSI \cos(\theta_s)$ depends on the time-variable θ_s

Significance/Benefits to JPL and NASA

- A dedicated EEI measurement complements NASA's vision of a space-based Earth System Observatory; EEI represents the integrated Earth system response to surface and atmospheric changes observed by many NASA missions.
- *Space Balls* would 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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Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

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Publications:

- "Measuring Earth's Energy Imbalance using spaceborne accelerometers" – abstract submitted to AGU25
- "Measuring Earth's Energy Imbalance using spaceborne accelerometers" – abstract submitted to GRACE science team meeting

PI/Task Mgr. Contact Information:
David.N.Wiese@jpl.nasa.gov | (626) 590-0193