National Aeronautics and Space Administration

FY24 Topic Areas Research and Technology Development (TRTD)

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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Strategic Focus Area: Climate Science

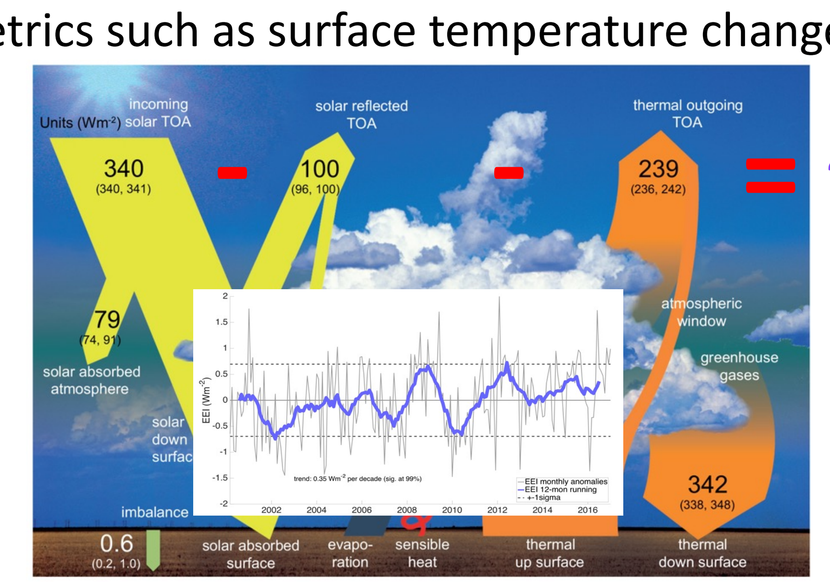
Objectives

The goals of this research task were to 1) develop a **simulation environment** for "*Space Balls*", multiple near-spherical LEO spacecrafts equipped with accelerometers at their center of mass which measure radiation pressure-induced radial accelerations to quantify Earth's Energy Imbalance (EEI) and its variability in time; and to 2) formulate critical aspects of **Science and Mission implementation/architecture** in preparation for a potential Earth Venture proposal.

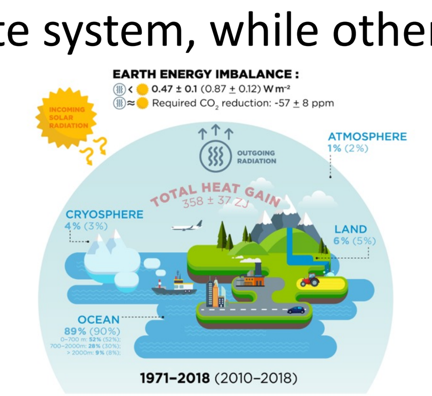
1. Improve upon the representation of Earth Radiation and spacecraft properties in our simulation toolkit.
2. Study the impact of orbital and spacecraft characteristics, such as shape, spin, size, mass and surface properties to refine our Science Traceability Matrix.
3. Understand the significance of confounding effects related to aerodynamic drag and thermal variations across the spacecraft skin.
4. Refine our integrated GN&C model, identify payload and mission architecture, design a data processing pipeline, and perform costing analysis

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:

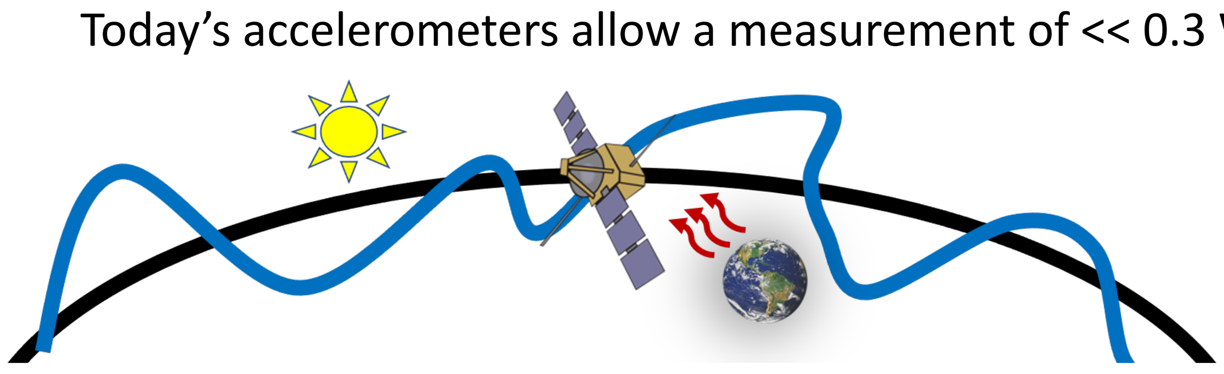
1. Quantify the global long-term (~ 1yr) accumulation of heat in the Earth system
2. Constrain radiative forcings, feedbacks & climate sensitivity with observations
3. Anchor data products (i.e., CERES EBAF) and 'tune' global climate models that lack energy balance closure
4. Track climate change mitigation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

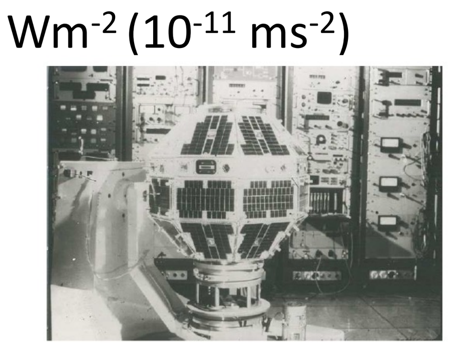
Current Earth Radiation Budget (ERB) observations lack the absolute accuracy (± 4 Wm^{-2}) to resolve EEI as the ERB components' residual.

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 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})

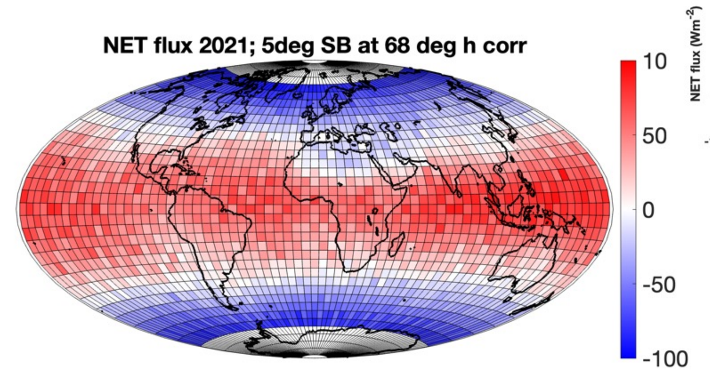


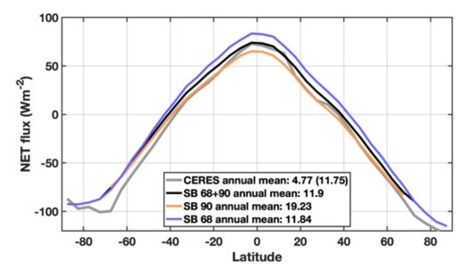


CASTOR D5B Satellite

Approach and Results

Sampling of net radiative flux with spacecraft in precessing orbits



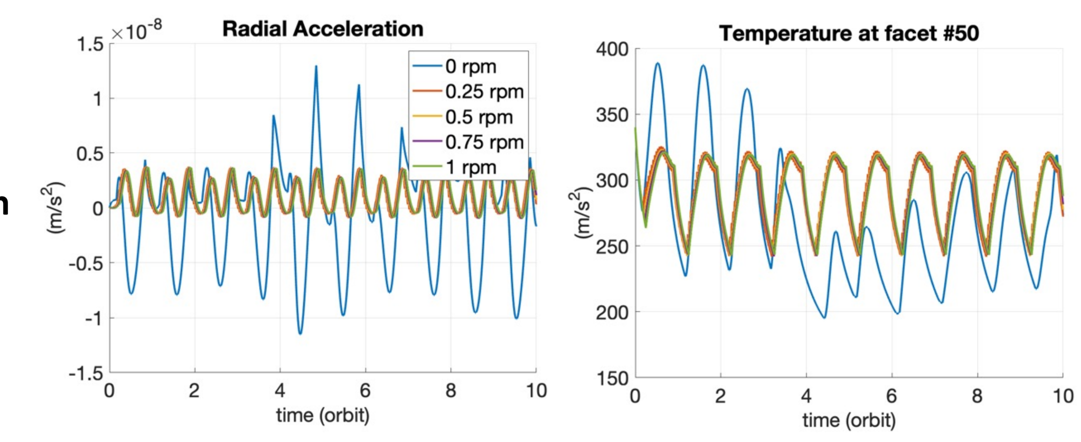


NET flux Wm^{-2}	68deg SB	CERES	bias	rms	STM
5deg			1.52	12.54	
zonal			1.52	7.47	10
NH	8.53	11.39	2.86		
SH	15.16	12.10	-3.06		
global	11.75	11.84	0.09		0.3

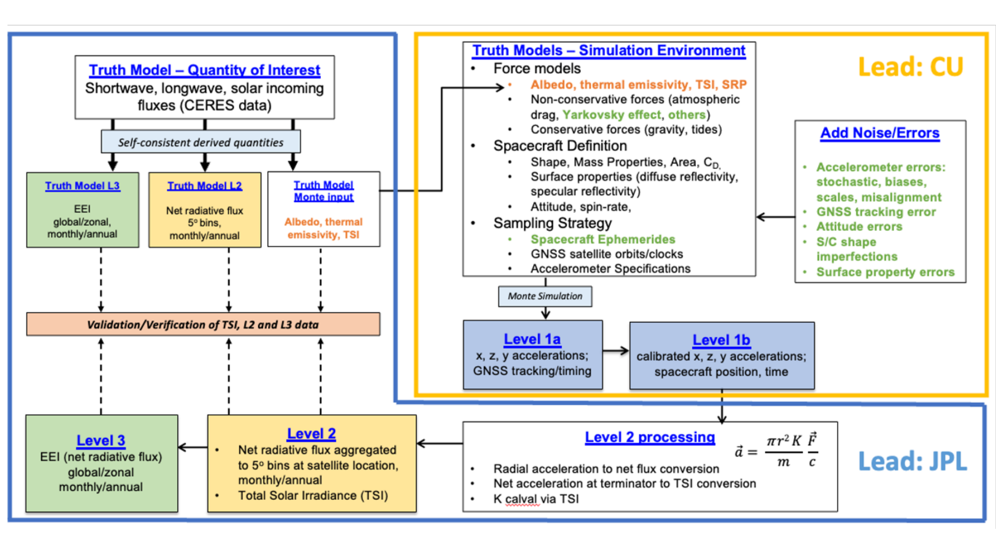
(left) Annual mean net radiative flux at 5° resolution as sampled by one *Space Ball* at 750 km, 68° inclination over the course of one year. (top right) Zonal averages of 5° net radiative fluxes for 68° and 90° inclinations compared to "truth" from CERES SYN data. The table summarizes results and differences compared to "truth".

Spin reduces thermal gradient and Yarkovsky acceleration effects

(Left) Radial acceleration at different spin rates due to Yarkovsky acceleration effect for a black, near-spherical spacecraft (90kg, r=0.5 m) in a sun synch orbit at 1000 km. (right) Temperature variations for a specific facet of spacecraft skin at different spin rates.

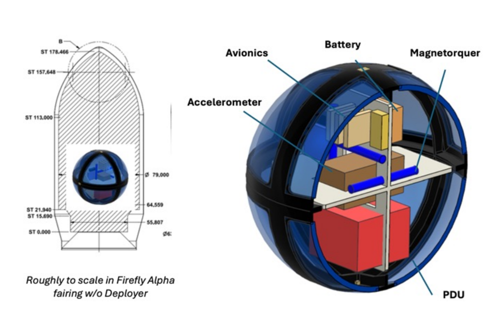


Software and Data Product Flow for Space Balls



Software and Data Product Flow for the Space Balls concept. Level 1 calibrated and filtered accelerations serve to produce net radiative fluxes at 5° spatial resolution at monthly and annual time scales (Level 2) . These serve to establish global and zonal EEI values (Level 3). The models serve to estimate sensitivities, refine the STM, quantify system noise/errors and the impact of different orbital sampling strategies.

Preliminary payload, mass budget and ROM cost estimate



Subsystem	BTM [kg]	MGA [%]	PTM [kg]
Payload	13.0	50%	19.5
CDH	0.3	20%	0.3
Power	17.1	27%	21.7
ACS	1.4	55%	2.1
Telecom	2.0	52%	3.1
Structure	40.0	33%	53.3
Thermal	1.0	50%	1.5
Space Ball	74.7	36%	101.4
Deployer	30	100%	60
Stack	166.2	46%	243.0
LV Performance to SSO [kg]			500
JPL Mass Margin			155%

WBS	2 Space Balls	3 Space Balls	4 Space Balls	Comment
1	9	9	9	Average of three EVM-3 proposals
2	8	8	8	Average of three EVM-3 proposals
3	6	6	6	Average of three EVM-3 proposals
4	12	12	12	Average of three EVM-3 proposals
5	21	27	33	NICM, 50% cost for four units.
6	32	42	52	WAG, assuming $20M first unit. Includes deployers.
7	28	30	33	Scaled from three EVM-3 proposals
9	13	14	15	Scaled from three EVM-3 proposals
Subtotal	128	148	168	
Reserves	35	40	45	27% Phases A-E
8 (LV)	30	45	60	4x market price of Firefly Alpha
Total	193	233	274	Including LV

Requirements were defined for mission architecture, launch, checkout and end-of-mission (drag skirt). Considering standard engineering to develop air core magnetorquers, curved solar cells, a custom spherical structure and 90° phased patch antennas, together with high TRL CubeSat avionics, results in a spherical spacecraft of 100 kg mass, 1m diameter and 100W power consumption. A preliminary ROM cost estimate suggests that four Space Balls, excluding launch, fall within the typical Earth Venture cost cap.

Significance/Benefits to JPL and NASA

- EEI represents the integrated Earth system radiative response to changes in surface & atmospheric properties observed by NASA missions (e.g., future AOS).
- A dedicated EEI measurement complements NASA's vision of a space-based Earth System Observatory.
- *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 processing algorithms may support other projects such as GRACE-FO non-gravitational force modeling.

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Publications:

1. M. Hakuba, C. Reynerson, B. Quadrelli, D. Wiese, C. Mccullough, G. Stephens, F. Landerer, "Measuring Earth's Energy Imbalance with "Space Balls"," *AIP Conf. Proc.* 18 January 2024; 2988 (1): 070007. https://doi.org/10.1063/5.0183868
2. M. Z. Hakuba *et al.*, "Measuring Earth's Energy Imbalance via Radiation Pressure Accelerations Experienced in Orbit: Initial Simulations for "Space Balls"," *2023 IEEE Aerospace Conference*, Big Sky, MT, USA, 2023,, doi: 10.1109/AERO55745.2023.10115678.
3. M. Z. Hakuba et al., "Modeling Radiation Pressure Accelerations: Earth Radiance Anisotropy, Spacecraft Shape and Global Sampling," *2024 IEEE Aerospace Conference*, Big Sky, MT, USA, 2024, doi: 10.1109/AERO58975.2024.10521289.
4. C. Reynerson, M. Hakuba, B. Quadrelli, D. Wiese, C. Mccullough, et al., "Real-Time Modeling of Albedo Pressure on Spacecraft and Applications for Improving Trajectory Estimation and Earth's Energy Imbalance Measurements," AIAA SciTech Forum, 2023.
5. C. Reynerson, M. Hakuba, B. Quadrelli, D. Wiese, C. Mccullough, "Modeling Spacecraft Earth Radiation Pressure to Improve Spacecraft Trajectory Estimation and Design", AAS/AIAA Astrodynamics Specialist Conference, Big Sky, MT, 2023.
6. Mazouz, R., Quadrelli, M., Hakuba, M., Amini, R., Reynerson, C., Wiese, D.: Modeling and Control for Distributed Measurements of Earth's Energy Imbalance, submitted to 2025 AAS/AIAA Spaceflight Mechanics Meeting, Kaua'i, Hawaii.

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