6th June 2023

6th International Symposium on Space Sailing

Space and Exploration Technology Group

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SOLSPACE Solar Reflectors: Commonalities with Solar Sailing

Iain Moore, Onur Çelik, Temitayo Oderinwale, Litesh Sulbhewar, Andrea Viale and Colin R. McInnes

The Team!

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Principle investigator	– **Prof Colin R. McInnes**
Orbital dynamics lead	– **Dr Onur Çelik**
Attitude control lead	– **Dr Iain Moore (previously Dr Andrea Viale)**
Structures lead	– **Dr Litesh Sulbhewar**
Energy, economics and regulatory lead	– **Dr Temitayo Oderinwale**

SOLSPACE: INTRODUCTION

Introduction

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- Solar PV farms currently contribute 3.6% to global electricity generation [1]
- Limited to daytime use
- 80% of solar energy production is limited to 26% of hours of the year.
- With OSR, yearly productive hours of a typical solar PV can be increased by at least 8%

- Solar energy provides a clean energy source
- Orbiting solar reflectors (OSRs) can 'extend the day' at these sites
- Demand for clean energy, falling launch costs and in-orbit manufacturing technologies now overlap to lay a fertile ground for development of such a project

OSR can be useful for different applications such as:
  - Night illumination
  - Electricity generation with solar PV.
  - Food and biomass production
  - Fresh water production

Video credit: Dr Andrea Viale

[1] IEA (2022), Solar PV, IEA, Paris https://www.iea.org/reports/solar-pv, License: CC BY 4.0

SOLSPACE: ORBITAL DYNAMICS

Orbital Dynamics

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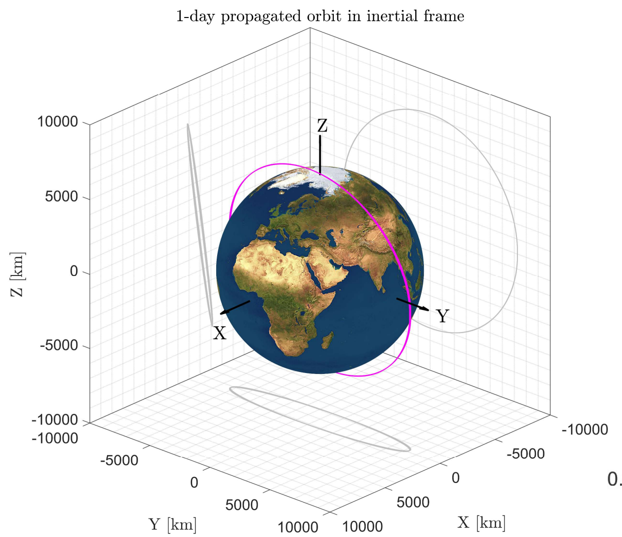
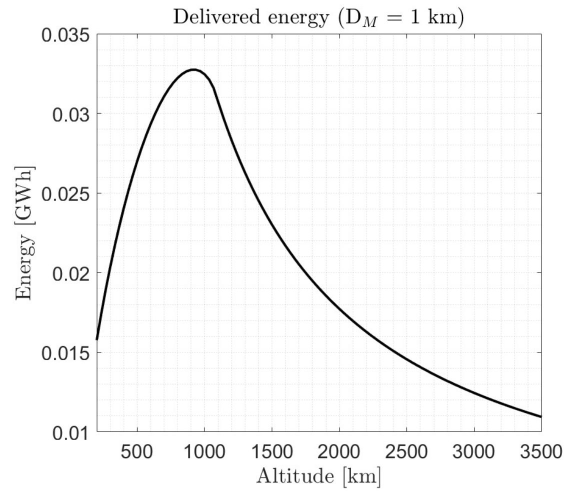
- Orbit design essentially seeks to maximise the quantity of energy delivery per day to multiple solar power farms
- Polar Sun-synchronous orbits typically provide global accessibility to solar power farms [1,2]
- Alternative reflector concepts available with displaced non-Keplerian orbits by using solar-radiation pressure [3]





[1] Çelik, O., Viale, A., Oderinwale, T., Sulbhewar, L. and McInnes, C.R. (2022). Enhancing terrestrial solar power using orbiting solar reflectors. Acta Astronautica, 195, pp.276-286.

[2] Viale, A., Çelik, O., Oderinwale, T., Sulbhewar, L., & McInnes, C. R. (2023). A reference architecture for orbiting solar reflectors to enhance terrestrial solar power plant output. Advances in Space Research (under review)

[3] Çelik, O., & McInnes, C. R. (2022). Families of displaced non-keplerian polar orbits for space-based solar energy applications. In 73rd International Astronautical Congress (IAC 2022). Paris, France: IAF. Paper no. IAC-22-C1.IP.37.x69012.

Orbital Dynamics

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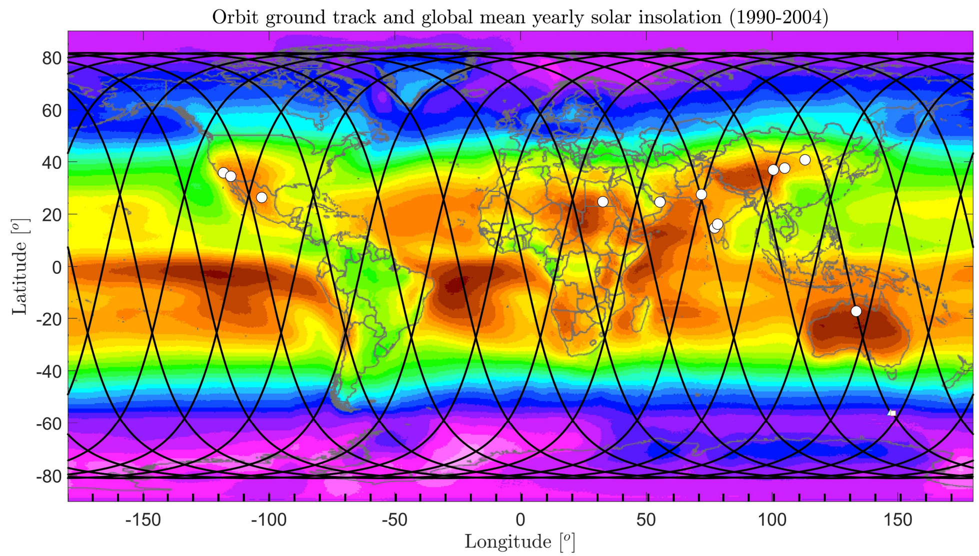
- A high-fidelity energy delivery model is developed, including time-dependent geometrical and atmospheric losses [1]

- An optimal altitude can be found for a given ground target size [1]



[1] Çelik, O., & McInnes, C. R. (2022). An analytical model for solar energy reflected from space with selected applications. Advances in Space Research, 69, 647–663.

SOLSPACE: ATTITUDE CONTROL

Attitude Control

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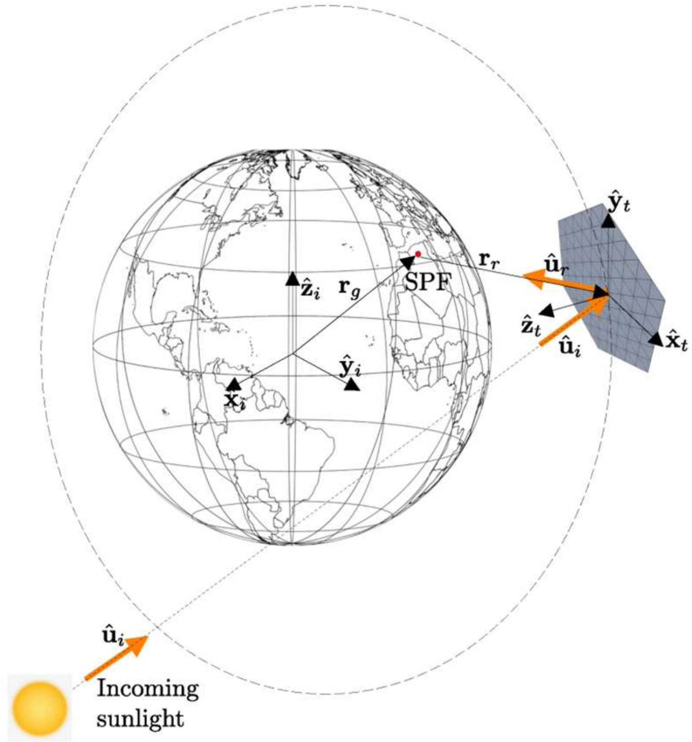
- Objective is to deliver maximum possible energy to the solar PV farm. Figure taken from Ref. [1]
- Control actuation via 4 Control Moment Gyros (CMGs)
- Trade-off showed high power demand from reaction wheels as compared with CMGs [2,3]
- CMGs sized to max Starship fairing radius (6.5 m)
- CMGs of this size, can control hexagonal reflector of 250 m side length [1]
- Can achieve slew rates up to 0.7 deg/s



[1] A. Viale, O. Çelik, T. Oderinwale, L. Sulbhewar, C. R. McInnes, A reference architecture for orbiting solar reflectors to enhance terrestrial solar power plant output, Advances in Space Research (Accepted)"

[2] Andrea Viale, Colin R. McInnes, *Attitude control actuator scaling laws for orbiting solar reflectors*, Advances in Space Research, Volume 71, Issue 1, 2023, Pages 604-623, ISSN 0273-1177

[3] Hedgepeth, J. M., Miller, R. K., and Knapp, K., "Conceptual design studies for large free-flying solar-reflector spacecraft," NASA Contractor Report, 3438, 1981.

Attitude Control

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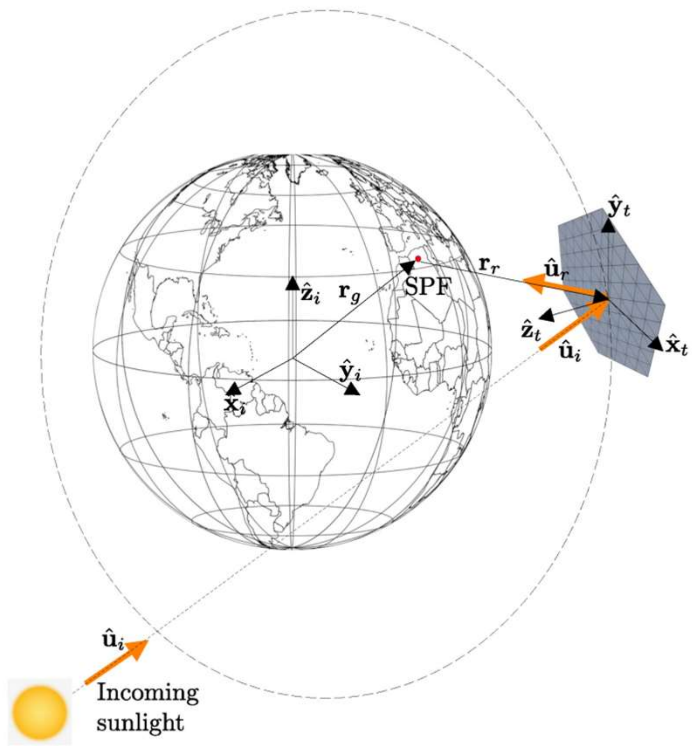
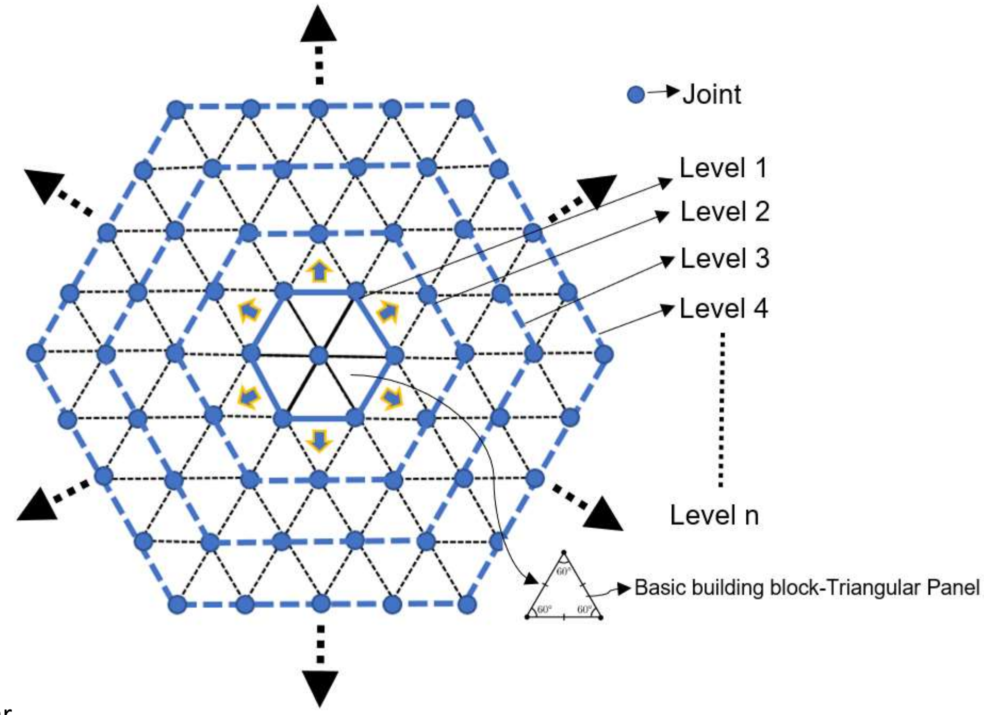
- When tracking a PV farm, primary constraint requires z-axis to point such that reflected light guided to target
- When not tracking, moves to idle phase where reflector is edge-on to Sun, to prevent stray light. Primary constraint is x-axis towards Sun.
- Pointing error analysis for rigid and flexible body currently underway
- Continuing work looking at energy delivery losses due to pointing errors (see you at the IAC!)



SOLSPACE: STRUCTURAL CONSIDERATIONS

Structural considerations

- A modular approach is proposed to construct, in principle, an arbitrary large structure.
- A hexagonal shaped mirror is constructed using a number of individual tensioned planes of equilateral triangles, connected at corners. The triangles will support the stretched reflecting film. A metalized light-weight thin polyimide film is used as reflective surface [1].



[1] O. Çelik, A. Viale, T. Oderinwale, L. Sulbhewar, C. R. McInnes, Enhancing terrestrial solar power using orbiting solar reflectors, Acta Astronautica 195 (2022) 276–286."

Structural considerations

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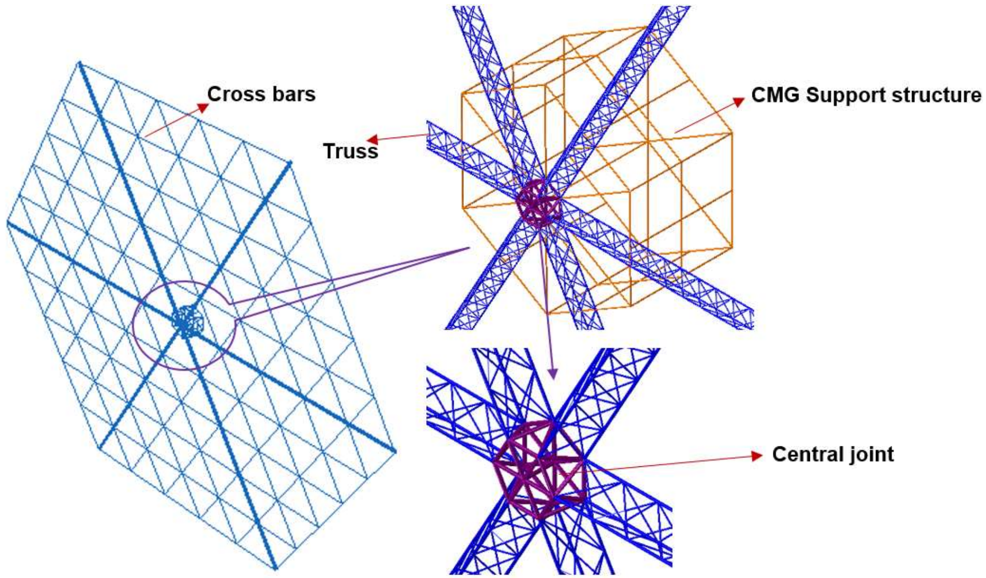
- The present design is modified to meet the areal density constraints for the gossamer structure.
- Diagonal of the hexagon are strengthened by employing truss beam structure and are connected at the centre using a central joint. Cross bars support the reflector film.
- A lightweight Kapton™ film is used as the reflecting material while lightweight composites for the support structure.
- The size of the reflector is governed by the control capacity of CMGs employed. A typical design with 250 m side of hexagon and 5 levels is presented in Ref. [1].
- Apart from modularity, this design facilitates on-orbit assembly, standardized quantity production, ease of manufacturing, easy maintenance and prevents the tear propagation. And above all, this can be achieved using present day technology.



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DEVELOPMENT SYNERGIES: IN-ORBIT MANUFACTURING

In-Orbit Manufacturing

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- Challenge to deploy such a large structure in-orbit.
- Ability to manufacture in-orbit would be game-changer for both reflector and also control actuators.
- SpiderFab™ provided a means by which in space structures could be assembled [1]. Follow-on MakerSat will launch in 2025 on OSAM-1.
- Redwire Space developing the Archinaut™ in-orbit 3D printer [2].

Image credit: Tethers Unlimited/NASA
Redwire Space

[1] R. P. Hoyt, Spiderfab: An architecture for self-fabricating space systems, in: AIAA Space 2013 conference and exposition, 2013, p. 5509.

[2] E. R. Joyce, M. Fagin, P. Shestople, M. P. Snyder, S. Patane, Made in space archinaut: Key enabler for asteroid belt colonization, in: AIAA SPACE and Astronautics Forum and Exposition, 2017, p. 5364.

SOLAR SAILING: ADDITION OF A SCIENCE PAYLOAD

SOLSPACE Reflector as a Solar Sail

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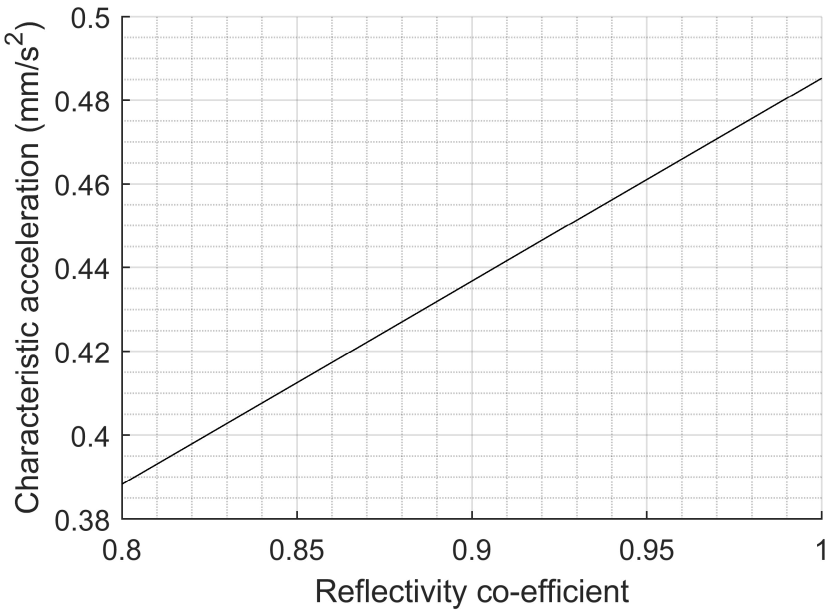
SOLSPACE 250 m reflector characteristic acceleration, with reflector mass = 3051.5 kg



Addition of a science payload

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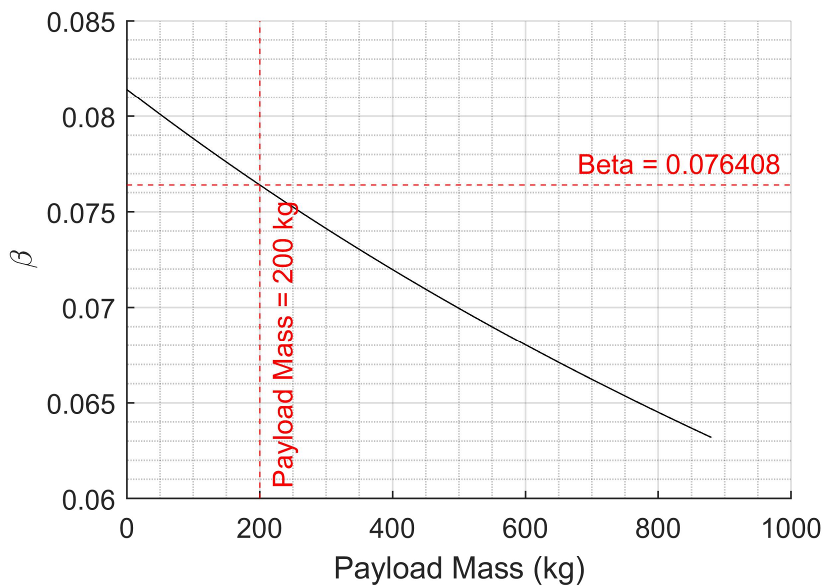
Effect of additional mass on 250 m hexagonal sail performance, with sail mass = 3051.5 kg



Approximate time to Earth escape

- $\tau = \frac{2805}{\sqrt{637}}$ [1]
- h is the initial orbit altitude [km]
- β is the sail lightness number
- From 900 km orbit, with science payload of 200 kg:

$$\boldsymbol{\tau = 430.52} \textbf{ days}$$

- From Earth escape, approx. 250 days to transfer to Mercury [2].

[1] C. R. McInnes, Solar Sailing: Technology, Dynamics and Mission Applications. Chichester: Springer-Praxis, 1999.

[2] B. Dachwald, (2004). Minimum Transfer Times for Non-perfectly Reflecting Solar Sailcraft. Journal of Spacecraft and Rockets, 41, 693-695.

Addition of a science payload

- The SOLSPACE project envisages large constellations of OSRs in orbit, servicing multiple solar PV farms around the globe.
- Given the large number of reflectors being constructed, the cost to purchase a single reflector from this large production run would be relatively small, compared with developing and manufacturing a dedicated platform for a single task.

SOLAR SAILING: NON-TERRESTRIAL REFLECTORS

Non-Terrestrial Reflectors

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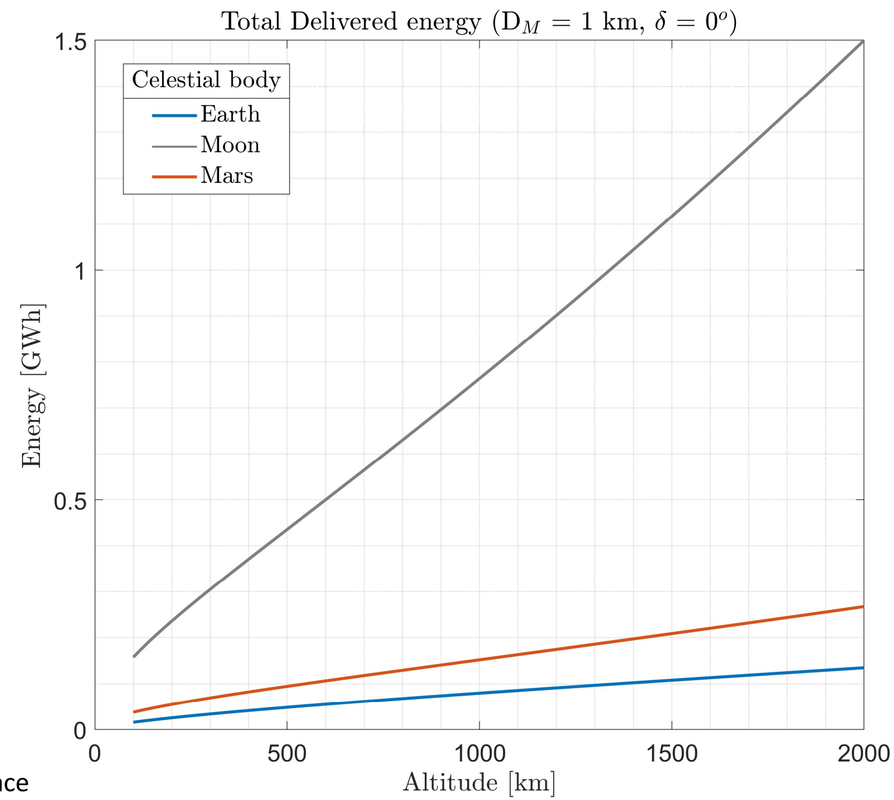
- The quantity of energy delivery is higher on the Moon and Mars than on the Earth due to [1]:
  - Absence of (for Moon) and thinner (for Mars) atmosphere
  - Smaller size of the Moon and Mars, which results in slower orbits, longer pass duration and energy delivery
  - Angle subtended by the Sun is smaller at Mars, resulting in a smaller solar image, higher energy density
  - This does not consider finite PV farm size, just projected solar image.



[1] Çelik, O., & McInnes, C. R. (2022). An analytical model for solar energy reflected from space with selected applications. Advances in Space Research, 69, 647–663.

Non-Terrestrial Reflectors

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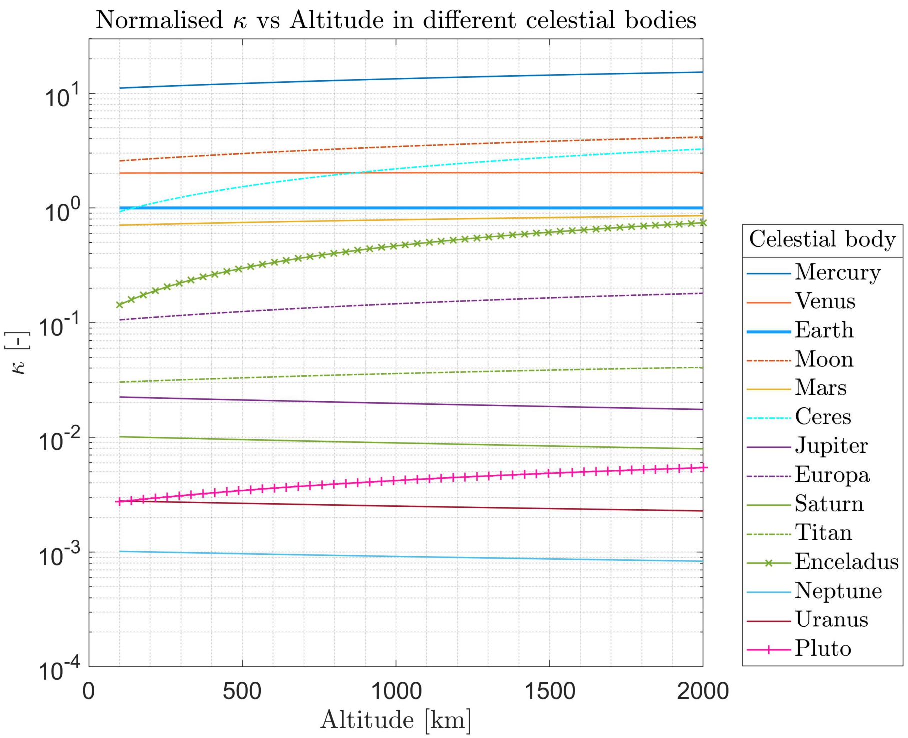

- When no atmosphere is considered, these results are scalable across the solar system [1], for example:

  Energy delivery may be higher at Ceres than that of the Earth beyond ~300 km altitude, and than that of Venus beyond ~700 km

$$\kappa = \frac{1}{\rho_{sun}^2}\sqrt{\frac{(R+h)^3}{M}}\beta = \frac{1}{\rho_{sun}^2}\sqrt{\frac{(R+h)^3}{M}}\arccos\frac{R}{R+h}$$

[1] Çelik, O., & McInnes, C. R. (2022). An analytical model for solar energy reflected from space with selected applications. Advances in Space Research, 69, 647–663.

SUMMARY

Summary

- SOLSPACE envisages large OSRs in Earth orbit which can augment the productivity of terrestrial solar PV farms.
- A reference architecture has been presented in the literature for such a system.
- Ongoing work will establish effects of flexible structure, pointing errors on the system performance.
- Laboratory scale testing to begin in late 2023.
- SOLSPACE and solar sailing would mutually benefit from further advances in in-orbit manufacturing.
- Each reflector can be adapted to become a high-performance sail and perform science missions, either at the Earth or another body.
- Alternatively, reflectors can be sent throughout the solar system, to provide their services in support of non-terrestrial missions/infrastructure.

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Thank you

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DEVELOPMENT SYNERGIES: ATTITUDE CONTROL ACTUATORS

Attitude Control Actuators

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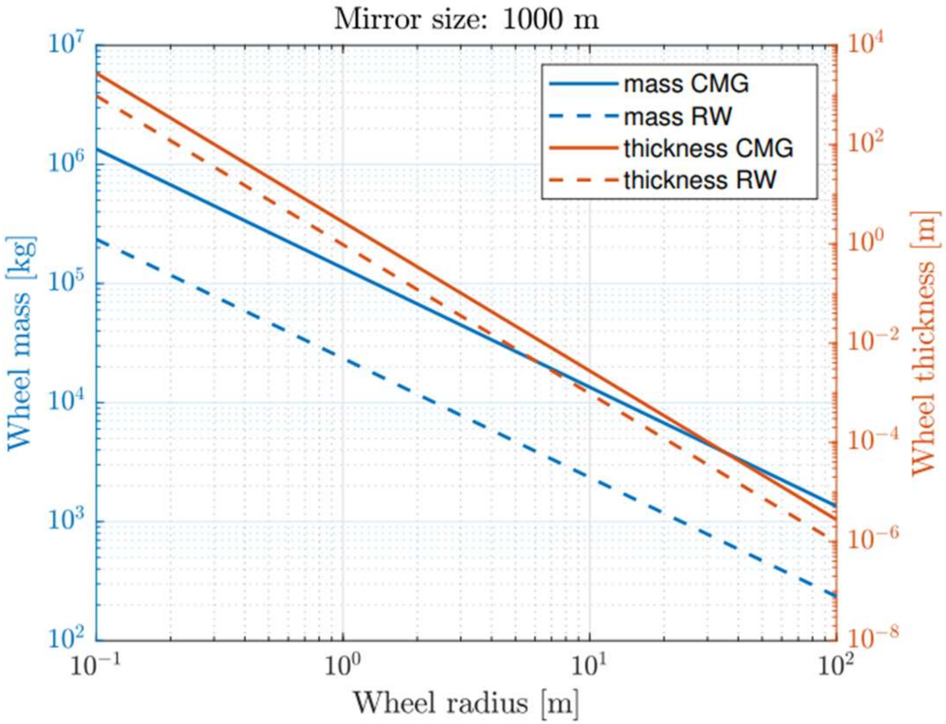
- Inertia scales with fourth power of reflector side length.
- As size of reflector increases, there will be large increase in size of actuators required to provide the required torques.
- For given torque requirements, CMG required mass approx. 5.7 times higher than reaction wheels [1].



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Attitude Control Actuators

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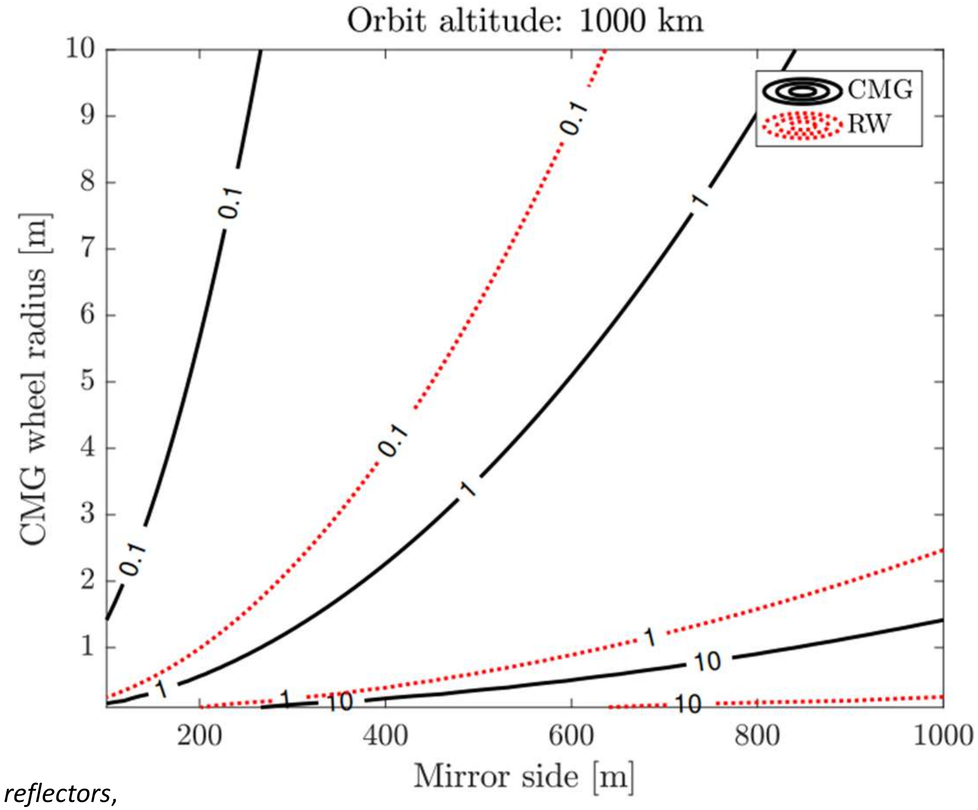
- For very large reflectors, wheel radius becomes excessive for $^{m_w}/_{m_r} < 1$.
- For demanding slew manoeuvres, SRP-based actuation cannot provide required torques to very large structures [1].
- Large sails and SOLSPACE reflectors would mutually benefit from advances in large actuators.



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