SBSP Interaction of Structural Dynamics with Orbital Mechanics

Final Presentation

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- Scope & Objectives
- Overview of Work Packages
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    - Orbital Loads
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    - Perturbation Analysis
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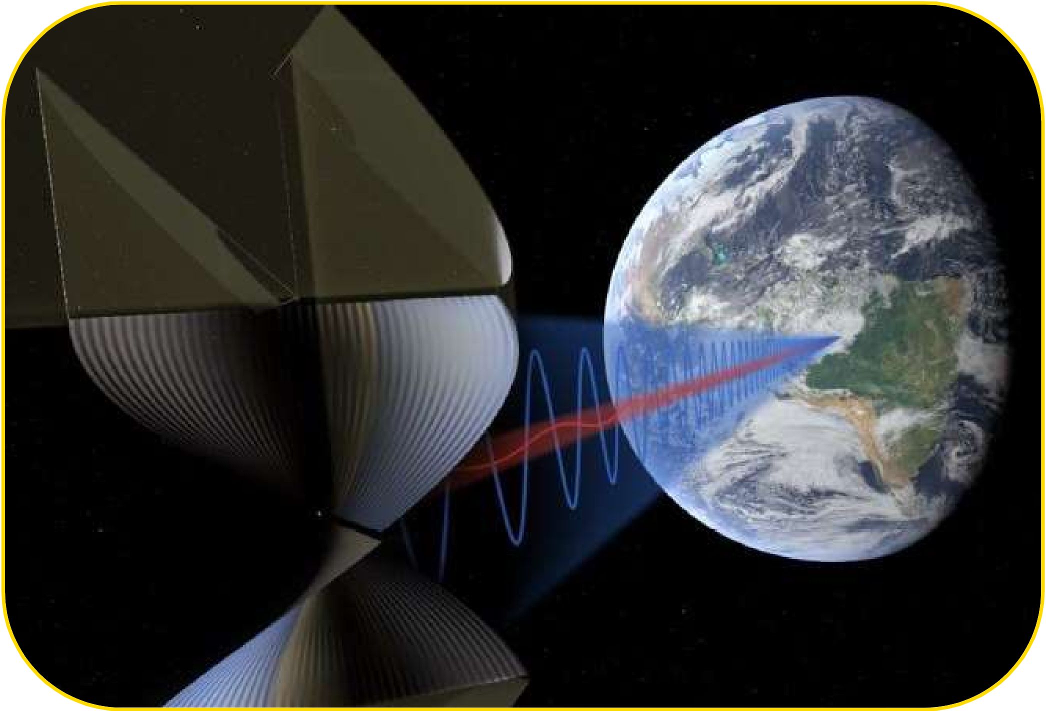
- Conclusions & Recommendations

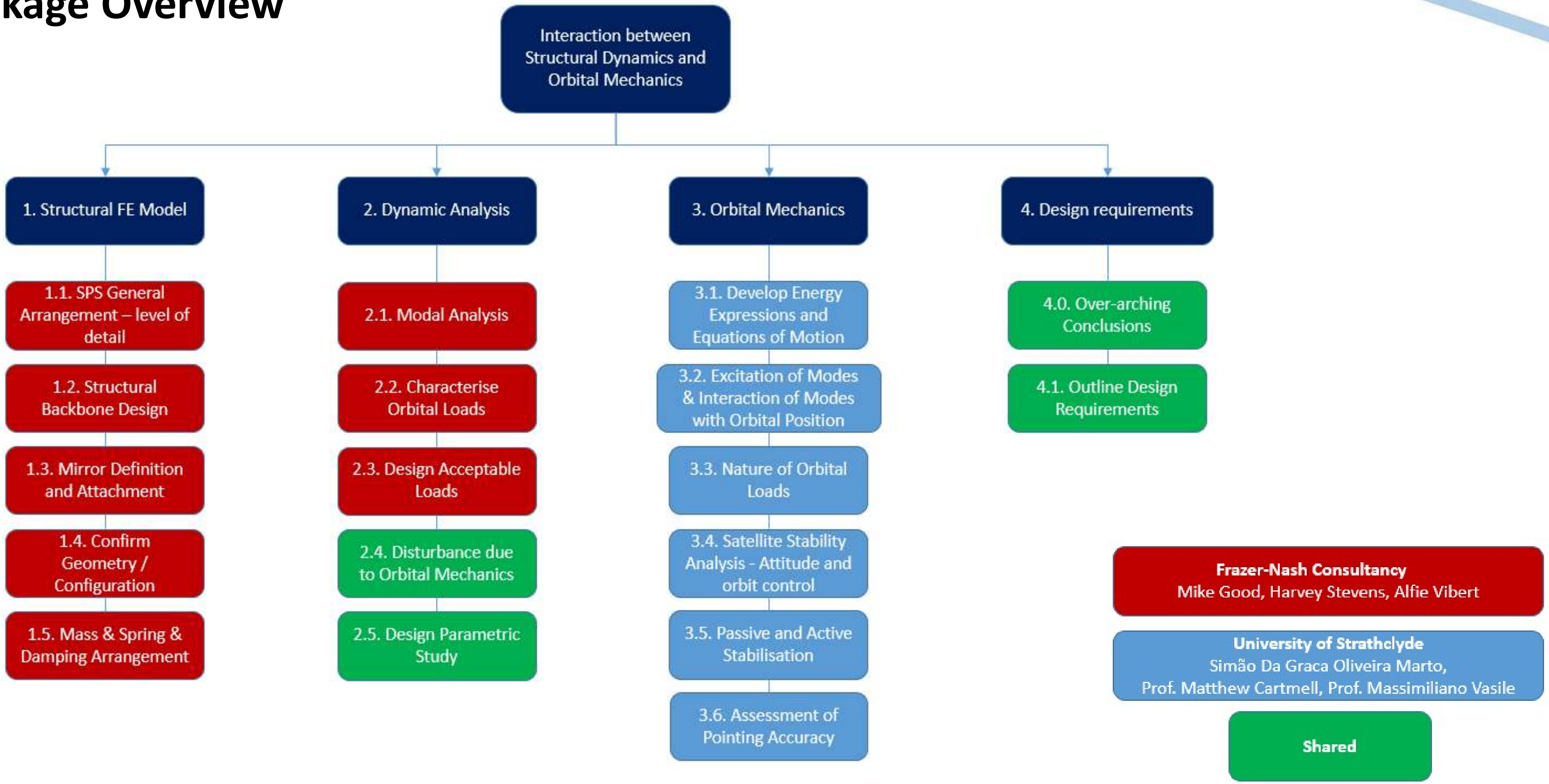


Project Objectives

1. Investigate the magnitude of coupling between the structural dynamics and orbital mechanics of Solar Power Satellites (SPSs)
2. Quantify the potential disturbance to the orbit of SPSs
3. Identify trends in the structural response for a range of design parameters
4. Devise outline design guidelines for the SPS structure to minimise the disturbance to their orbits

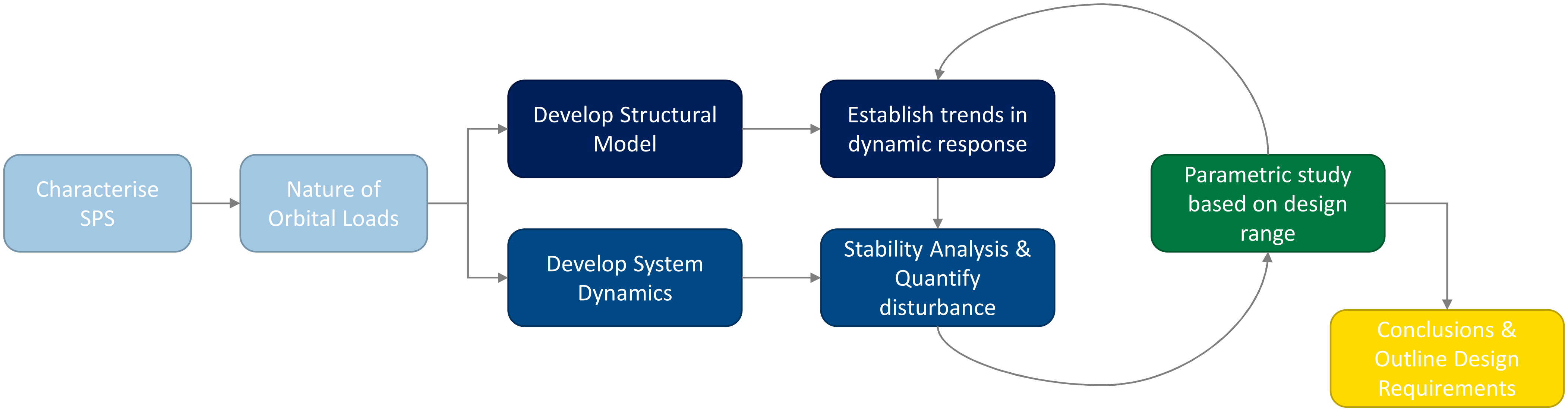
The coupling between structural dynamics and orbit mechanics is a key consideration in the development of a Solar Power Satellite. Our research follows a comprehensive and novel approach that aims to quantify the disturbance to the orbit of Solar Power Satellites and outline a set of design guidance for an SPS spacecraft.

Work Package Overview



Project Overview

- The project workflow progresses from the characterisation of the SPS structure and an understanding of the orbital loads to the development of two analytical tools.
- These analytical tools have been used to study the interaction between the orbital mechanics and structural dynamics and derive a set of outline design requirements.



1 Characterise Solar Power Satellite

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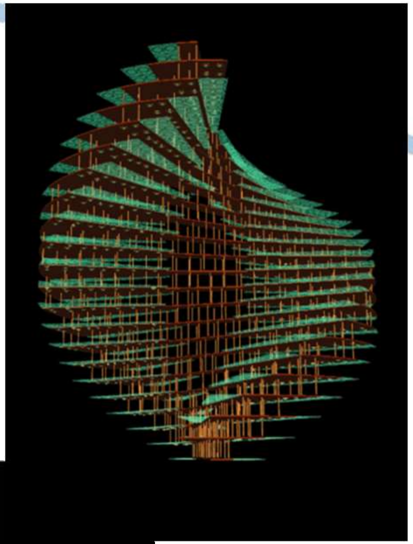
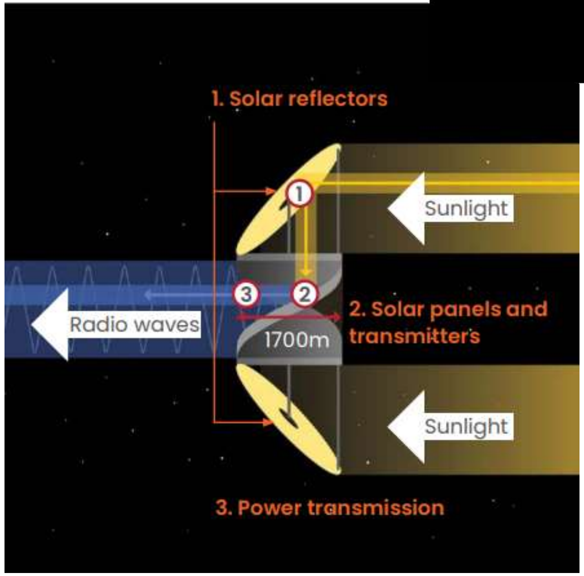
Study Concept - CASSIOPeiA

- CASSIOPeiA concept with the “2 sun” configuration was selected as the basis for this study.
- Design details are based on information provided by Ian Cash at IECL, and summarised in Frazer-Nash’s SBSP engineering feasibility report.
- The design comprises:
    - Two elliptical solar reflectors;
    - A helix constructed in a stepped arrangement, which supports the PV panels and antennae;
    - Structural frame, which fixes the components relative to one another.
- From the outset some basic design information was available for the helix and reflectors. However, no arrangement or design detail was available for the structural frame.

CASSIOPeiA	
Power	**2GW**
Diameter	~2 km
Length	**6 km**
Mass	2,000 tonnes

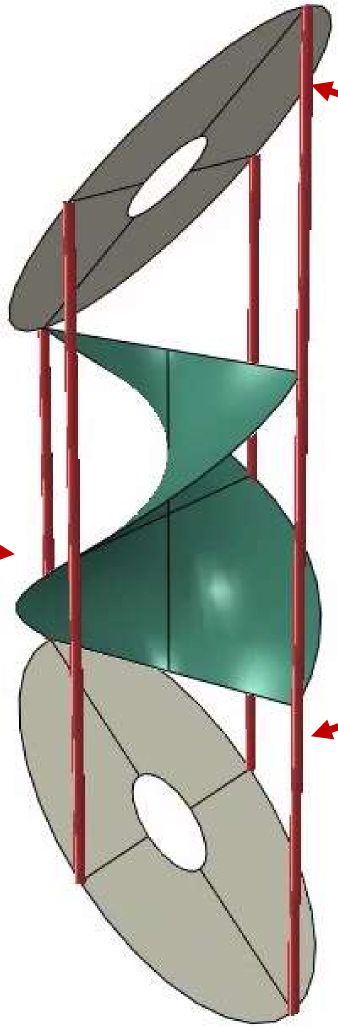




Study Concept

Legend
- Supplied
- Assumed
- Calculated

Helix
- Kapton polyimide film
- Mass = 1500 te
- E = 0.02 GPa (assumed to be several orders of magnitude lower than the reflectors)
- ν = 0.3
- Thickness = 1 m
- ρ ≈ 0.283 kg/m^3 (this has been calculated to achieve the target mass given the assumed dimensions)



Reflectors (x2 – top and bottom)
- Reflective film stretched over a carbon fibre frame
- Mass = 150 te (combined mass of mirrors and frame)
- Assumed thickness of 1 m
- ν = 0.3
- E = 200 GPa (assumed to be comparable to steel)
- ρ ≈ 36x10^{-3} kg/m^3 (this has been calculated to achieve the target mass given the assumed dimensions)

Structural Beams
- Thin wall carbon fibre tube
- Assumed 1 m diameter, 50mm wall thickness
- ρ = 83.8 kg/m^3 (representative of typical carbon fibre)
- E = 200 GPa (assumed to be comparable to steel)
- ν = 0.3
- Mass = 200 te (calculated from assumed values)

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2 Orbital Loads & Thruster Loads Summary

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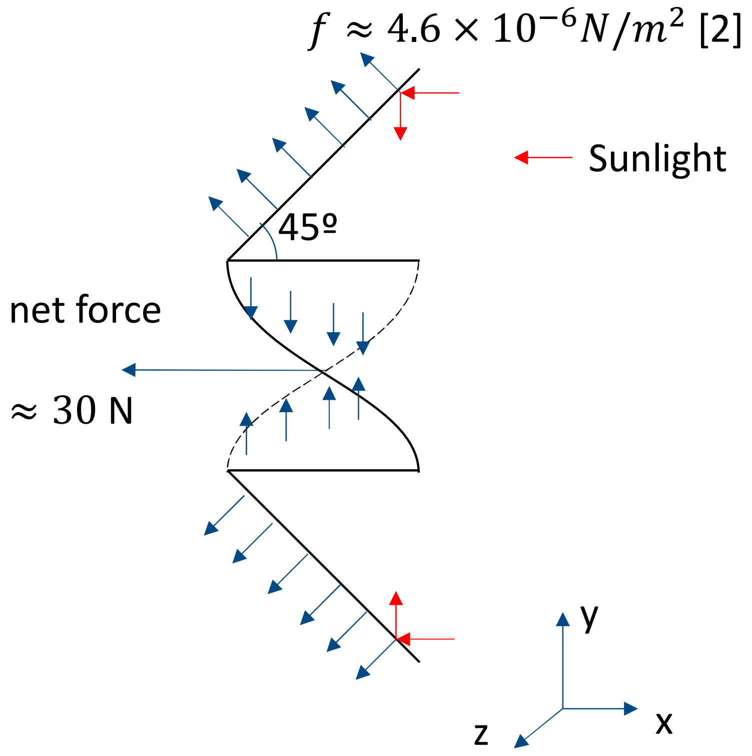
Orbital Loads

- The orbital loads are forces applied on the SPS, and can cause:
  - orbital effects, through their resultant force
    - E.g.: Spherical potential, third body effects, Solar Radiation Pressure (SRP) force
  - structural deformation, through their variation along the structure
    - E.g.: Gravity gradient, SRP force

- If a resultant force varies with the deformation of the SPS, it may cause an interaction between structural and orbital dynamics
  - The SRP force is the most significant in this regard

- If a structure deforming load varies along the orbit, it may cause an interaction between structural and orbital dynamics

Solar Radiation Pressure



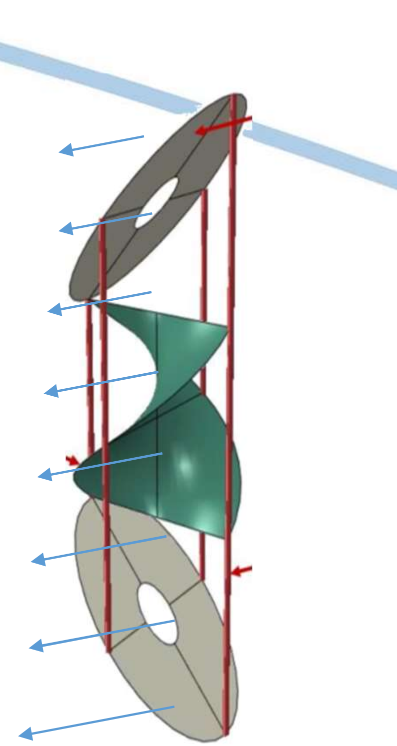
- The SPS captures sunlight, which carries an amount of linear momentum and results in a force of around 40N.
- Compared with typical satellites, even other SPS designs, the baseline CASSIOPeiA design has a high area-to-mass ratio [1], and so the SRP force has significant effect in its orbital dynamics.

SPS	A/m [m^2/kg]
Cylindrical	0.15
Abacus	0.40
ISC	0.87
CASSIOPeiA	3.1

- This effect causes a precession of the orbital plane and of the line of apsides, causing the eccentricity of orbit to reach at least 0.035, introducing some variation in the longitudinal direction of the SPS.
- As the SPS stays with fixed attitude with respect to the Sun, this force does not vary, unless the structure deforms.

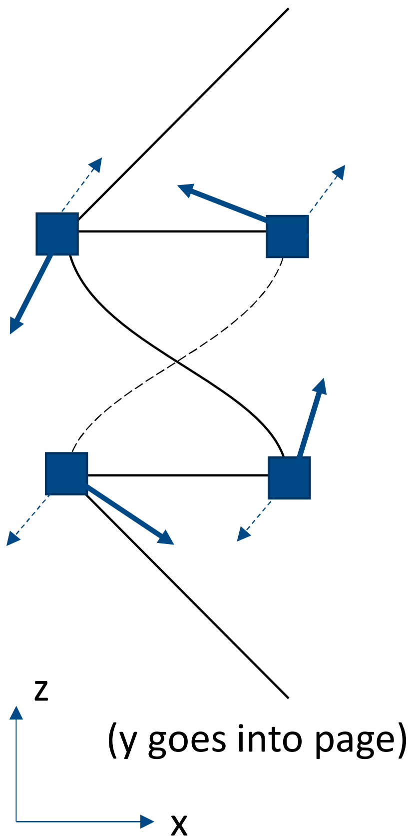
Gravitational gradient

- The gravitational gradient across the SPS is can be approximated using the first and second order terms of the Taylor expansion around the center of mass [3]:
  - $g_1 = \frac{\mu}{R_C^3}(2x, -y, -z)$
  - $g_2 = \frac{3\mu}{R_C^4}\left(\frac{1}{2}y^2 + \frac{1}{2}z^2 - x^2, xy, xz\right)$
- This load has a period of half an orbit, or around 12h for GEO
- It also produces a torque that introduces a need for attitude control, proportional to $I_{xx} - I_{zz}$, that is highly significant
- The g_2 component, unlike g_1, produces a resultant force G_2 that varies with the attitude with respect to the Earth, but this was found to be negligible



Orbit altitude	g1 [m/s^2]	g2 [m/s^2]	G2 [g]
LEO (~500km)	5×10^{-3}	2×10^{-6}	1×10^{-7}
MEO (~5000km)	1.1×10^{-3}	2×10^{-7}	4×10^{-8}
GEO (~35,786km)	2×10^{-5}	1×10^{-9}	3×10^{-9}

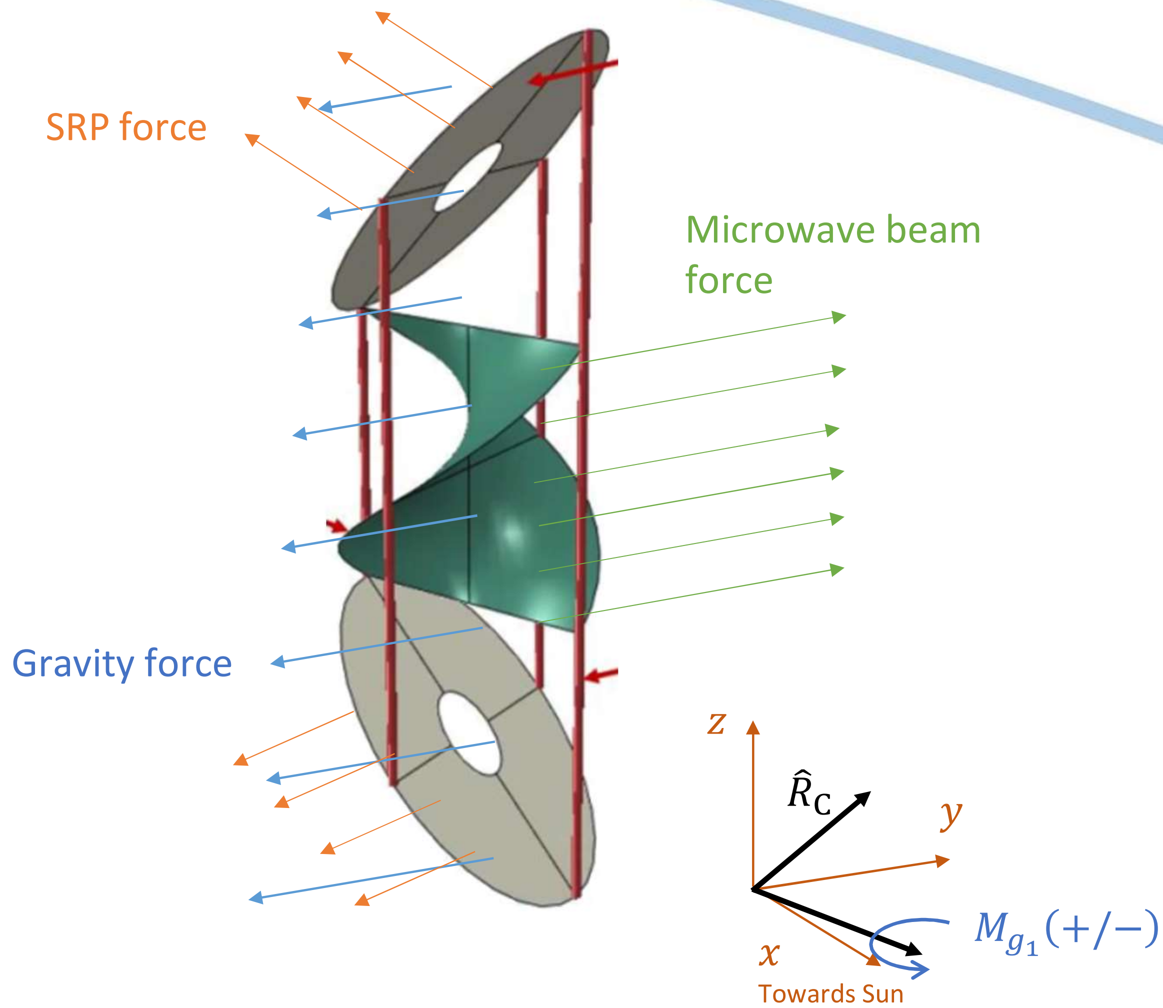
Attitude Control



- Thruster forces are required to counteract the gravity gradient torque
  - Making $I_{xx} = I_{zz}$ would require adding thousands of tonnes of mass or other significant changes to the design
  - Momentum wheels would have to be extremely large to be able to have the necessary momentum storage
  - This leaves thrusters as the only viable solution for attitude control
- The thruster forces at each corner of the helix are dependent on the Earth's position, and add to the loads applied on the structure

Microwave beam force

- In addition, there is also the microwave beam force
    - A 50% transmission efficiency results in a microwave force of 15N
    - Assuming this force is uniformly distributed, this gives a pressure of $2.3 \times 10^{-6} N/m^2$, similar to solar radiation pressure.



Orbital Loads Summary

Body Forces	Maximum Body Force densities (m/s²)
Gravitational Gradient, g_1	**2×10^{-5}**
Gravitational Gradient, g_2	1×10^{-9}
J2	1×10^{-9}
J3	2×10^{-13}
C22	1×10^{-9}
Third Body – Sun	10^{-10}
Third Body – Moon	10^{-10}
Variation of g_1 due to eccentricity	$4e \times 10^{-5}$ e (1.6×10^{-6})

e: eccentricity

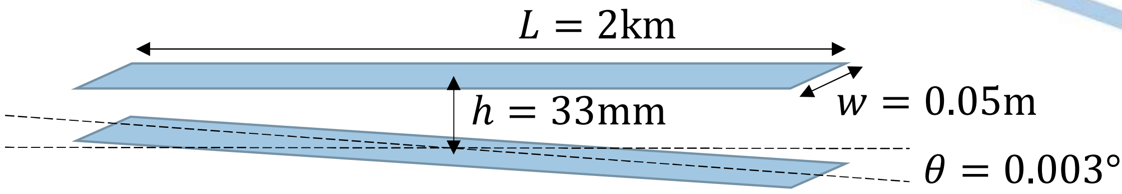
Surface Forces	Maximum Surface Pressure (N/m²)
SRP	**4.6×10^{-6}**
Earth Albedo + IR	4.6×10^{-8}
Microwave beam *	**2.3×10^{-6}**
SRP variation in orbit	5×10^{-9}

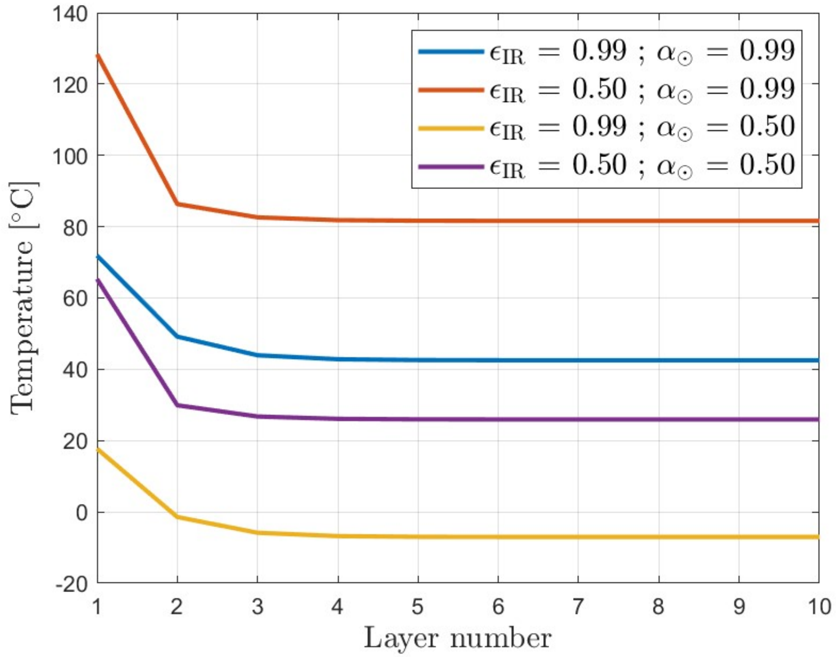
* Assuming the force is uniformly distributed over the profile area of the helix.

Note that the forces shown in bold are most notable in magnitude

Thermal analysis

- A thermal model was run with purely radiative heat transfers
- Solar heat and the refrigerative effect of microwave beaming were considered
- Earthshine is negligible (1% of direct solar power) [4]
- The result is a very sharp temperature gradient near the first and last layers, and a nearly constant temperature elsewhere
- Thermal expansion makes the first and last layers around 0.1% longer than the others





3 Structural Modelling



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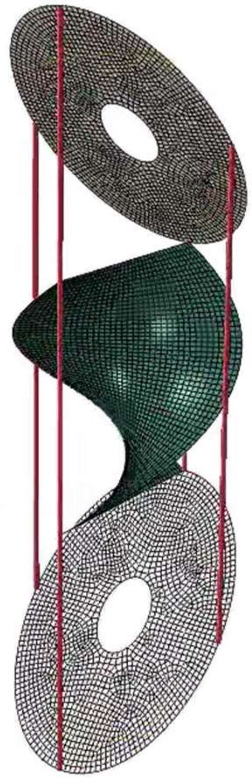
Structural Finite Element Model

A structural Finite Element (FE) model was developed for the purpose of carrying out the following analyses:

1. Modal analyses – to identify the global mode shapes and modal frequencies.
2. Static analyses – to quantify the static deformation of the SPS, where there is a notable separation between the excitation frequency and the response (modal) frequency.



FE model of the CASSIOPeiA concept developed as follows:

- Reflectors modelled as a shell surface (S8R and STRI65 elements)
- The helix modelled as a simplified shell surface (S8R elements)
- Structural beams modelled with 1D beams elements (B31 elements)
- Total number of elements: 7,026
- Total number of nodes: 20,951

Modal Analysis Results

First 20 Modes:

Frequencies of the six rigid body modes are less than 1e-5 Hz

Mode Number	Frequency (Hz)	Time Period (s)	Mode Number	Frequency (Hz)	Time Period (s)
1*	0	/	11	7.3 E-3	137
2*	0	/	12	7.6 E-3	132
3*	0	/	13	8.6 E-3	117
4*	0	/	14	9.1 E-3	109
5*	0	/	15	9.5 E-3	105
6*	0	/	16	9.9 E-3	101
7	2.2 E-3	445	17	10.9 E-3	91
8	2.4 E-3	409	18	11.0 E-3	91
9	3.9 E-3	255	19	11.1 E-3	90
10	3.9 E-3	254			

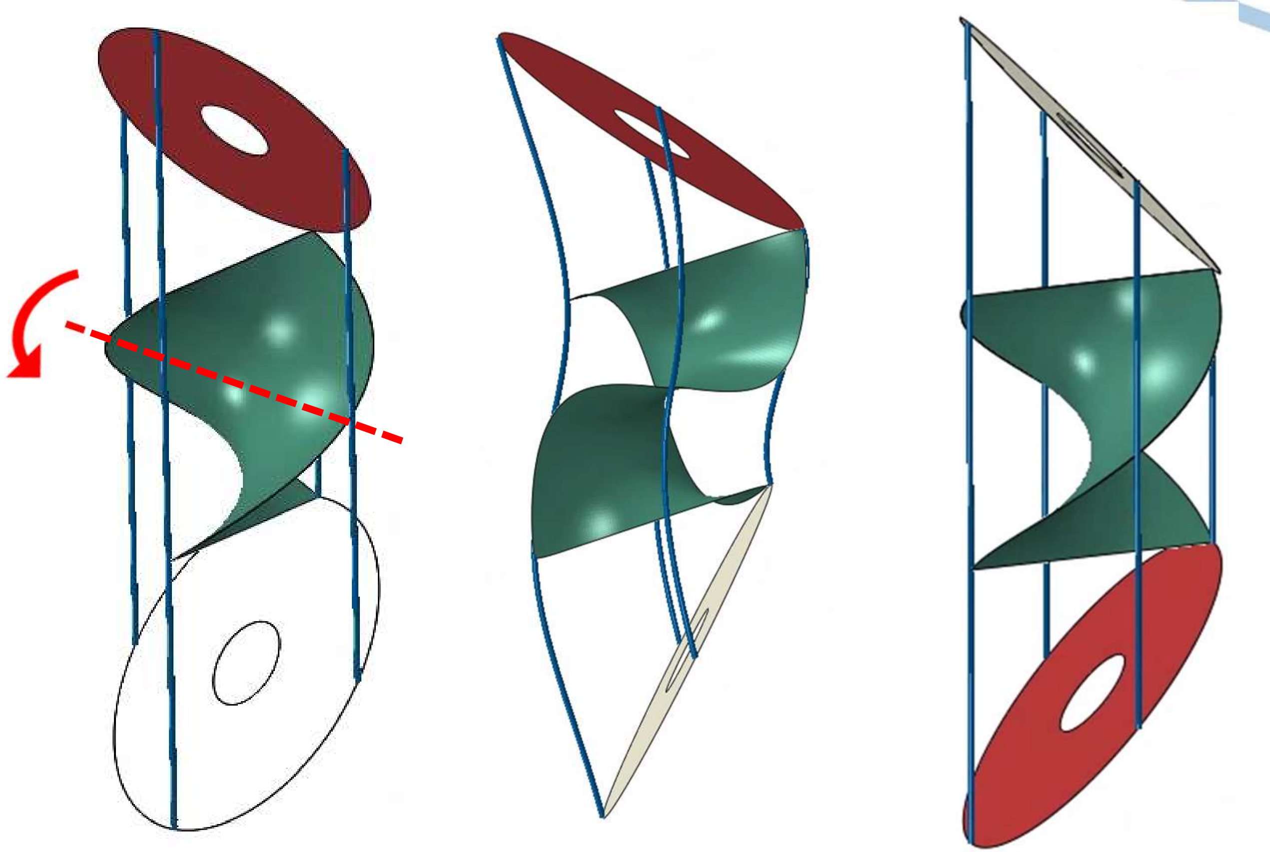
Period of orbital loads (Gravity Gradient loads) is approx. 12hrs, or 2.3e-5 Hz

* Indicates rigid body mode

Modal Analysis Results

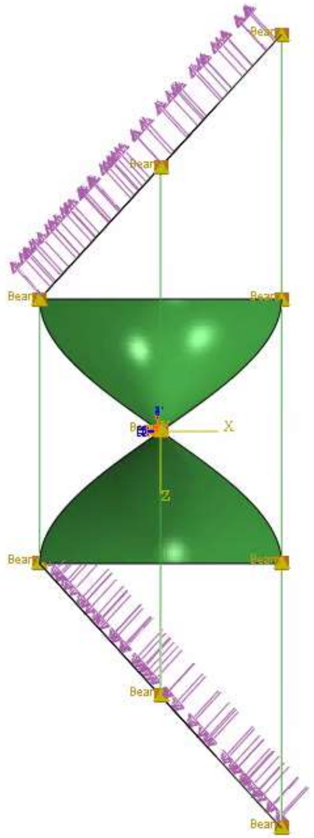
Mode 7 represents the first flexural mode shape.

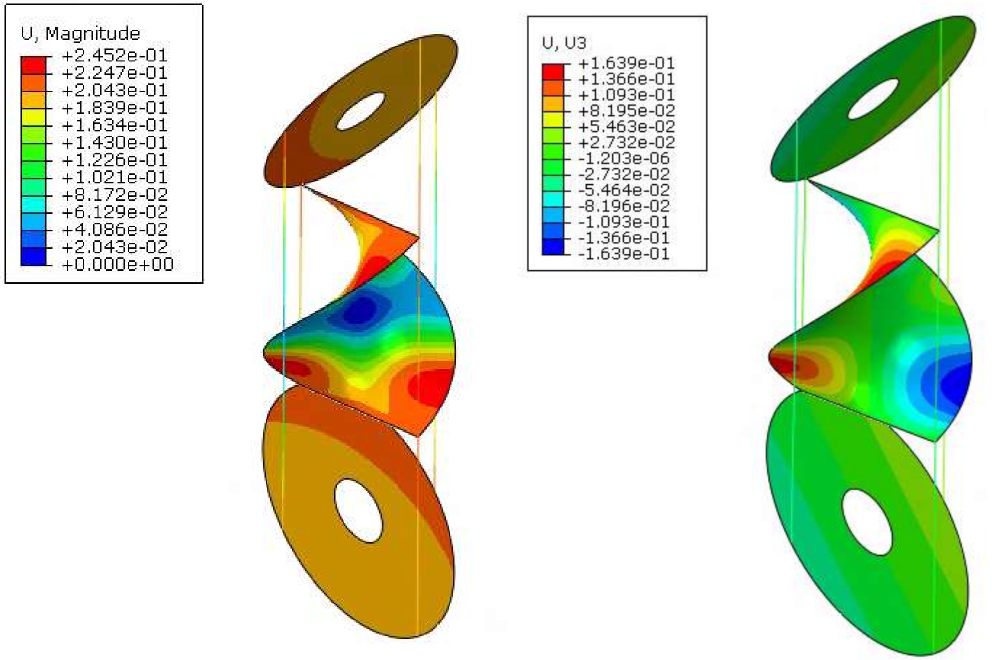
- A helix mode, where the reflectors rotate about the helix minor axis.
- The reflectors do not rotate relative to one another.
- Frequency of 2.2E-3 Hz (time period of 445 s).
- For reference, the excitation load has a period of 12 hours (i.e. a frequency of 2.3E-5 Hz).
- Therefore, there is notable separation between the excitation and response frequencies for the 'baseline' model



Deforming Forces that do not vary with Orbital Position

- Solar Radiation Pressure (SRP) is the only significant force that does not vary with orbital position.
- SRP applied as a pressure to the helix and the reflectors.
- Net force on helix (on the top and bottom surface) is zero.
- Pressure acting on reflectors seeks to bend the helix and cause misalignment of the reflectors.
- Maximum displacement is ~0.2m
- Negligible relative deflection between the two reflectors.

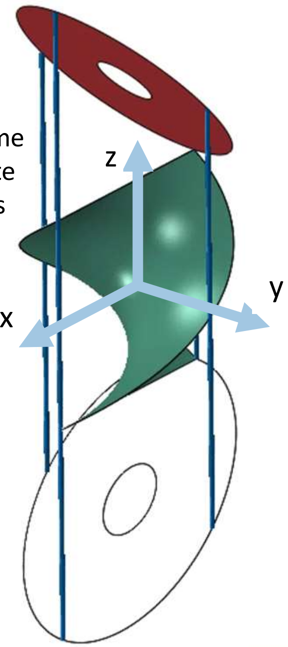


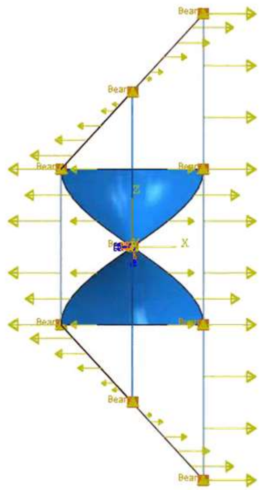


Deforming Forces that do vary with Orbital Position

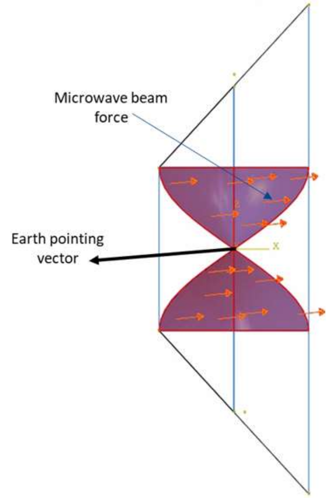
- The most significant forces that do vary with orbital position are gravitational gradient, microwave force and thruster forces.
- Analyses carried out for 2100 Earth positions (relative to the body frame). This includes 100 equally spaced positions on the local X-Y plane, repeated for 21 different equally spaced declinations between -23.4° and +23.4°.

Body frame coordinate directions

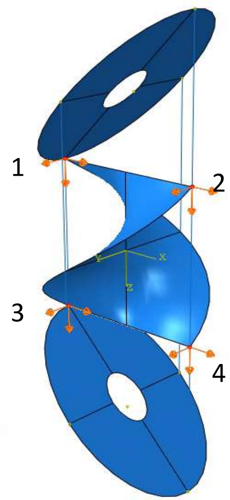




1. Gravitational accelerations in the three coordinate directions have been applied as a distributed gravitational load



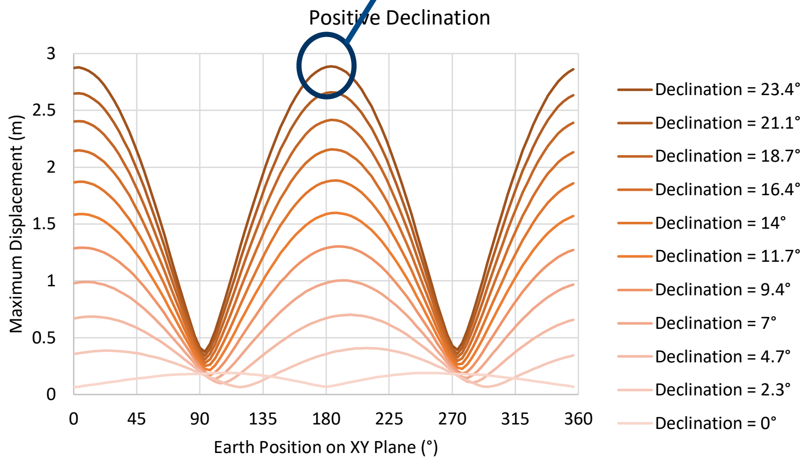
2. Microwave force of 15N acts in the opposite direction to the Earth pointing vector and has been applied as a surface traction

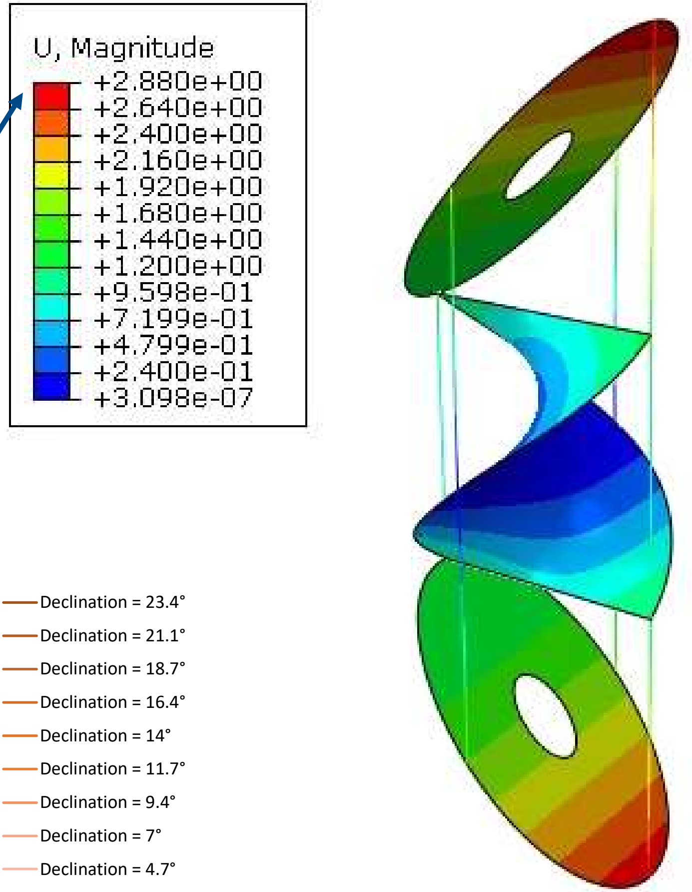


3. Thruster forces have been applied as concentrated loads in the three coordinate directions at the four corners of the helix

Deforming Forces that do vary with Orbital Position

- Deformations are greatest at maximum declination and when the Earth pointing vector is aligned with the local X-axis.
- Declination has greatest influence when the Earth pointing vector is aligned with the local X-axis.
- Maximum displacement anywhere on the structure is expected to be ~3m.
- The maximum displacement occurs at the tip of the reflectors.
- The maximum displacement is driven by the gravity gradient and thruster forces.





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4 SPS Perturbation Analysis (WP3)

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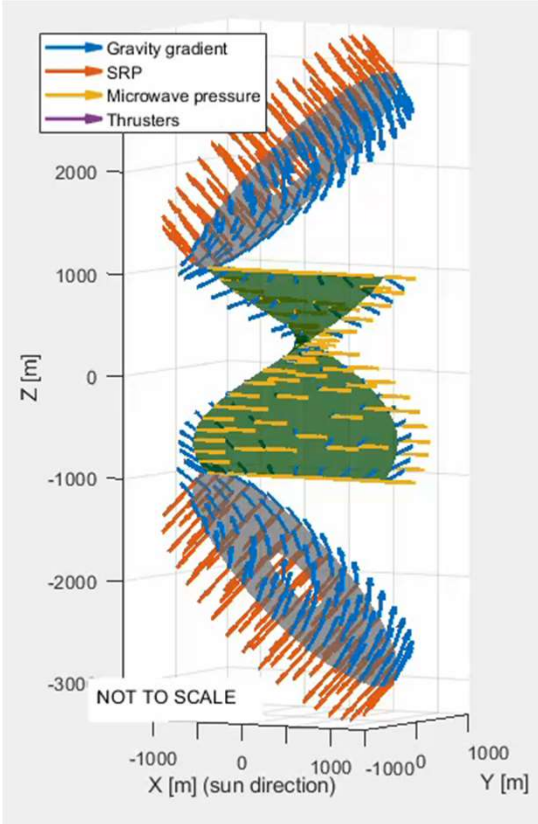
SPS Perturbation Analysis

- The following forces, as mentioned, can deform the spacecraft in a way that varies as the spacecraft moves in its orbit:
  - Gravity gradient force
  - Microwave force
  - Attitude control thruster forces
- Although in nominal conditions the SRP loads are constant, as the spacecraft deforms, its resultant force varies, possibly affecting the orbital dynamics
- These two effects lead to structural dynamic interactions
- This section outlines the toolset that has been developed to analyse this interaction

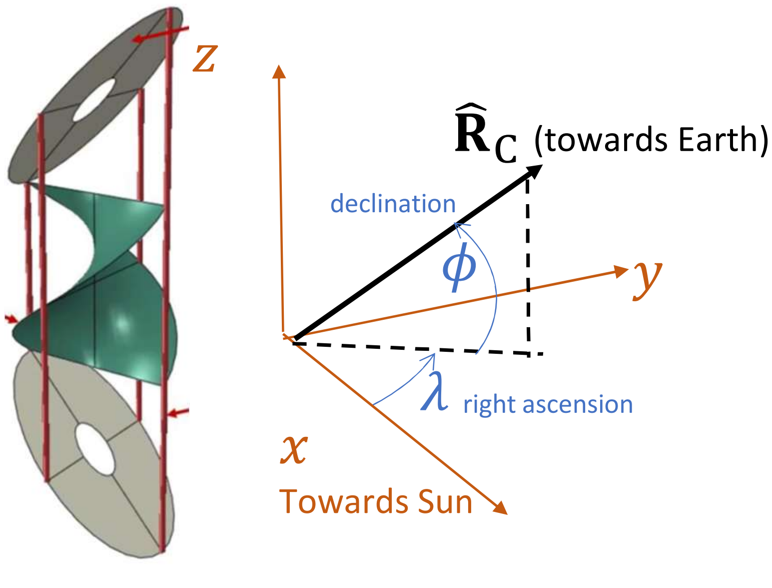


Perturbation on SRP due to distortion

- We write the total SRP force as a sum of a nominal component and one due to the distortion of the SPS:
- $\boldsymbol{a_{SRP}} = a_{SRP}\left(\begin{bmatrix}-1\\0\\0\end{bmatrix} + \boldsymbol{\gamma}(\hat{\mathbf{R}}_{\mathrm{C}})\right), \boldsymbol{\gamma} = \frac{\boldsymbol{F}_{def} - \boldsymbol{F}_0}{F_0}$
- where $\boldsymbol{\gamma}$ is a dimensionless vector which represents the direction and magnitude of this perturbation relative to the nominal value of the SRP acceleration.
- a_{SRP} is the nominal value of the SRP acceleration calculated previously
- Due to the time cost of FE analyses, we use a spherical harmonics model as a surrogate:

$$\boldsymbol{\gamma}(\phi,\lambda) = \sum_{l=1}^{\infty}\sum_{m=0}^{l} P_{l,m}(\sin(\phi))\big(\boldsymbol{C}_{l,m}\cos(m\lambda) + \boldsymbol{S}_{l,m}\sin(m\lambda)\big)$$

Acceleration in harmonics model on the SPS's frame

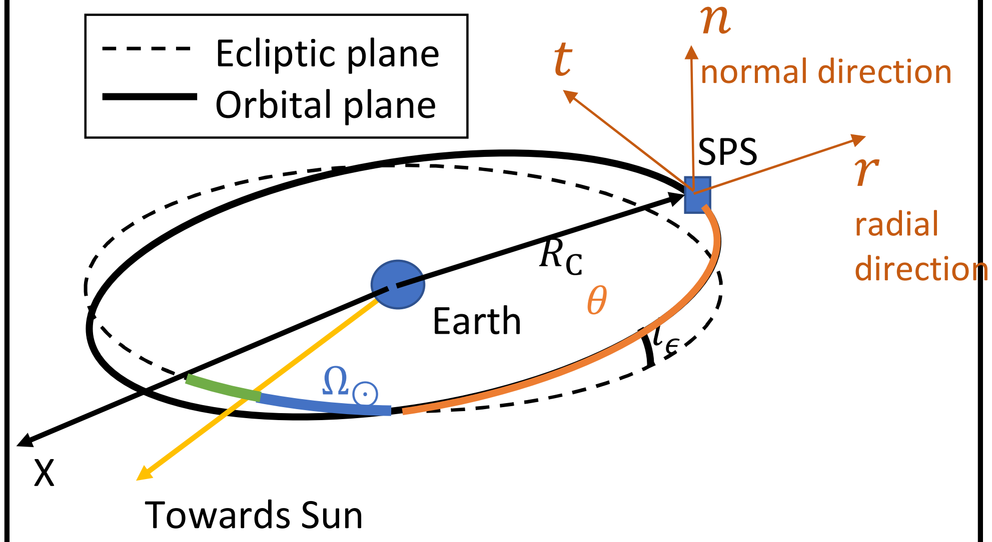


$$\boldsymbol{\gamma}(\phi,\lambda) = \sum_{l=1}^{\infty}\sum_{m=0}^{l} P_{l,m}(\sin(\phi))\left(\boldsymbol{C}_{l,m}\cos(\lambda) + \boldsymbol{S}_{l,m}\sin(\lambda)\right)$$

Acceleration in orbital frame

$$\gamma^{rtn} = \sum_m \widehat{\boldsymbol{C}}_m^{rtn}(\Omega_\odot, i_\epsilon)\cos(mL) + \widehat{\boldsymbol{S}}_m^{rtn}(\Omega_\odot, i_\epsilon)\sin(mL)$$

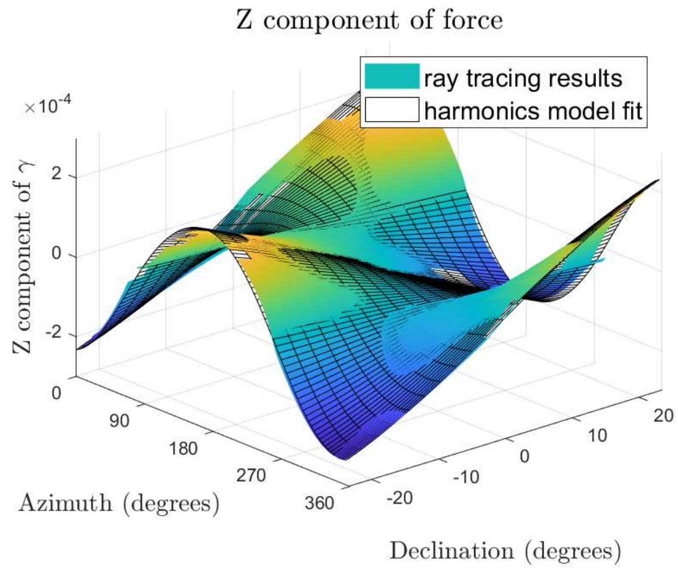
$$L = \Omega_\odot + \theta$$

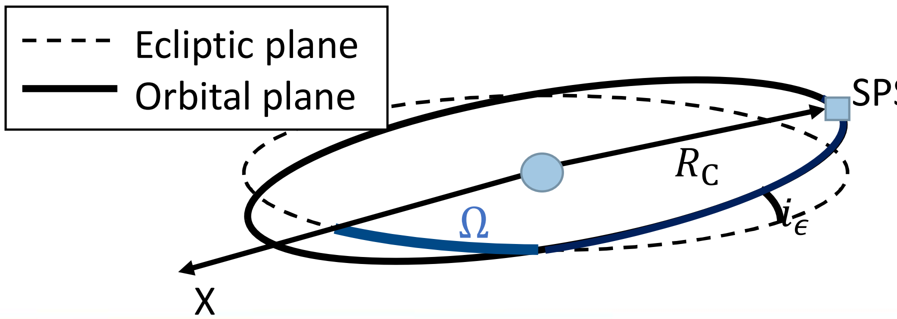


- The perturbing acceleration is more naturally represented in the SPS's frame. The VoP equations, which give the evolution of the orbit over time, are usually written with accelerations in the RTN frame or similar.
- This results in coefficients that are dependent on the orbital plane's orientation, resulting in secular and yearly variations

Harmonics Model Fit – baseline results

- The value of $\boldsymbol{\gamma}$ along x and y was found to be negligible. The z component is approximately:
- $\gamma^z \approx C_{10}^z \sin(\phi) - \frac{3}{2} C_{21}^z \sin(2\phi)\cos(\lambda) + \frac{1}{2} C_{30}^z \left(5\cos^3(\phi) - 3\cos(\phi)\right)$
- The C_{10}^z and C_{30}^z components introduce orbital precession
  - $\dot{\Omega} \approx k_{SRP} \frac{2C_{10}^z - 3C_{30}^z}{6\tan\left(\frac{i}{2}\right)} \approx 8 \times 10^{-6}$ rad/year
- The C_{21}^z component would cause a negligible variation in the eccentricity





5 Ray Tracing Study (WP3)

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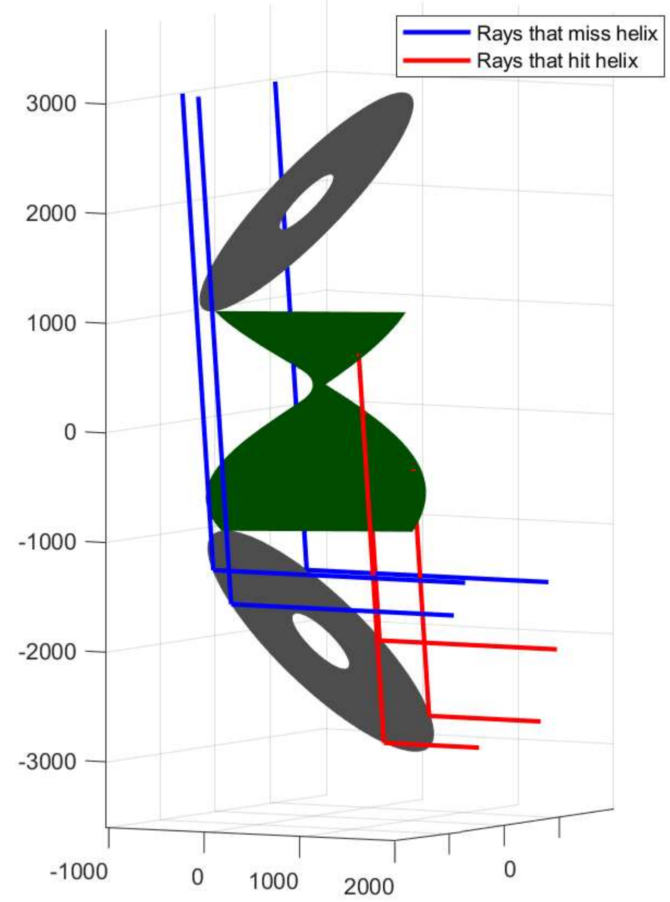
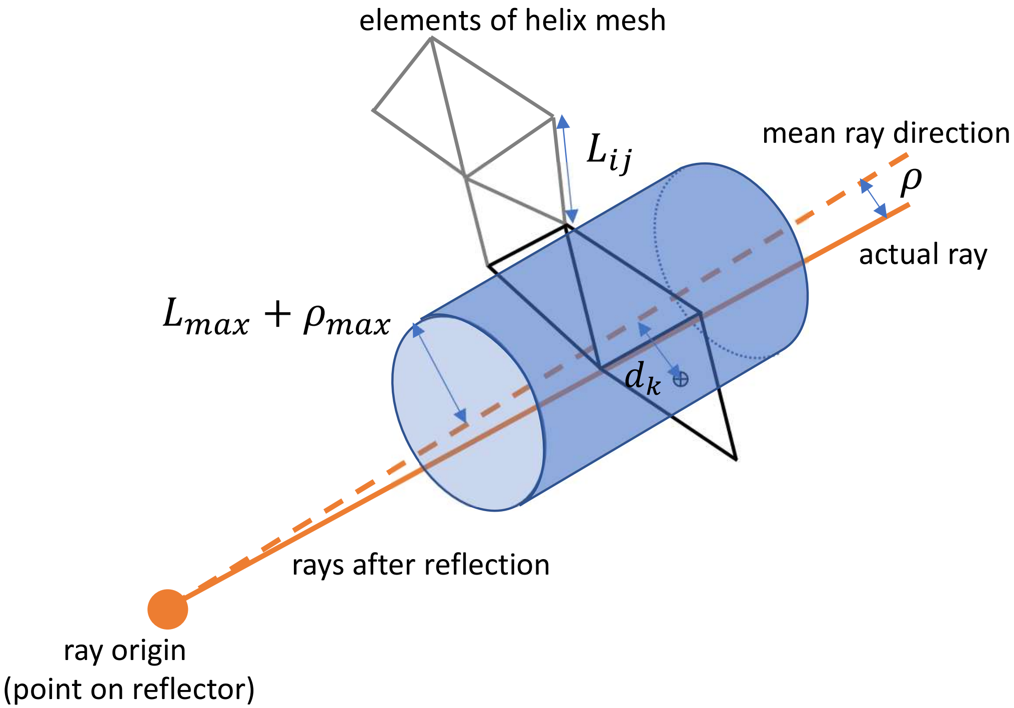
Ray Tracing Analysis

- To quantify the variation of the SRP force due to the deformation of the structure, a ray tracing analysis has been performed
- Due to the deformation, the rays may no longer hit the helix and instead miss it, creating a force in the vertical direction
- Ray propagation assumptions:
    - The Reflectors are purely reflective
    - The Helix is purely absorptive
- Variation of momentum in photons causes force



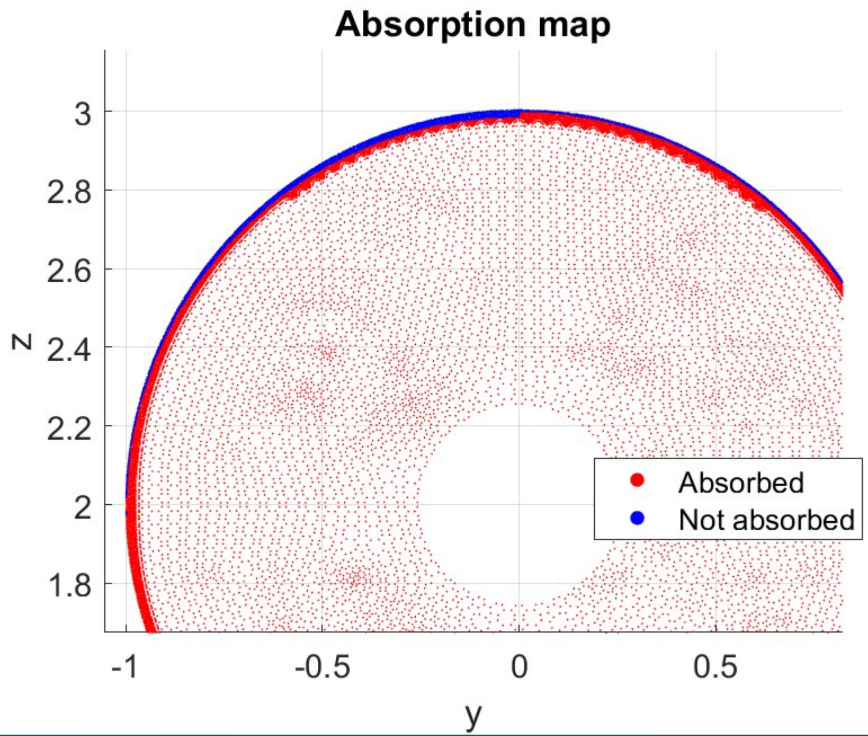
Ray Tracing Analysis – KD Tree Based Pruning



- Elements of the helix mesh that are too far away from the mean ray are not tested for collision with the ray.
- This pruning is done by projecting the CoMs of the helix mesh elements onto the plane perpendicular to the mean ray, and performing a KD-tree range search (using MATLAB's implementation) around the ray origin points
- For each ray, this prunes out all triangles for which
  - $d_k > L_{max} + \rho_{max}$

Ray Tracing Analysis - Results

- The majority of the variation in the resultant SRP force comes from the rays that no longer hit the helix due to the deformation of the SPS, which is why the rim of the reflector is sampled more densely.
- $\boldsymbol{\gamma = \frac{F_{def} - F_0}{F_0}}$
- X and Y components are negligible.



Ray Tracing Analysis - Results

- The magnitude of the force resulting from this deformation, for the baseline design of the SPS, was found to be very small, and so we do not expect significant orbital effects when compared with other orbital perturbations.

Perturbation	F/W for the resultant force [nondimensional]
Variation due to eccentricity	0.08
SRP	6.4×10^{-5}
J2	4×10^{-5}
Microwave beam*	3.2×10^{-5}
3rd body - Moon	1.6×10^{-5}
3rd body - Sun	7.4×10^{-6}
Earth Albedo + IR	3×10^{-7}
C22	5×10^{-8}
SRP variation in orbit	2×10^{-8}
J3	1.3×10^{-8}
γ	1.2×10^{-8}
Gravitational gradient	2×10^{-9}

6 Parametric Study

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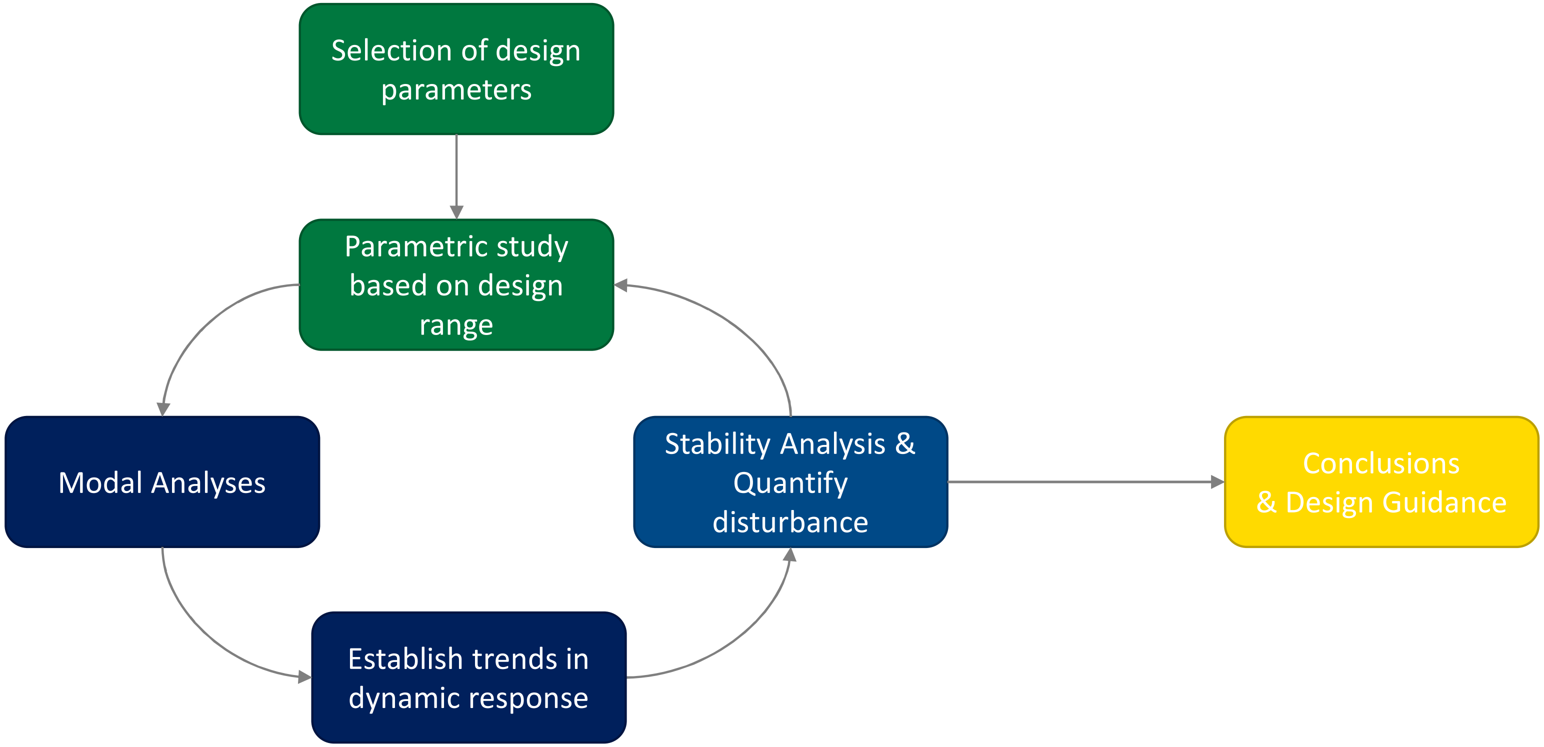
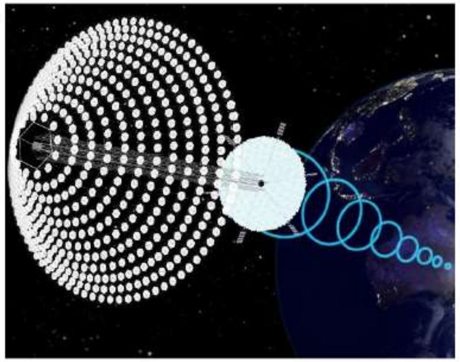
Parametric Study Overview





Consideration of Other SPS Concepts

- Common aspects between the leading SPS concepts have been reviewed, such that the conclusions of our study may be applicable to other SPS concepts (aside from CASSIOPeiA).
- Our comparison has focused on comparing the following aspects of a range of leading SPS concepts:
    - Mass
    - Mass distribution
    - Length
    - Operating Orbit

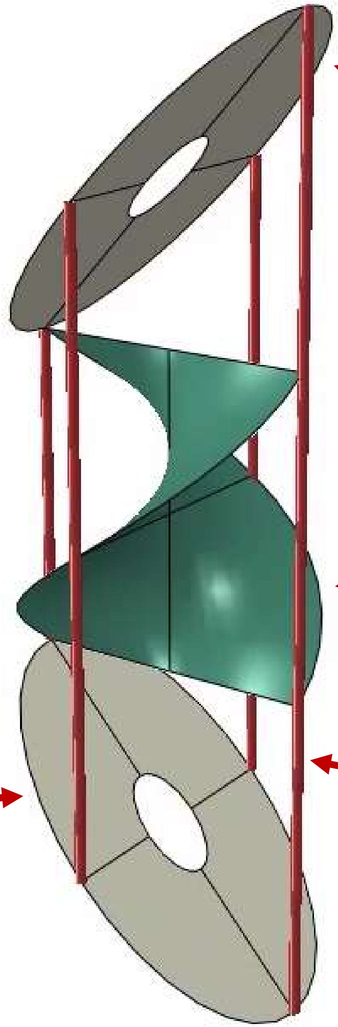
Concept	Mass (Tonnes)	Length (km)	Orbit	Mass Distribution	Notes
SPS-Alpha	8,000	13	GEO	Located at the ends	Gravity gradient stabilised. Mirrors are motorised.
CASSIOPeiA	1,500	6	GEO / GLP	Focused in the centre	No moving parts. Reflectors/antennae participate equally. Not restricted to circular orbits.
MR-SPS	10,000	12	GEO	Uniform	Motors used to align PV panels and antennae. Heaviest concept considered.
NASA Sun Tower	6,000	15	GEO	Uniform	Motorised collectors. Collectors spaced to minimise shadowing.

Parameters Considered

SPS Length
- Baseline helix length = 2 km
- Baseline total length = 6 km
- Other SPS concepts are notably longer

Total SPS Mass
- Total SPS Mass = 2,000 tonnes
- Other SPS concepts are much heavier

Reflector Stiffness
- Baseline E = 200 GPa
- Sparse structure may compromise stiffness



Mass Distribution (Reflector Mass)
- Baseline mass = 150 tonnes (per reflector)
- Reflector mass represents ~15% of the total SPS mass
- Mass distribution varies notably between the different concepts

Helix Stiffness
- Baseline E = 0.02 GPa
- Significant variation likely

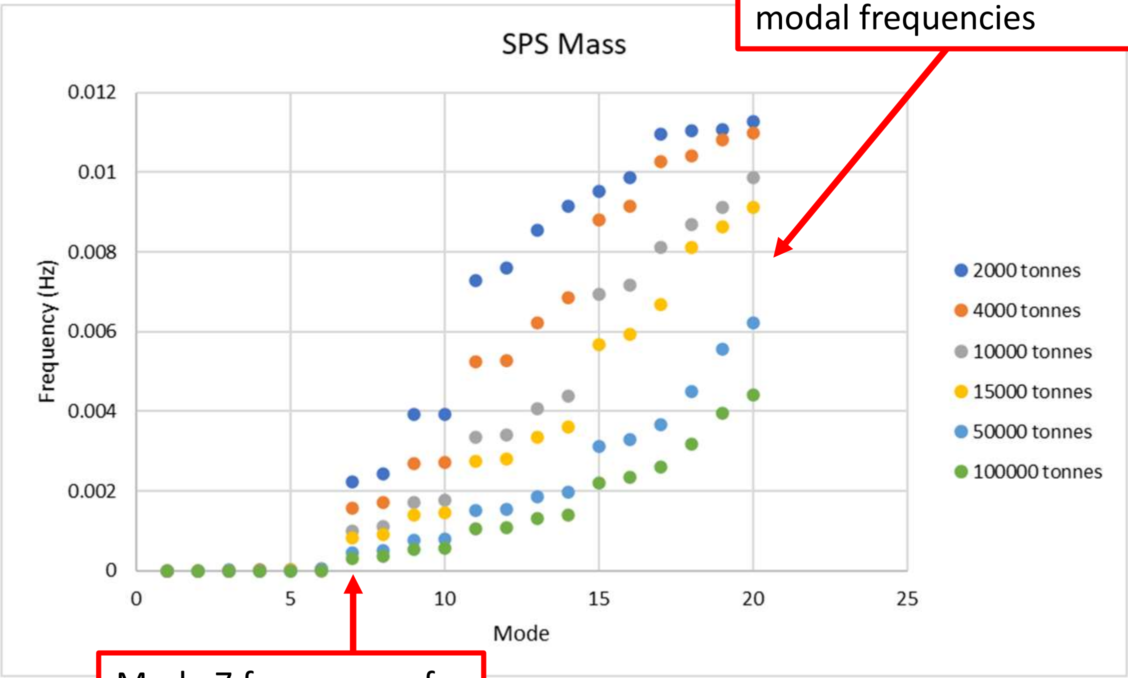
Structural Beam Stiffness
- Thin wall carbon fibre tube
- Baseline E = 200 GPa
- Significant variation likely

Modal Parametric Study: Total Mass

Increased masses were considered:

- To reduce the modal frequencies.
- To account for the additional structure that is likely to be required.
- Noting that other SPS concepts are much higher mass.

Total mass has a notable effect on reducing the modal frequencies



Mode 7 frequency of 3.2e-4 Hz for 100,000 tonnes

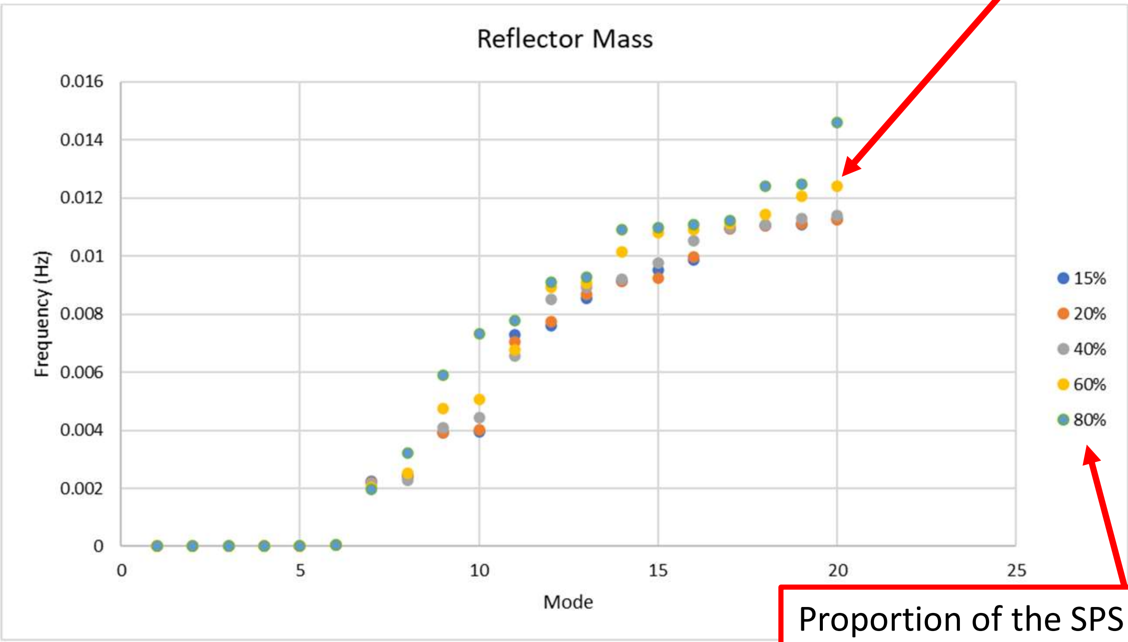
Fixed Parameters:
Total length = 6km
Mass distribution (densities uniformly scaled)
Helix, Beam and Reflector stiffnesses

Modal Parametric Study: Mass Distribution

An increased proportion of the mass in the Reflectors was considered:

- CASSIOPeiA has much of its mass focused at the centre
- To account for concepts where the mass is focused at the ends (e.g. SPS-Alpha)

Mass distribution has relatively little effect on the modal frequencies



Proportion of the SPS mass in the reflectors (15% represents baseline case)

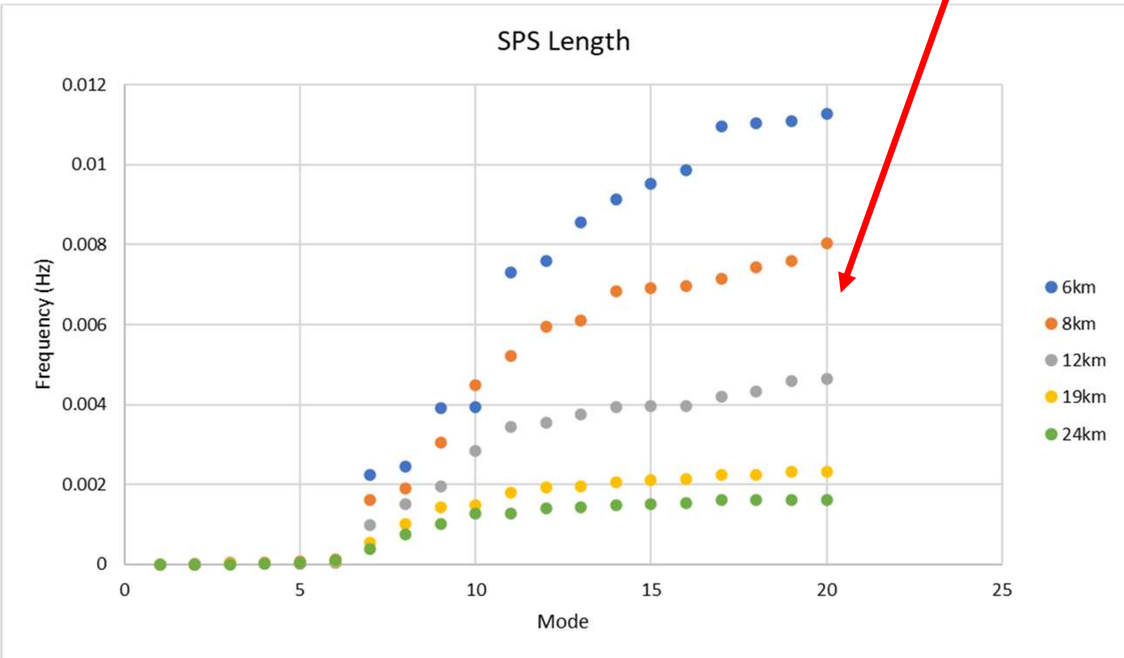
Fixed Parameters:
Total mass = 2,000 tonnes
Total length = 6km
Helix, Beam and Reflector stiffnesses

Modal Parametric Study: Total Length

An increase in the SPS length was considered:

- CASSIOPeiA is a particularly short concept
- Noting that other SPS concepts are much longer

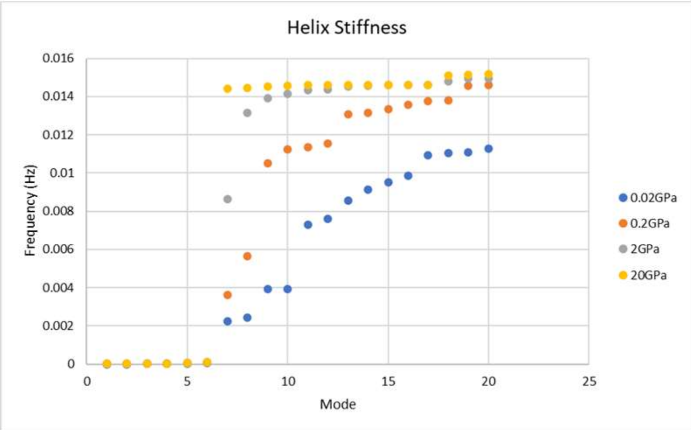
SPS Length has a notable effect on reducing the modal frequencies

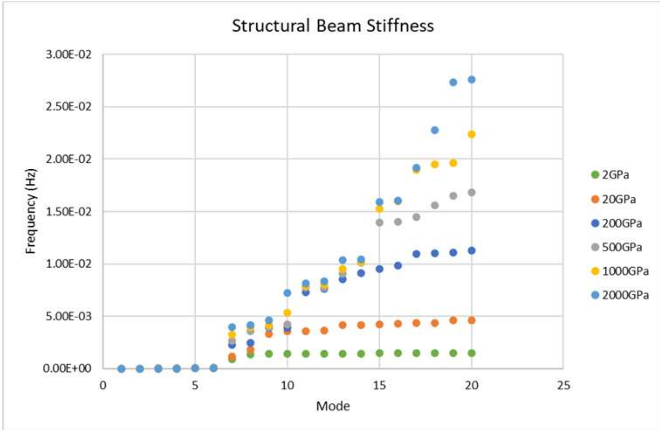


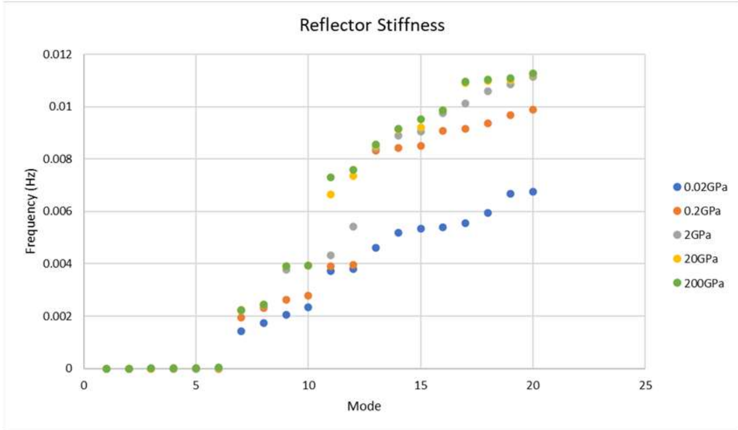
Fixed Parameters:
Total mass = 2,000 tonnes
(Densities scaled to keep mass constant)
Helix, Beam and Reflector stiffnesses

Modal Parametric Study: Stiffness

Young's Moduli have been adjusted to vary the stiffness of the components in turn (with the SPS mass of 2,000 tonnes and the length of 6km kept constant).







Baseline helix stiffness, E = 0.02GPa
Increase in the helix stiffness, increases the response frequency

Baseline beam stiffness, E = 200GPa
Reduction in the stiffness, reduces the responses frequency

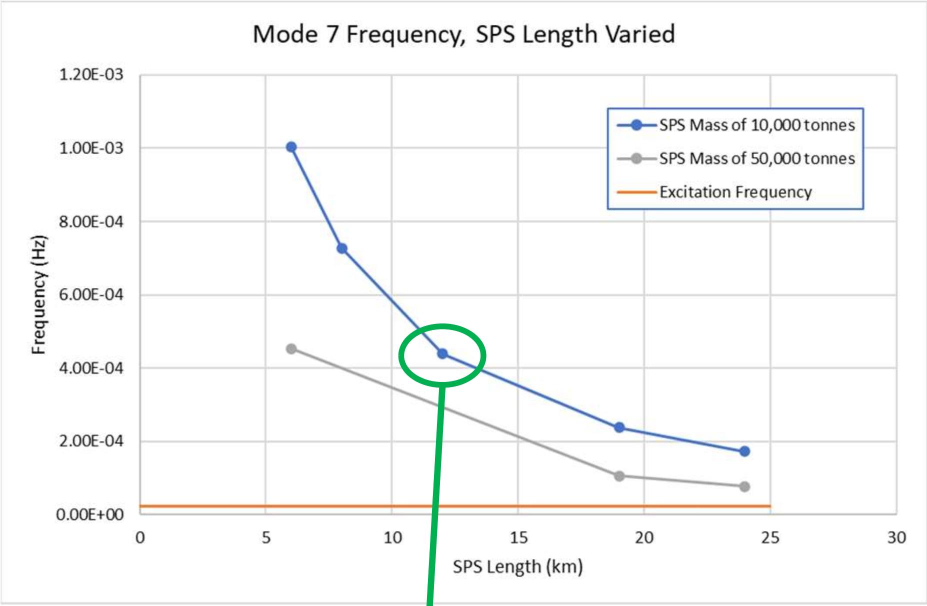
Baseline reflector stiffness, E = 200GPa
Variation in the reflector stiffness results in little change to the response frequency

Modal Parametric Study: Combined Mass and Length

- For the range of design parameters considered, the increase in SPS mass and length appear to result in the most notable reduction in the modal response frequencies.
- Additional cases have been considered for the combination of increased mass and increased length.
- The following SPS concepts may be considered for reference:
    - SPS-Alpha: Mass of 8,000 tonnes, length of 13km.
    - MR-SPS: Mass of 10,000 tonnes, length of 12km.

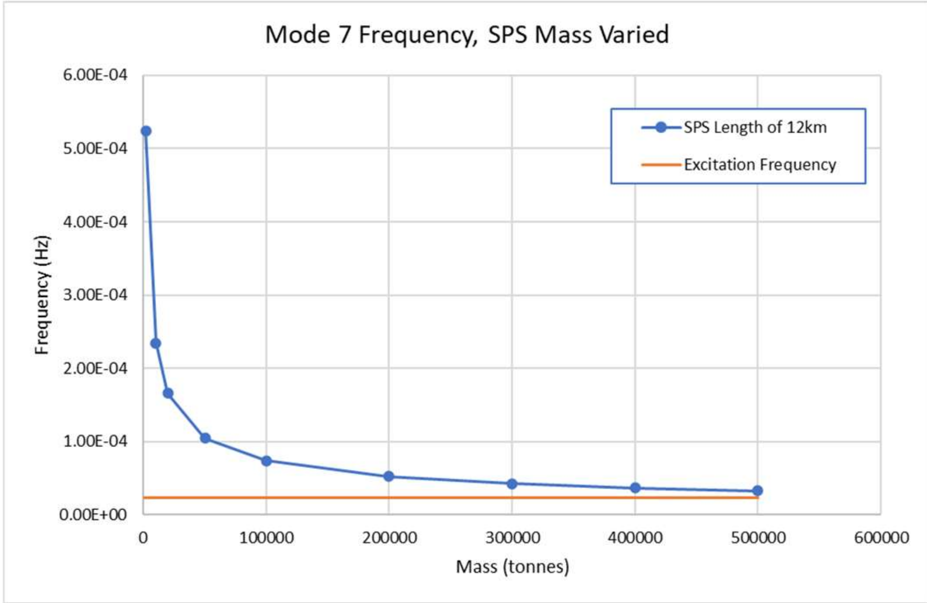
Concept	Mass (Tonnes)	Length (km)	Orbit	Mass Distribution	Notes
SPS-Alpha	8,000	13	GEO	Located at the ends	Gravity gradient stabilised. Mirrors are motorised.
CASSIOPeiA	1,500	6	GEO / GLP	Focused in the centre	No moving parts. Reflectors/antennae participate equally. Not restricted to circular orbits.
MR-SPS	10,000	12	GEO	Uniform	Motors used to align PV panels and antennae. Heaviest concept considered.
NASA Sun Tower	6,000	15	GEO	Uniform	Motorised collectors. Collectors spaced to minimise shadowing.

Modal Parametric Study: Combined Mass and Length



Mass and length representative of MR-SPS

Frequency of first flexural mode is 4.4e-4 Hz (c.f. 2.3e-5 Hz)



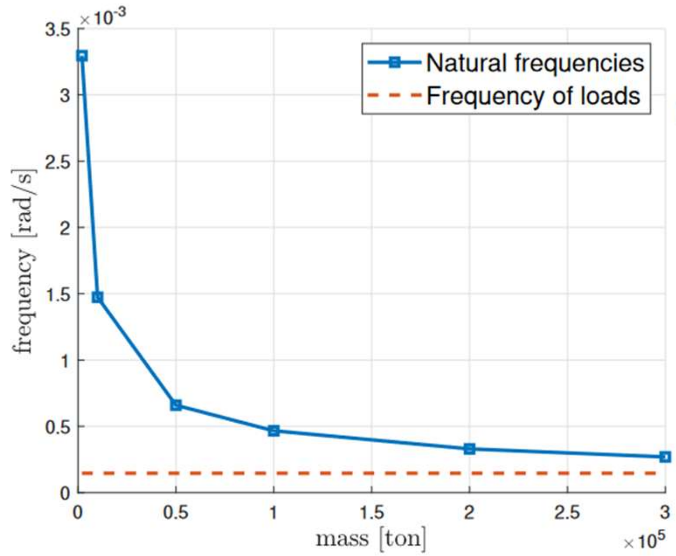
Perturbation Analysis

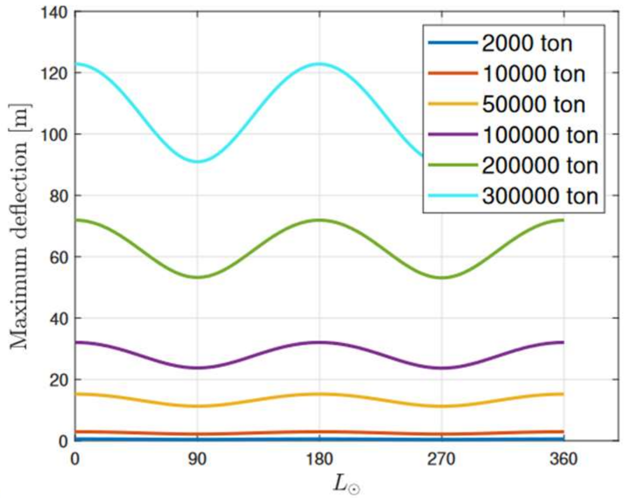
From the parametric study, a case has been selected to investigate the impact of the parameter changes on the SPS deformation and orbital loads:

- **Length of SPS extended to 12km and mass varied up to 300,000 tonnes**
  - Increased length of 12km selected, as this is representative of MR-SPS and SPS-Alpha.
  - Large increase of mass selected, in order to achieve closer alignment between the excitation and response frequencies.
  - Perturbation analysis undertaken to quantify the maximum displacement of the structure and the impact on the orbital loads.

Sensitivity Case Perturbation Analysis

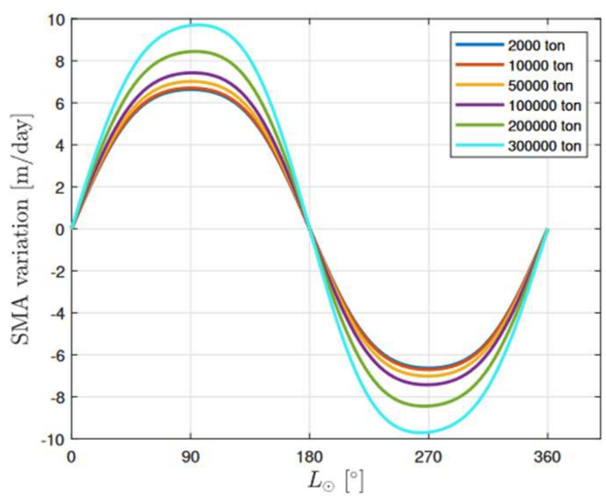
- Given the proximity of the natural frequencies in this case to the frequency of the orbital loads, instead of a static analysis, an analysis following linear vibration theory was carried out instead.
- The loads at each node are written as $\boldsymbol{f} = Re\left(\tilde{\boldsymbol{f}}\ \mathrm{e}^{2\mathrm{i}\theta}\right)$, where $\tilde{\boldsymbol{f}} = \boldsymbol{C} - i\boldsymbol{S}$ to represent that the phases of the loads vary throughout the structure.
- The higher the mass, the closer the natural frequencies get to the frequency of the applied loads (top figure) and thus the higher the displacements of the structure (bottom figure)

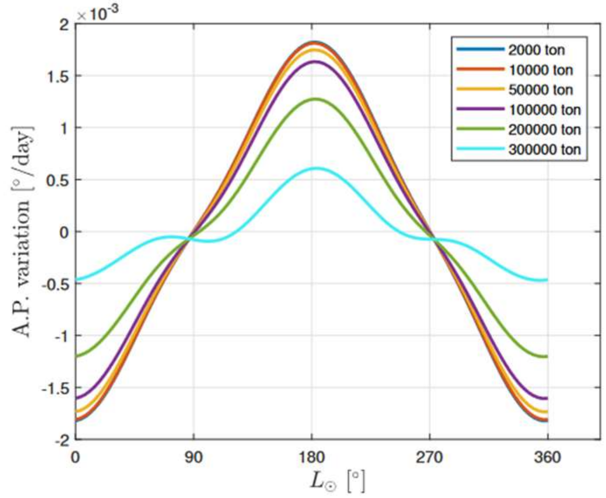




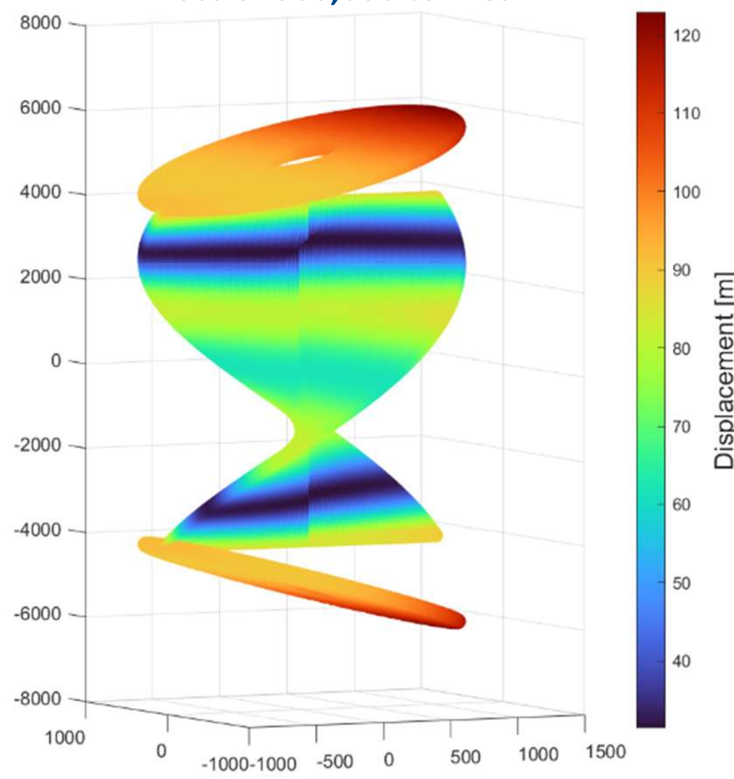
Sensitivity Case Perturbation Analysis

- The reflector stays flat, but rotated with respect to nominal. This angle increases as the natural frequency gets closer to the forcing frequency.
- The effect on the orbital dynamics is small, with variations of the order of 10m in the semi-major axis (SMA) and $10^{-3\circ}$ for the argument of pericentre (AP)



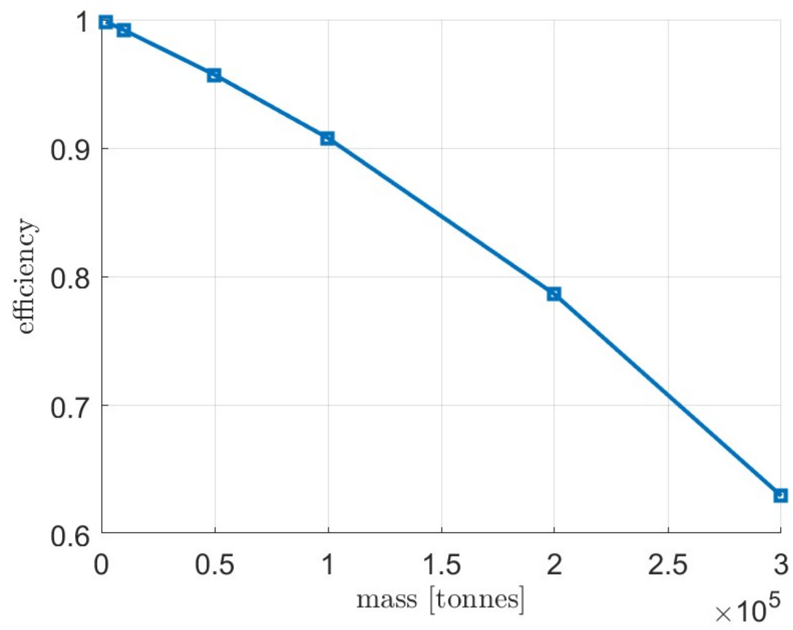


Displacement for a total mass of 300,000 tonnes



Sensitivity Case Perturbation Analysis

- The effects of this deformation on the orbital dynamics are minimal.
- However, the efficiency, measured as the fraction of sunlight that is captured by the helix, is affected by this deformation.
- At 300,000 tonnes, the efficiency drops to 63%.
- Of the SPS concepts considered, MR-SPS has the largest mass of 10,000 tonnes. Therefore, a mass of 300,000 tonnes is considered unlikely.



7 Conclusions

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Conclusions (Part 1)

- For the baseline CASSIOPeiA configuration:
  - The response frequency of the SPS first flexural mode is two orders of magnitude greater than the excitation frequency (gravity gradient effect).
  - The solar radiation pressure results in negligible displacement between the reflectors.
  - In response to the loads that vary with orbital position, the maximum displacement of the reflectors of 2.88 metres is tolerable (equates to 0.14% of the SPS diameter).
  - The deformation that varies along the orbit is not expected to cause an interaction between structural and orbital dynamics.
  - Given that the excitation frequency is so low compared to the first flexural mode, the response will be essentially pseudo-static and have negligible effect on the performance.

- From the parametric study
  - The SPS mass and SPS length are the most influential parameters on reducing the modal frequencies
  - Adjusting the mass distribution for the CASSIOPeiA model does not have a significant impact on the response frequency.
  - Adjusting the stiffness of the helix, reflectors and structural beams in isolation does not have a significant impact on reducing the response frequency.
  - For a 12km SPS, a total mass of 300,000 tonnes results in a response frequency close to that of the gravity gradient excitation frequency.

Conclusions (Part 2)

- From the perturbation assessment:
  - For a significantly increased mass (300,000 tonnes) and length (12km) the maximum deformation is approximately 120 metres (i.e. 6% of the SPS diameter).
  - Notably, the reflectors remain flat and the effect on the orbital dynamics is small, with variations of the order of 10m in the semi-major axis (SMA) and $10^{-3\circ}$ for the argument of pericentre (AP).
  - However the small deformation does result in a reduction in the SPS efficiency, measured as the fraction of sunlight that is captured by the helix.
  - Therefore for the example of a 12km long SPS, in order to achieve a sunlight capture efficiency of 90%, the total SPS mass should not exceed 100,000 tonnes.

Design Guidance

- The structure of the SPS will need to be assessed and designed to accommodate all construction and operating loads, including constant and orbital varying loads.
- As a matter of good engineering practice, the modal frequencies of the SPS should be determined at all stages of the structural design and compared with the orbital frequencies.
- For extremes of SPS design, deformations due to orbital varying loads may become significant (relative to the SPS size) and should be assessed statically or dynamically.
- Structural vibration may become an issue for SPS performance due to potential misalignment. However, this can easily be assessed using commonly used Finite Element software.
- Structural vibration may become an issue for the structural integrity of an SPS. However, this can easily be assessed using commonly used Finite Element software. Structural integrity and misalignment can be assessed simultaneously.
- Formal assessment of satellite vibration on orbital dynamics should be undertaken at key design gates as an ongoing check. It is likely that there will be sufficient stiffness in the design, to mitigate concerns of alignment and structural integrity, thereby ensuring that deformations are relatively small in comparison to the overall size of the satellite.

Recommendations for future work

1. Investigate the fatigue performance of SPS designs:

   A study is recommended to quantify component stresses and assess the fatigue performance over the operating life of an SPS. This may be extended to consider the fatigue performance of composites, which are likely to be used in many SPS designs.

2. Orbital Mechanics for a range of SPS concepts:

   A study to research and quantify the range of orbital loads on SPS spacecraft in general, and the implications on their stability.

3. AOCS for other SPS designs:

   A study is undertaken to consider the variation in the AOCS requirements and potential design solutions for other SPS designs.

4. SPS design development:

   During our review of SPS concepts, we have identified that most leading concepts currently lack significant design detail. We would propose a study is carried out to build on the outputs from our current work, focused on how we use the guidelines to develop the more detailed design for the SPS class concepts.

University of Strathclyde

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Thank you

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