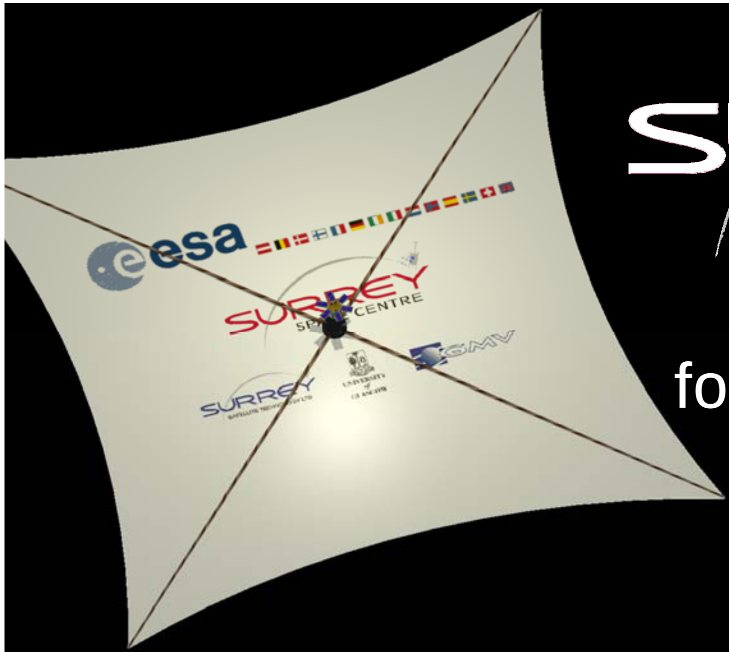
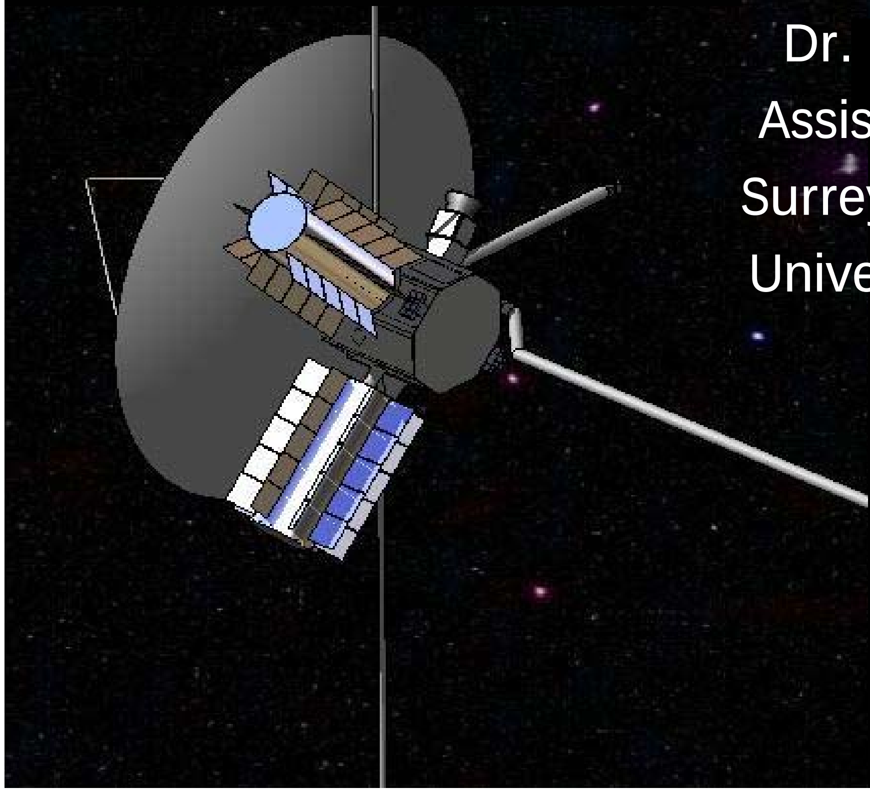
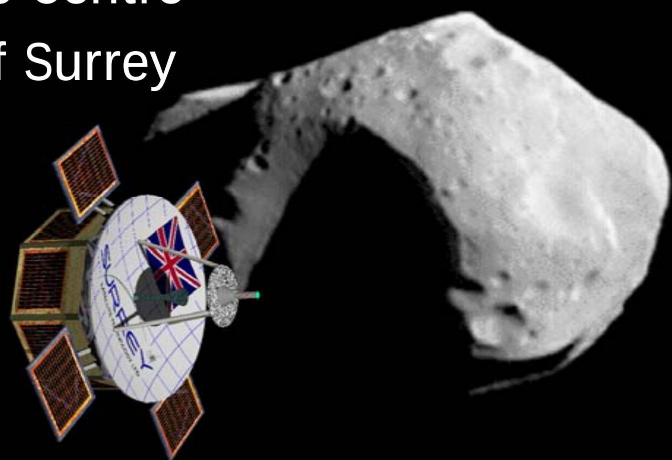


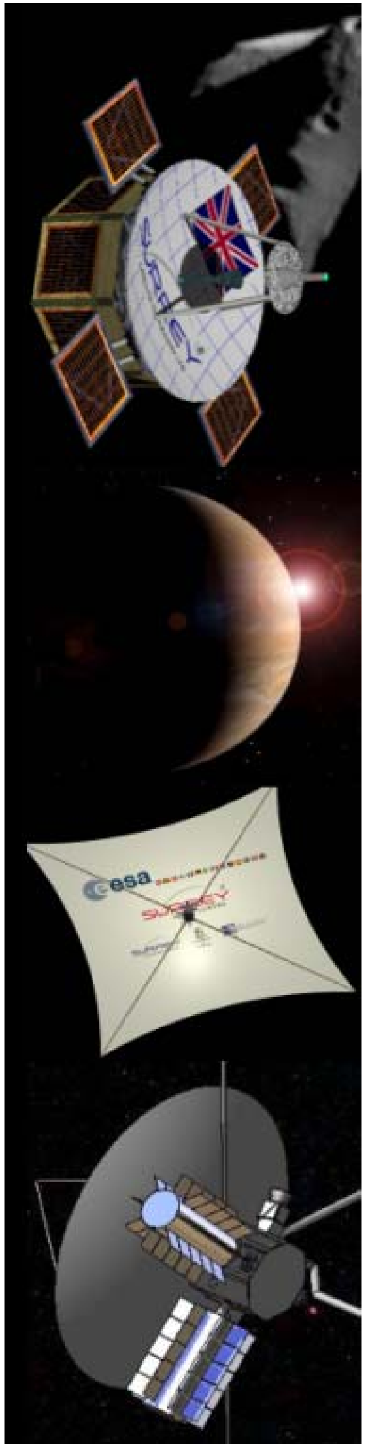
Attitude Control for Planetary Missions

February 21, 2006

Dr. Vaios Lappas
Assistant Professor
Surrey Space Centre
University of Surrey

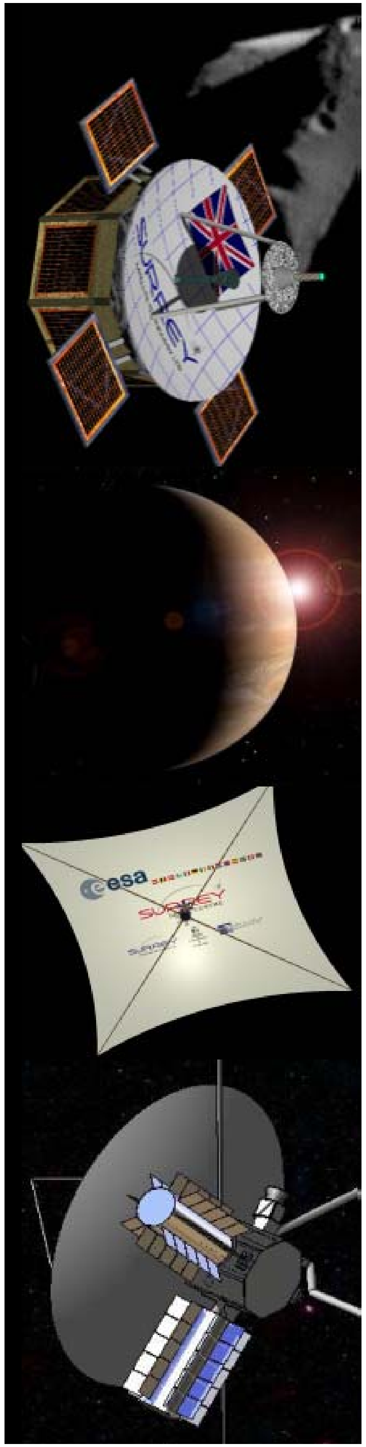






Presentation Contents

- Introduction
- The Attitude Control Problem
- Three Case Studies
  - Near Earth Object Fly-By Mission
  - Solar Kites (Micro Solar Sails)
  - Interstellar Heliopause Probe to 200 AU
- Conclusion



World Leaders in Small Satellites

SPACE AT SURREY

Minisatellites - Microsatellites - Nanosatellites (platforms & payloads)

- *Satellite Communications*
- *Remote Sensing*
- *Space Science*
- *Technology Demonstration*

- *200 professional staff*
- *11 faculty*
- *30 PhD researchers*
- *18 visiting staff*
- *dedicated space building*

26 Satellites in-orbit

Affordable access to space

Academic Research

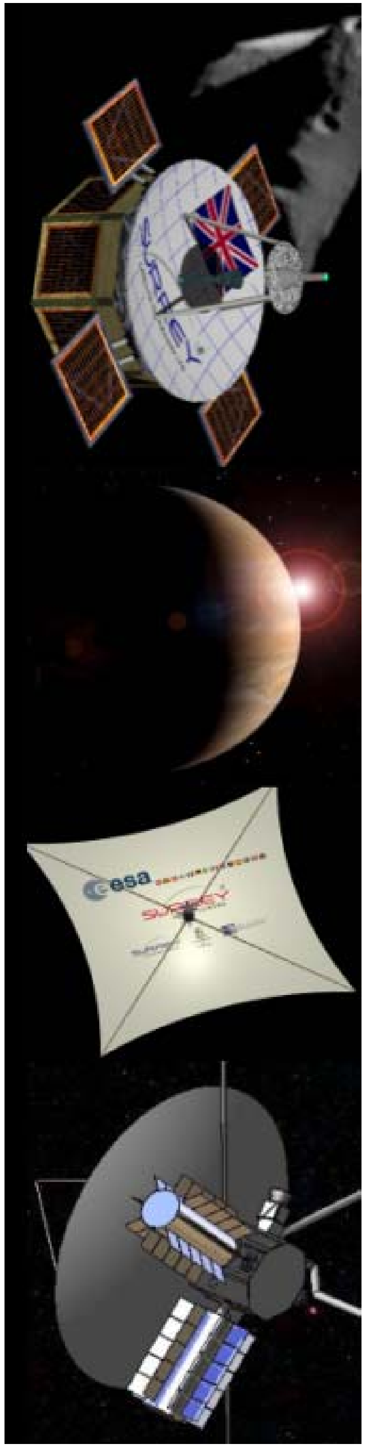
POSTGRADUATE EDUCATION

Research Degrees (MSc, PhD)

Short Courses for Industry

Commercial Exploitation

Surrey Satellite Technology Ltd



Research Group

- Attitude/Orbit Control Systems/Advanced Concepts
- 5 PhD students
  - CMGs
  - Combined Energy & Attitude Control (CEACS)
  - Solar Sails
  - Pulsed Plasma Thrusters
  - Micro Hollow Cathode Micro Thrusters
- 1 Research Fellow
- 3-4 MSc Students
- Research funded by European Space Agency, USAF/EOARD, British National Space Centre, SSTL

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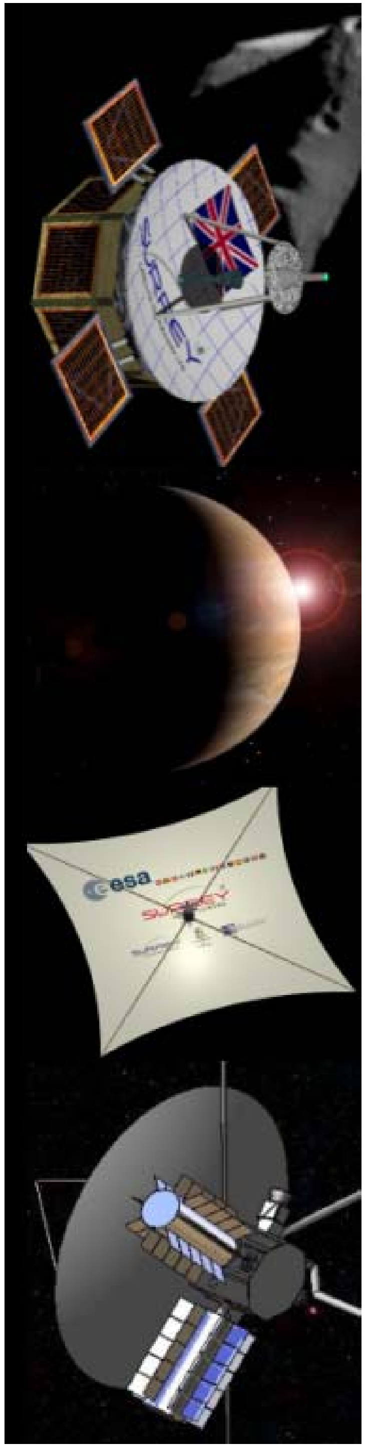
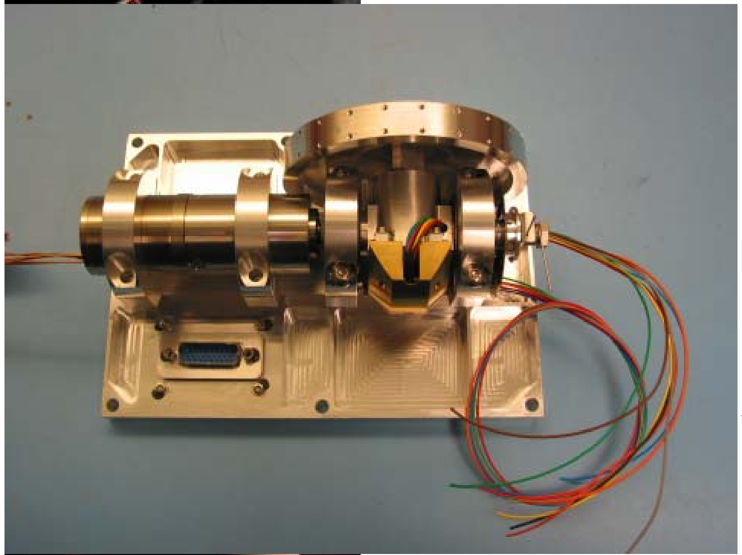


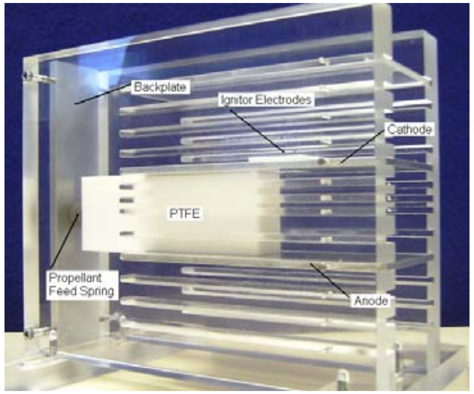
Research Group Topics

- Control Moment Gyros
  - Hardware design
  - Full ADCS architecture design based on CMGs
  - Singularity Avoidance
- Attitude Determination
  - Kalman Filters, Sun Sensors
- Micro-Propulsion
  - Plasma Pulsed Thrusters
  - Hollow Cathode Thrusters
  - Solar Sails (Attitude Control Design, Systems Design)
- Advanced Aerospace Systems
  - Combined Energy and Attitude Control Systems
  - 1 m resolution micro-satellites / deployable telescopes
  - 1-kg Palmsat
  - Mars Landers/Guidance Navigation and Control
  - Low Cost UAVs (Helicopters, disposable micro-UAV)
  - Formation Flying with Electrostatic Forces (Ariadna)

Hardware/Research Results



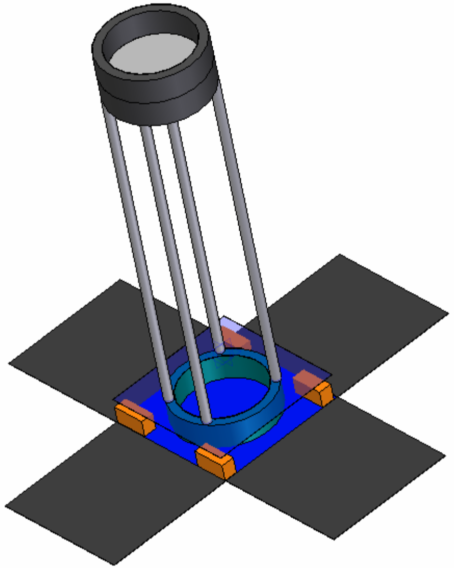
BILSAT-1 CMGs



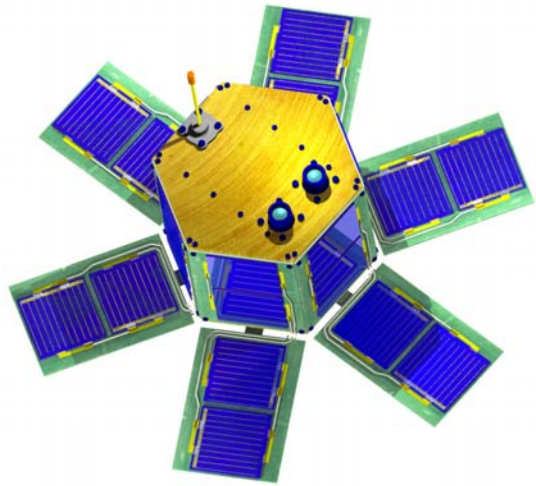
PPT Prototype

Solar Kites

Surrey 'ICARUS' UAV



1 m Resolution Microsat Deployable Telescope



1-kg Palmsat

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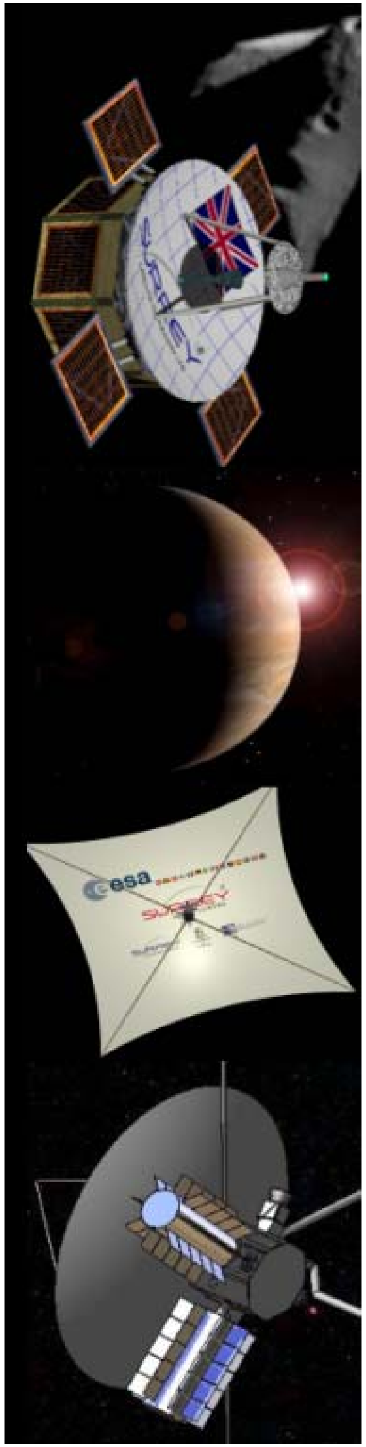
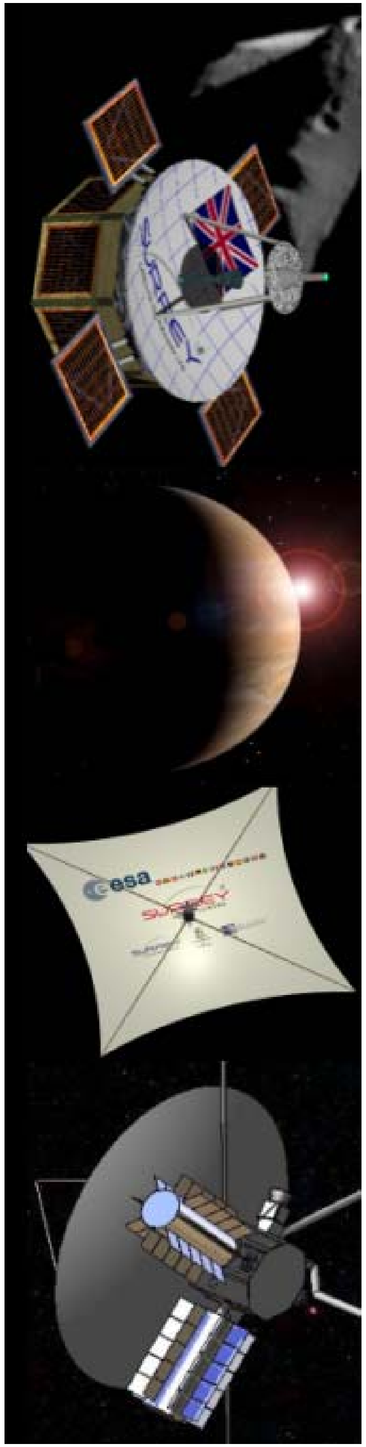


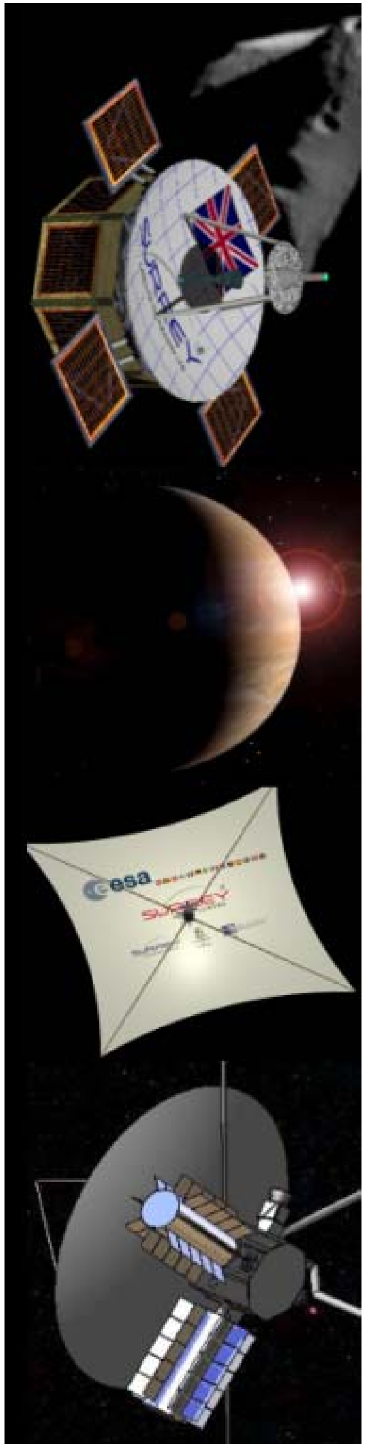
The Attitude Control Problem

- Advanced Concepts=Planetary Missions. Why?
- Planetary missions are challenging and expensive
- What is Attitude Control?
  - The ability to point and stabilise a spacecraft to directions of interest and to counter disturbances
- Why is Attitude Control a problem?
  - Mission requires high pointing and stability
  - Physical constraints: mass, power, volume, lifetime
  - Increased autonomy and robustness
  - Diverse requirements
- Planetary missions amplify the above issues
- Answer: Develop low cost, robust and versatile attitude control subsystems (ACS)



Case Studies

- Planetary Missions, Attitude Control, Small Satellites
- 3 Diverse and Challenging Case Studies:
  - Low Cost, Deep Space Near Earth Object Fly-By Mission
  - Solar Kites (Micro Solar Sails) for Earth Magneto-tail Monitoring
  - Interstellar Heliopause Probe Mission to 200 AU
- ESA Studies



Case Study 1: NEO Fly-By Minisatellite Mission (NEO2M)

- Co authors: G. Prassinos (1) Jozef Van Der Ha (2), Bong Wie (3), C. Phillipe (4)

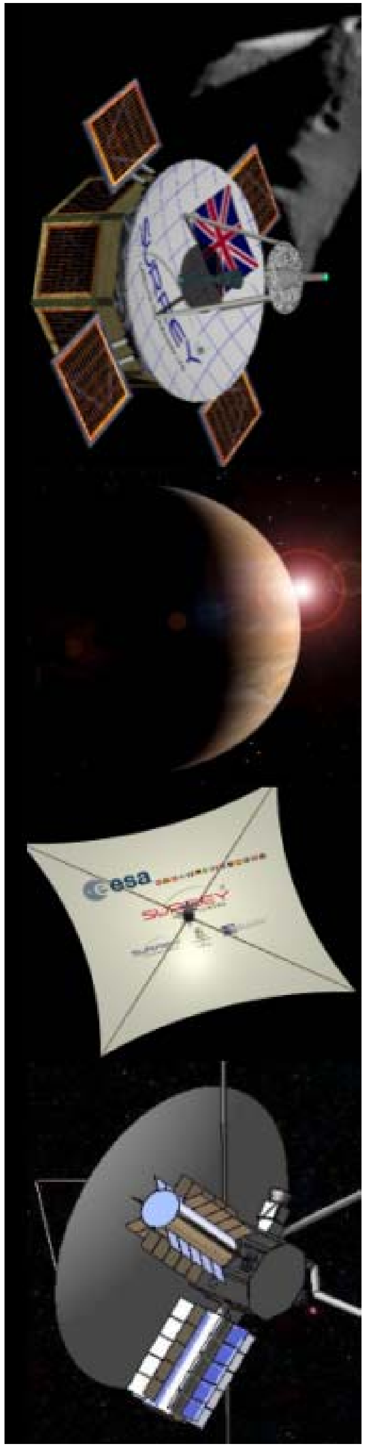
  (1) Surrey Space Centre, University of Surrey, GU2 7XH, United Kingdom

  (2) Consultant, 10001 Windstream Drive, Columbia, MD, USA

  (3) Arizona State University, Tempe, AZ 85287-6106, USA

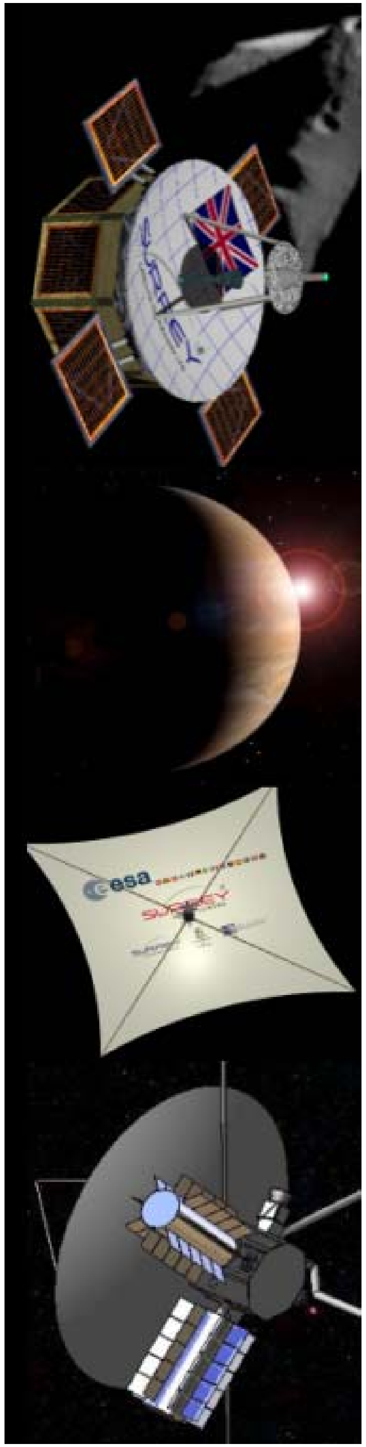
  (4) ESA-ESTEC, GNC

- Developments in micro-electronics have enabled small and low-cost deep space probes to complement conventional space platforms in long-duration deep space missions
- NEO tracking manoeuvre for imaging purposes
- A mini-satellite (400 kg) mission that is capable of supporting a 10-kg science payload is used



NEO2M Mission Analysis

- Near Earth Objects (NEO's) pose a potentially catastrophic danger for earth
- Low-cost deep space probes can be useful and cost-effective for gathering information on NEO's
- The main mission objective is to demonstrate the capability to intercept a NEO in deep space and to perform surface imaging
- The low-cost nature of the mission dictates that, during the fast fly-by phase, the satellite must execute a fast rotation about its pitch axis in order to be able to keep its imager pointing at the target object

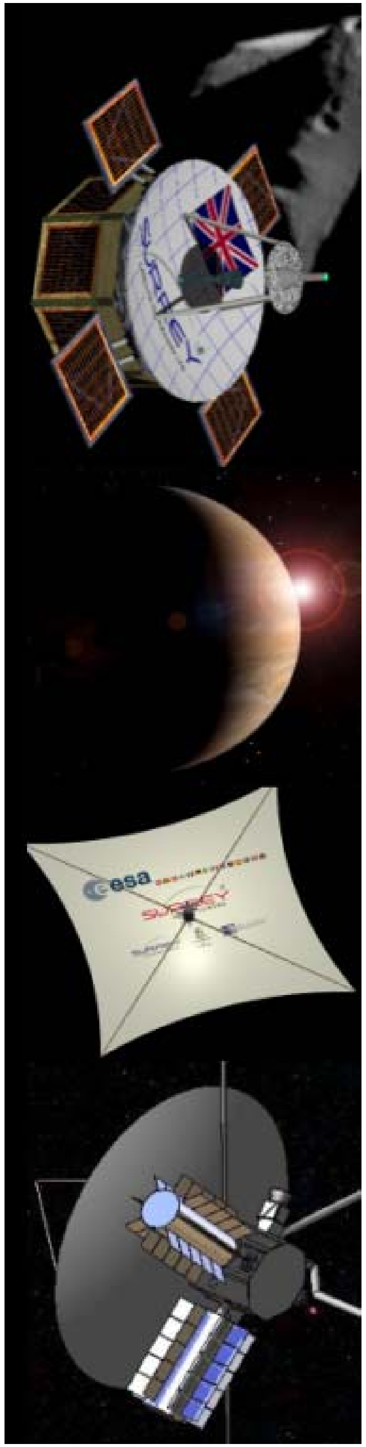


Mission Design: 4179 Toutatis

- A single suitable candidate NEO was selected for the present study: 4179 Toutatis

- It came within a scant 1.5 million kilometers of the earth on 29 September 2004 and will approach earth again in 2008.
- The Toutatis object is of interest because it achieves one of the closest earth approaches of any known asteroid or comet between now and 2060, and the approach occurs in the near term.

SURREY SPACE CENTRE



Mission Design: Trajectory

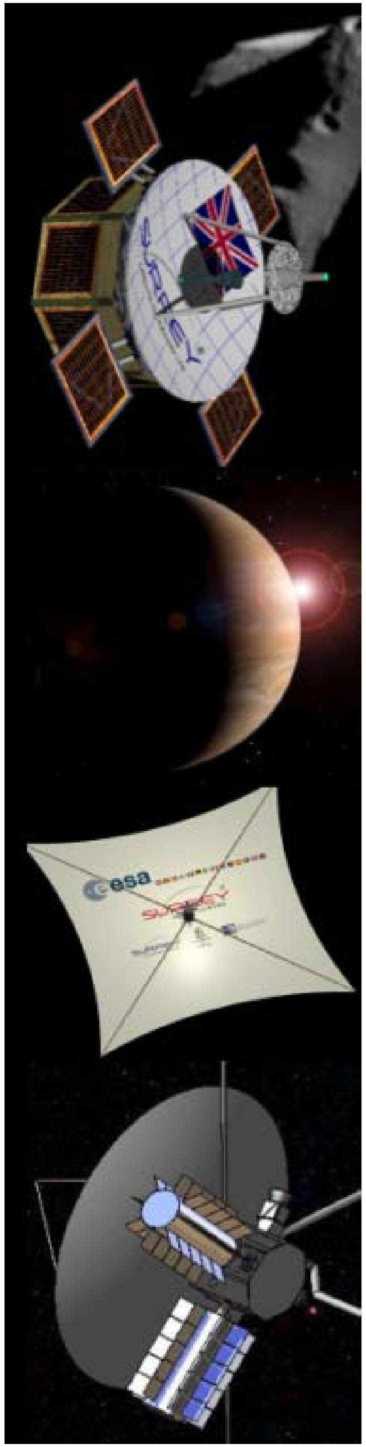
- When starting from a geo-stationary orbit orbit (Proton secondary payload), earth escape can be achieved at a cost of about 1300 m/sec.
- The proposed NEO2M (NEO Mini-satellite Mission) trajectory consists of three parts:

  (i) the 267-days escape phase, when the satellite escapes from the earth's sphere of influence starting from its initial geostationary orbit;

  (ii) the 134-days approach phase when the spacecraft cruises to the NEO Toutatis;

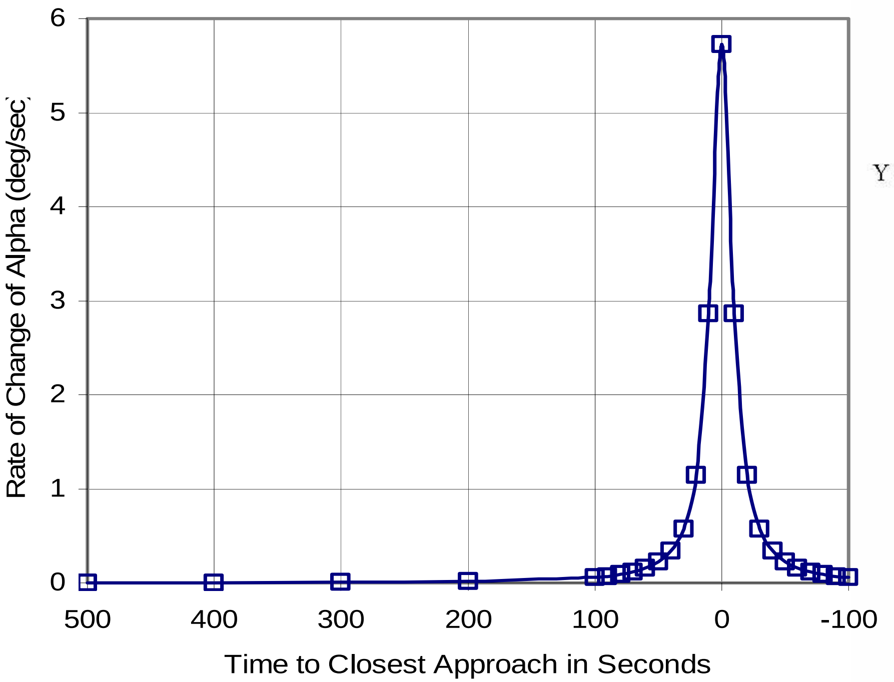
  (iii) the short encounter phase when it conducts the actual NEO flyby

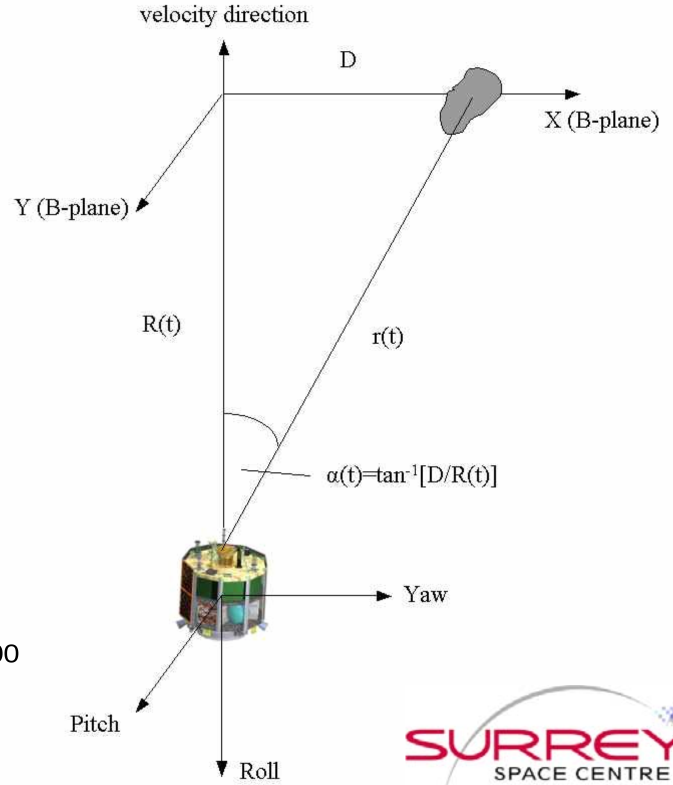
SURREY SPACE CENTRE

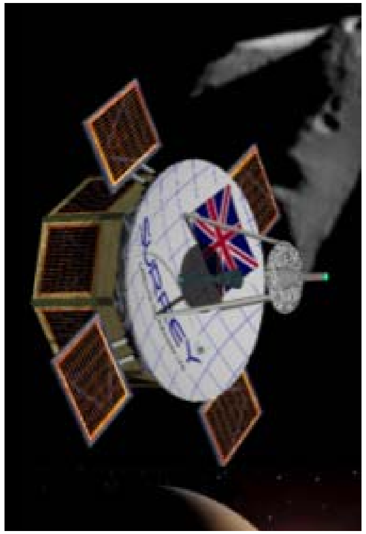


Imaging

- The collection of optical imagery would indisputably be a crucial objective of the Toutatis mission.
- The availability of 10-meter or better optical images would greatly increase our knowledge of this particular NEO and would improve our understanding of its complicated dynamics and structure

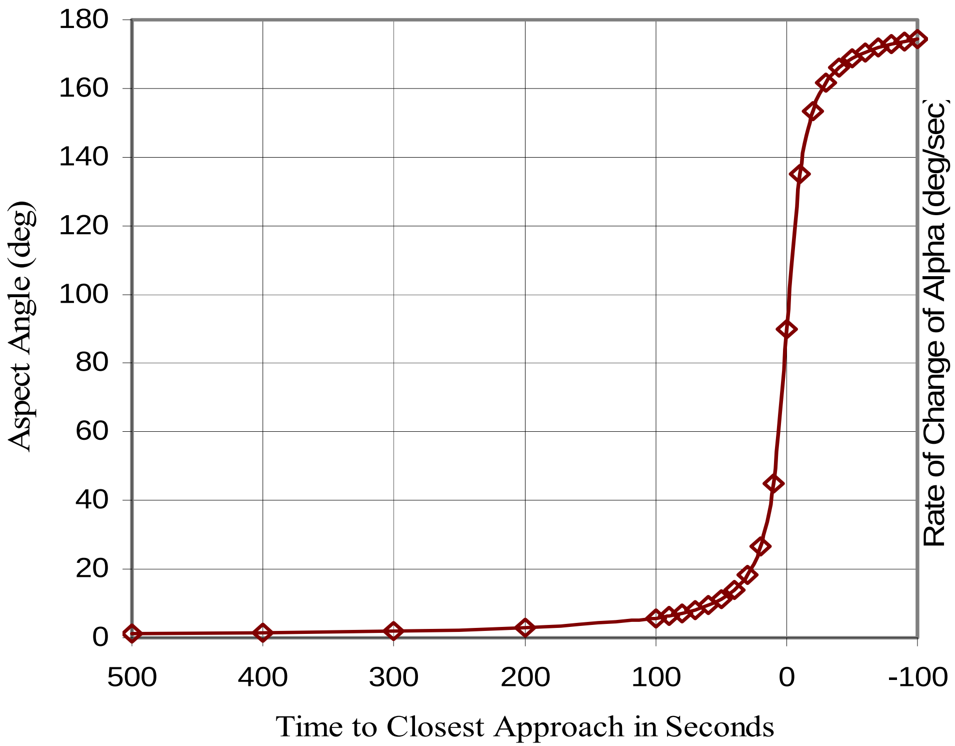


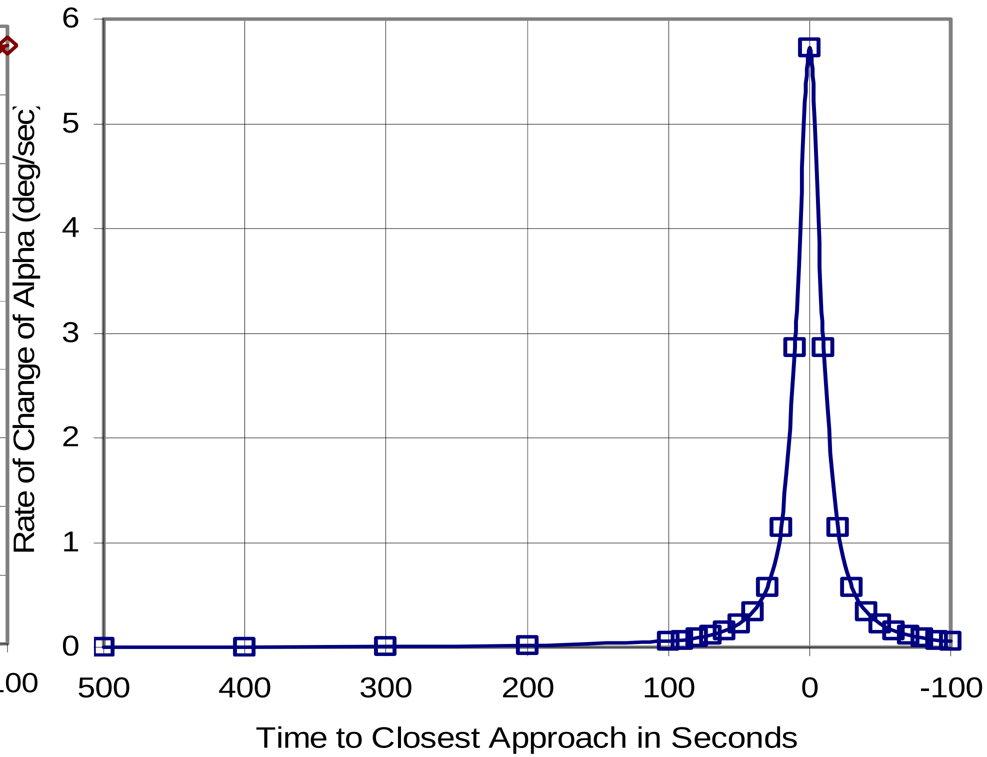


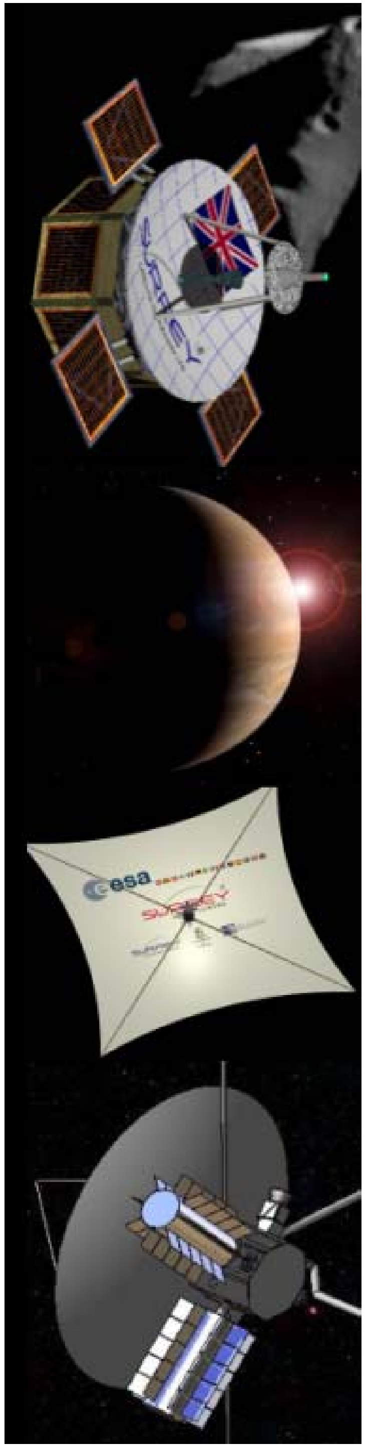


NEO Tracking Manoeuvre

- On the basis of the adopted values for the flyby velocity $V = 10$ km/s and the minimum miss distance $D_{min} = 100$ km, we find that the maximum required pitch rate (at the time of closest approach) equals 5.7 deg/sec. This result forms the basis for the sizing of the CMG control capability.







NEO Tracking Manoeuvre Requirement

- A 5.7 deg/s slew rate will lead to oversized reaction or momentum wheels with very high power consumption (> 100 W) and mass (>10 kg per RW)
- Torque needed: 2 N-m
- Attitude Control Problem: How should we conduct attitude control given the physical constraints?

Subsystems	**Mass (kg)**
Payload	10.0
Propulsion	208.5
Structure (includes harness and solar arrays)	54.3
Attitude Determination and Control	19.5
Power	16.2
Communications	11.6
Environment (radiation and thermal)	7.1
On Board Data Handling	2.8
Margin (20 %)	31.3
TOTAL	**396**

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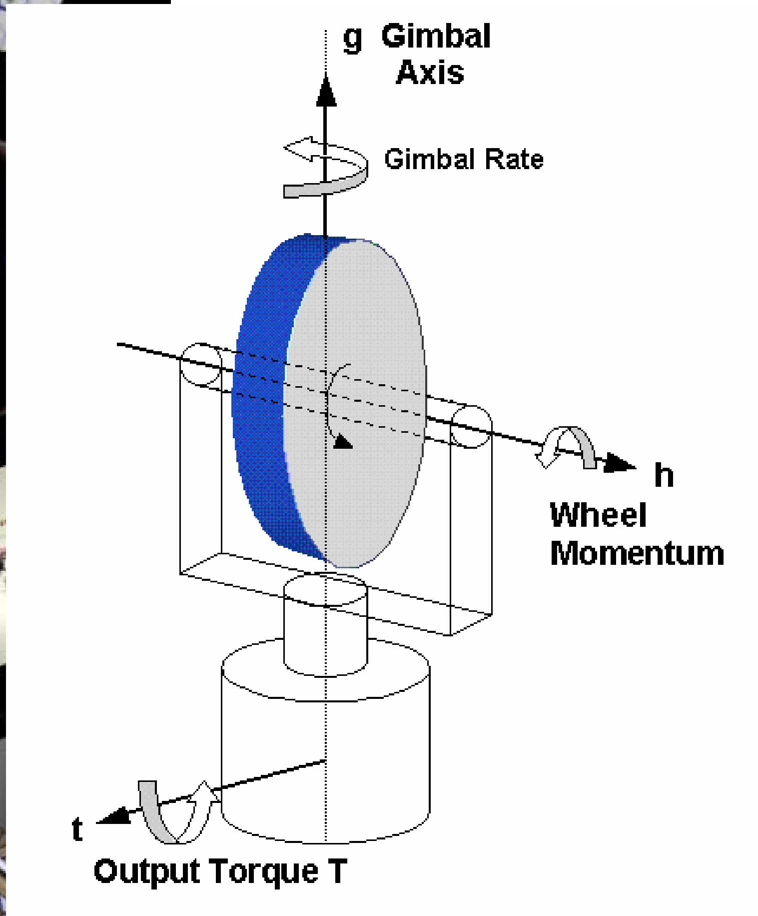
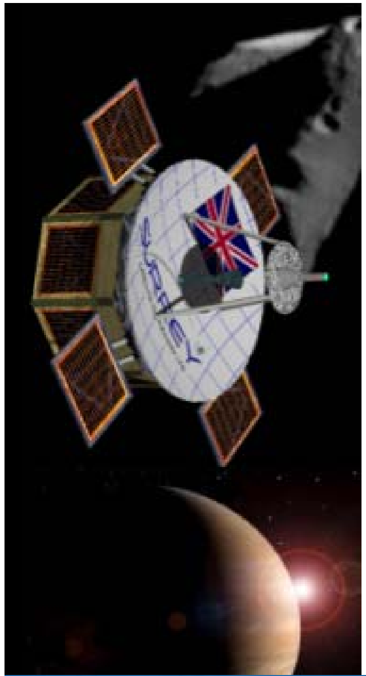
Control Moment Gyroscopes (CMGs)

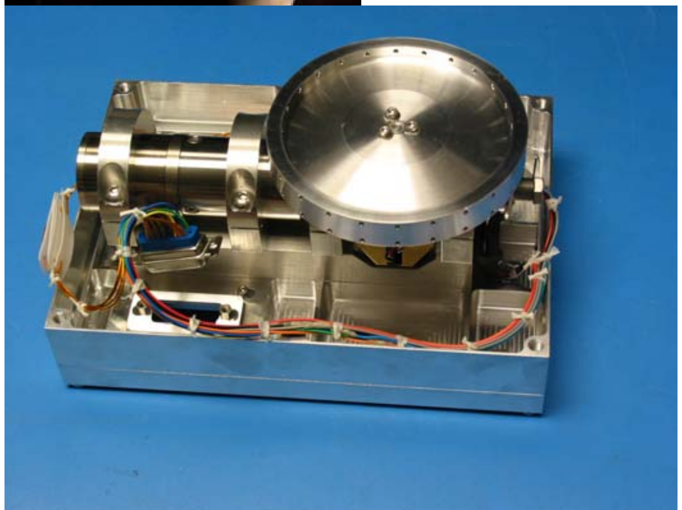


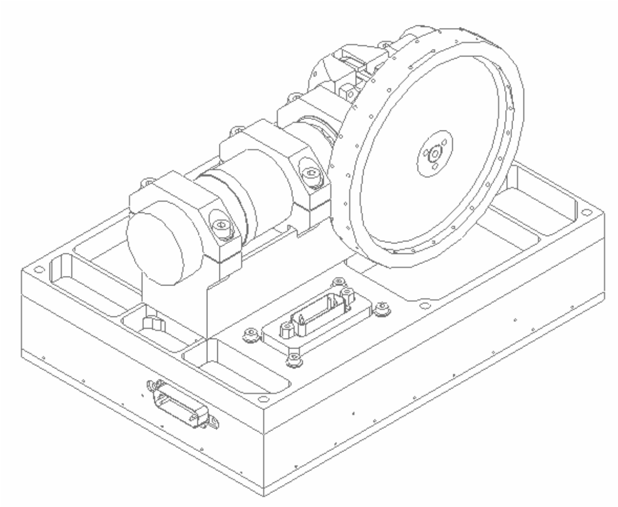
- Actuators, **'Torque Amplifiers'**
- A momentum wheel, gimballed in 1 or 2 axes
  - Single-Gimbal CMG (SGCMG)
  - Double-Gimbal CMG (DGCMG)
  - Variable-Speed CMG (VSCMG)
- Disadvantages
  - Mechanical Complexity, expensive
  - Singularities (No Torque generation)
  - Size
- Spacecraft Heritage
  - KH-11, KH-12
  - Skylab, MIR, ISS
  - Honeywell
  - Astrium (France)
  - 2-CMG Payload on BILSAT-1 Microsat

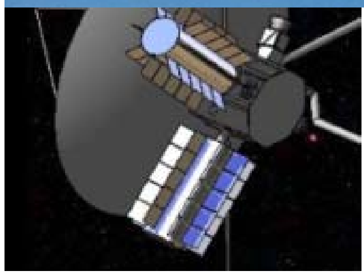
NEO2M Attitude Control System



- Use a cluster of 4-CMG for full agile redundant attitude control
- Surrey has developed the worlds smallest and first commercial CMGs...currently in orbit







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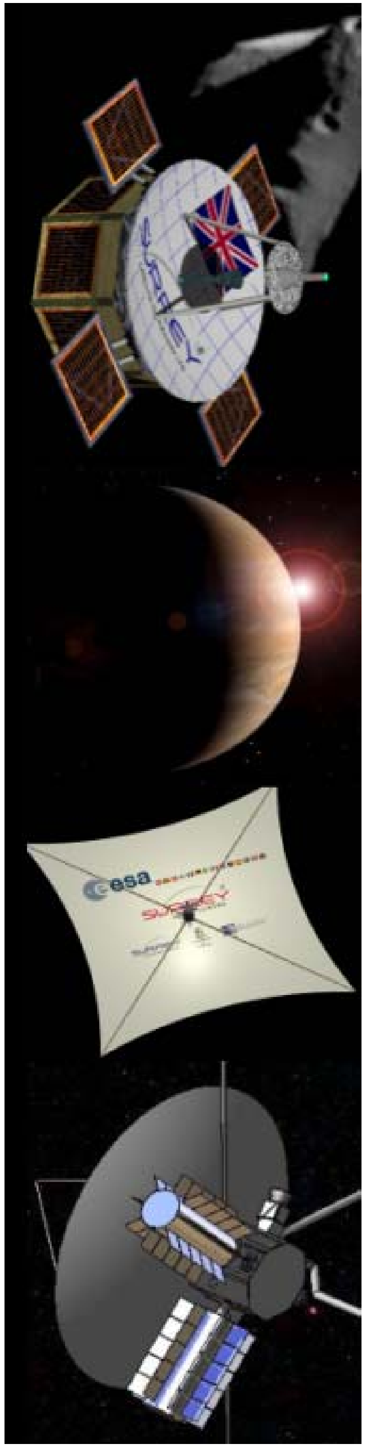
SPACE CENTRE



CMGs

DC Brushless Motor	
Max. Wheel Momentum	2.0 Nms
Wheel MOI	0.0032 kg-m^2
Max. Wheel Speed	± 6,000 rpm
Stepper/Gimbal Motor	
Max. Gimbal Rate	110 °/s
Nominal Gimbal Rate	85 °/s
CMG Module	
Mass	<3 kg
Supply	26-34 V
Max. CMG Torque	2.4 Nm (with 85 °/s gimbal rate)
Power	< 10 W
Interface	CAN-Bus
Dimensions	200 x 200 x 155 mm
CMG Cluster	
Mass	< 10 kg
Max. CMG Momentum	6.31 Nms
Max. CMG Torque	7.2 Nm
Agility [300 kg satellite, $I_x = I_y = I_z = 60$ kg-m^2]	10° < 5s , 90° < 20s, 120° < 150s

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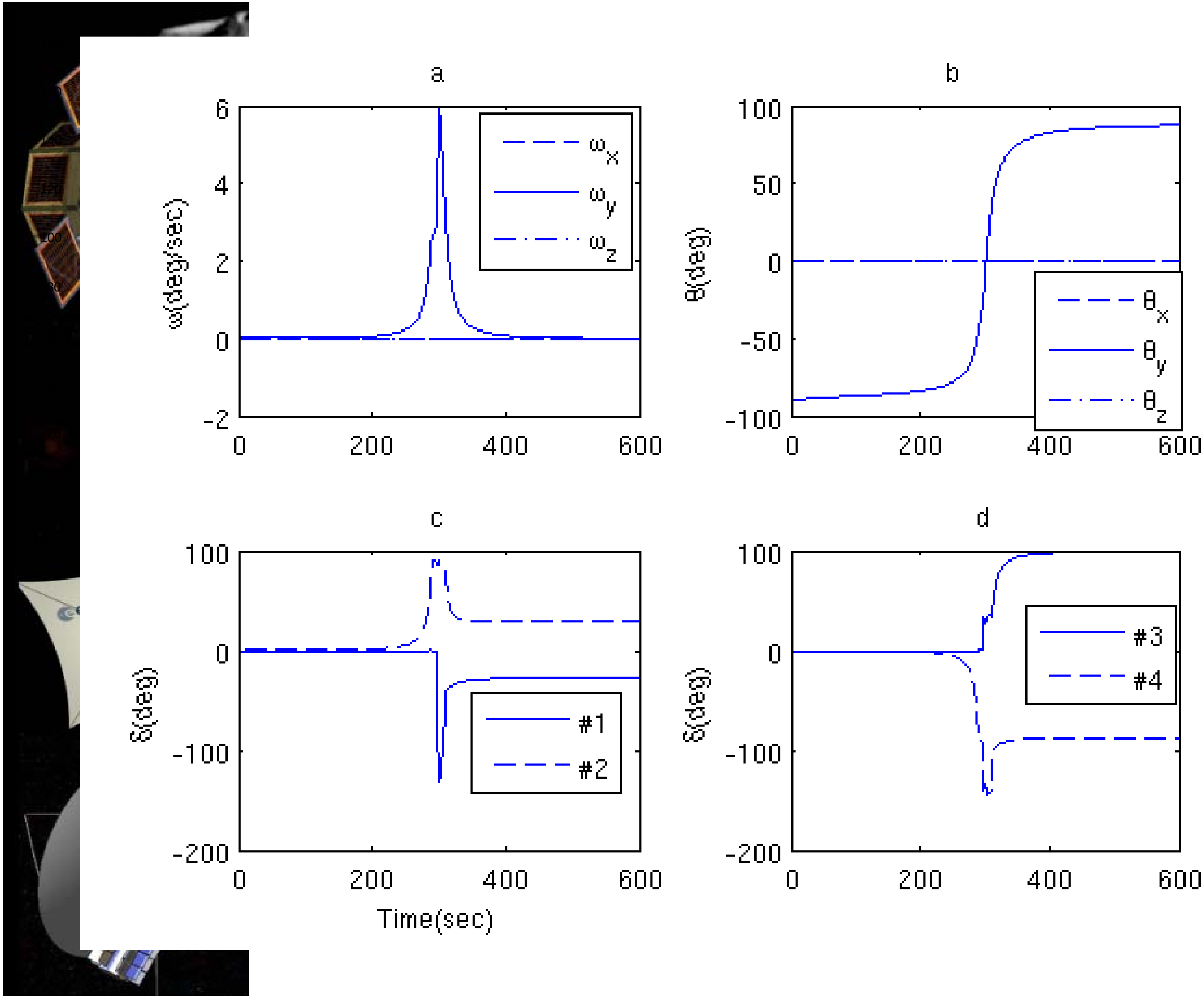
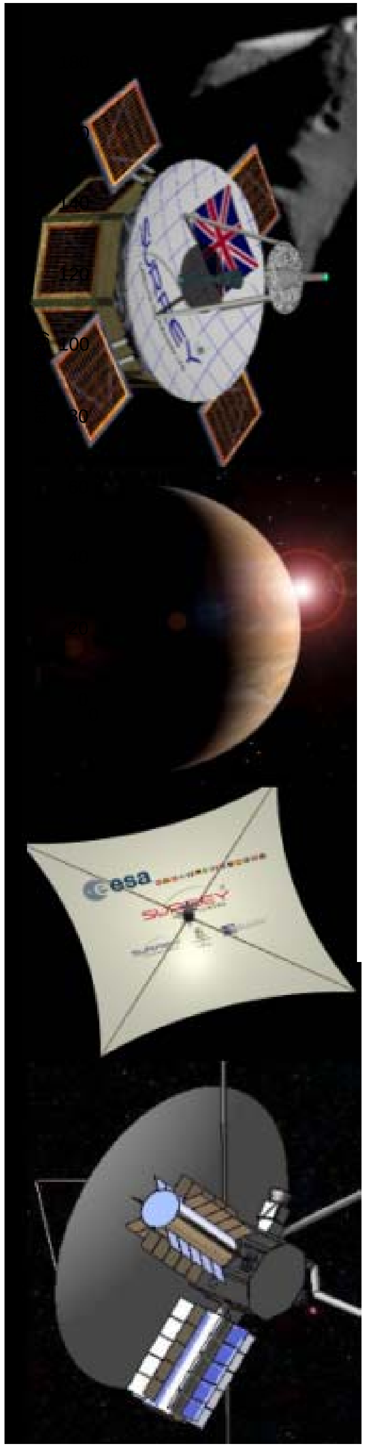
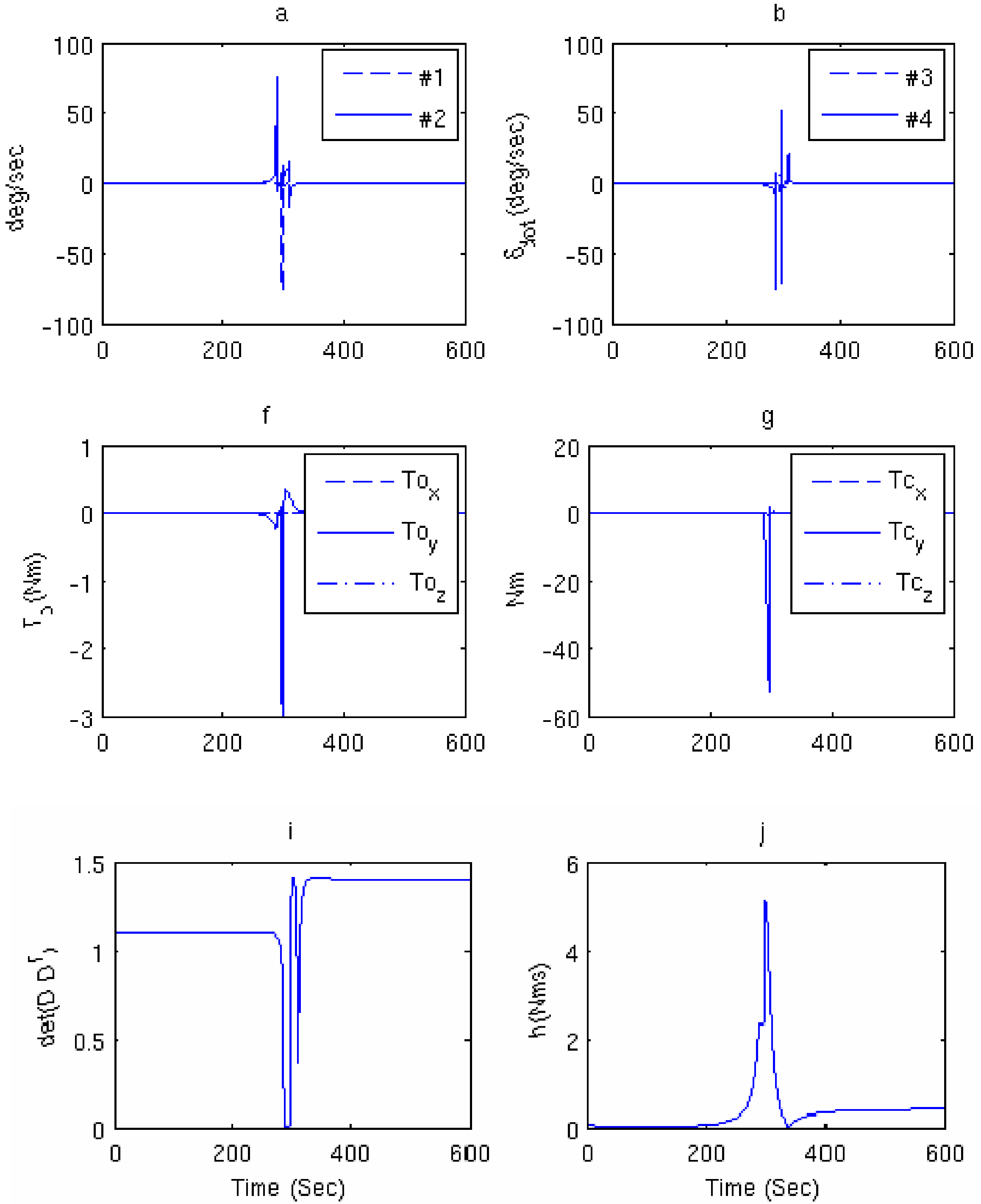

a
ω(deg/sec)
ωx
ωy
ωz
b
θ(deg)
θx
θy
θz
c
δ(deg)
#1
#2
Time(sec)
d
δ(deg)
#3
#4




a
deg/sec
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#2
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#3
#4
f
T_S (Nm)
To_x
To_y
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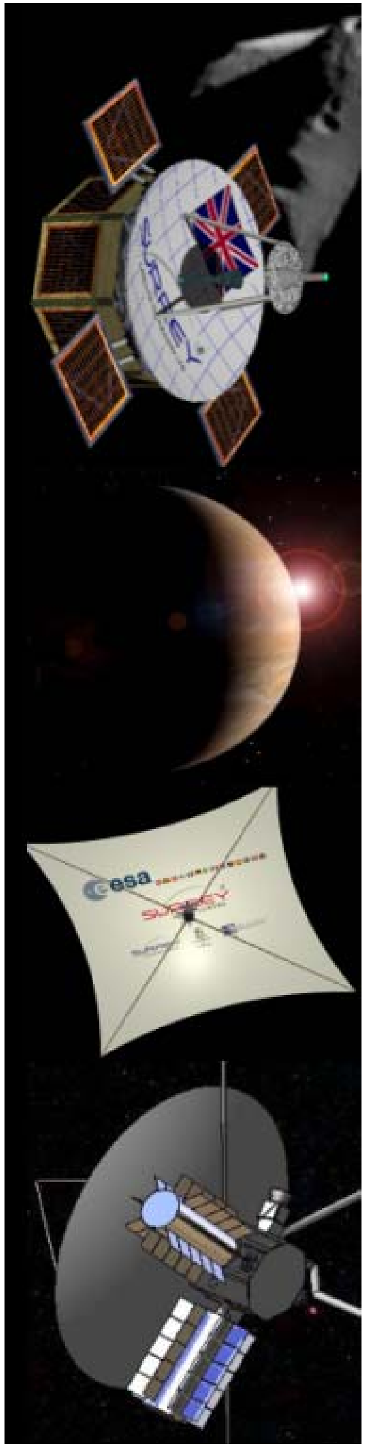
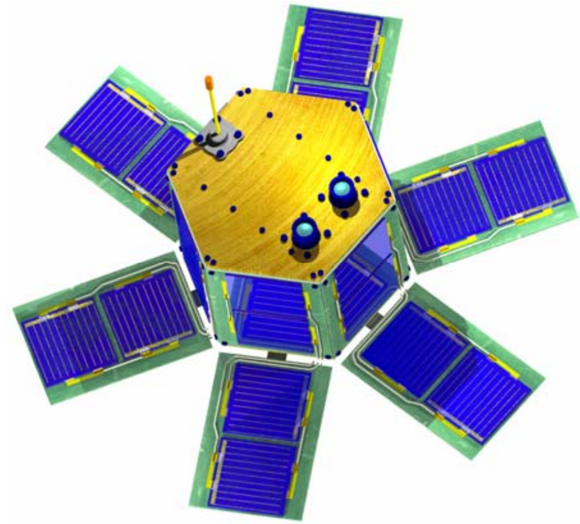
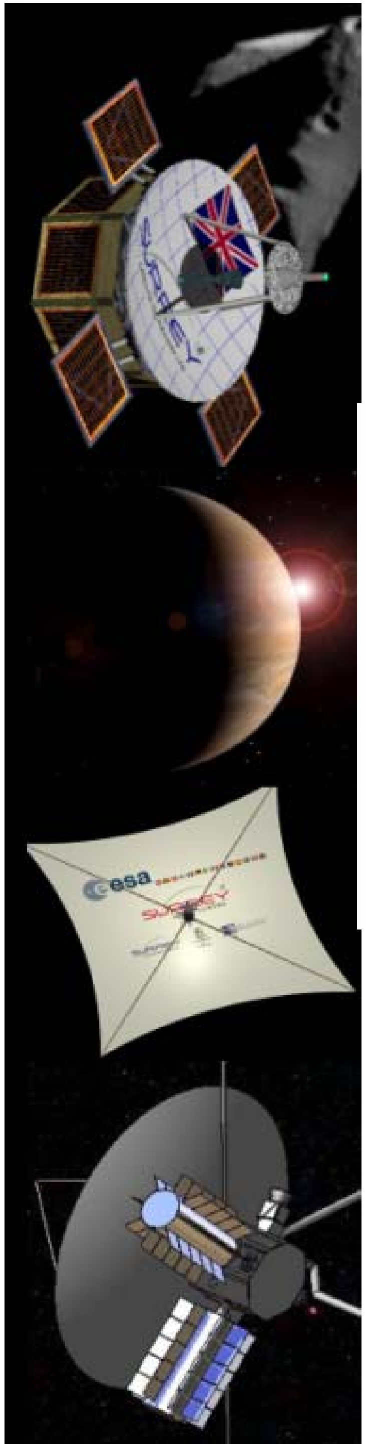


Case Study 2: Solar Kites (Micro Solar Sails) for Earth Magneto-tail Monitoring

- Wie, B.,*Arizona State University, Tempe, AZ 85287, USA*
- McInnes, C., *University of Glasgow, Glasgow, G12 8QQ, UK*
- Tarabini, L., *GMV S.A. C/Isaac Newton, Cantos, 28760 Madrid, Spain*
- Gomes, L., *Surrey Satellite Technology Ltd, Guildford, Surrey, GU2 7NE, UK*
- *Kotska Wallace, ESA-ESTEC*

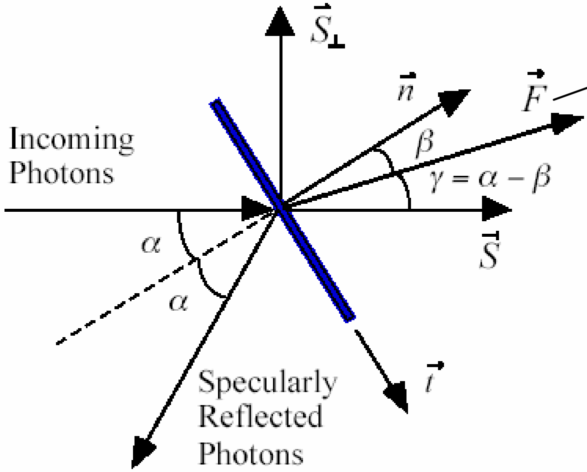
- Study Goal: Design a robust, affordable, low complexity solar kite mission with realistic requirements, a credible design and with a science return
- 2 kg, 5 x 5m solar sail !
- Use the Surrey 'Palmsat' as a platform





Solar Sail Fundamentals

- Solar Sails (SS) : Photons, coming from the sun, hit a particular area (surface) propel this particular structure by imparting a small force



$$F = \eta P A cos^2 \alpha$$

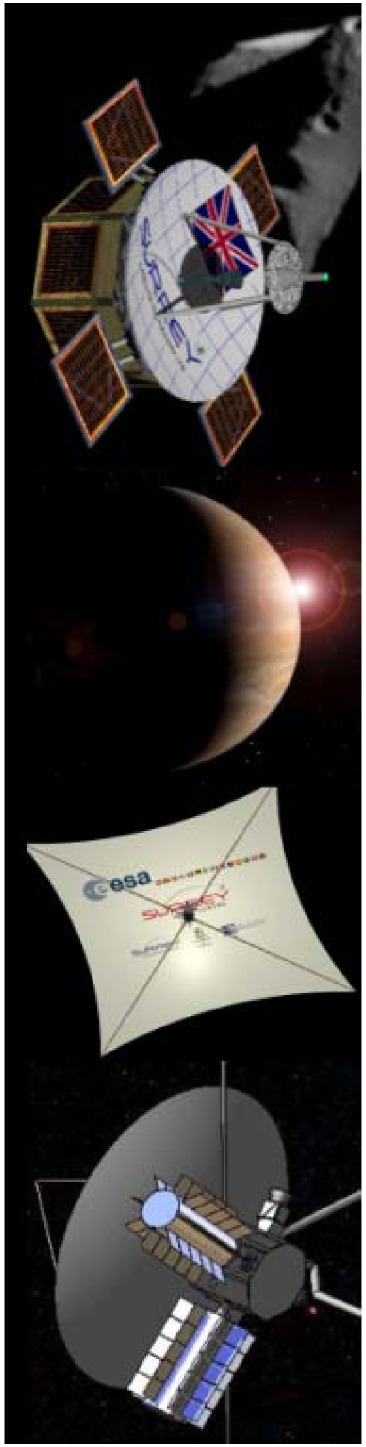
η: sail coefficient and has a typical value of 1.8 with film wrinkles

P: SRP constant at one astronomical unit (AU) from the sun,

A is the surface area of the SS

α is the sun angle between the surface normal and the sun line

- Still can be useful to propel spacecraft, for long distances, without carrying consumables (propellant)
- Significant mass reduction for the spacecraft and an increase in payload mass
- Another key advantage is the build-up of acceleration, which can be significant, which is ideal for high ΔV missions

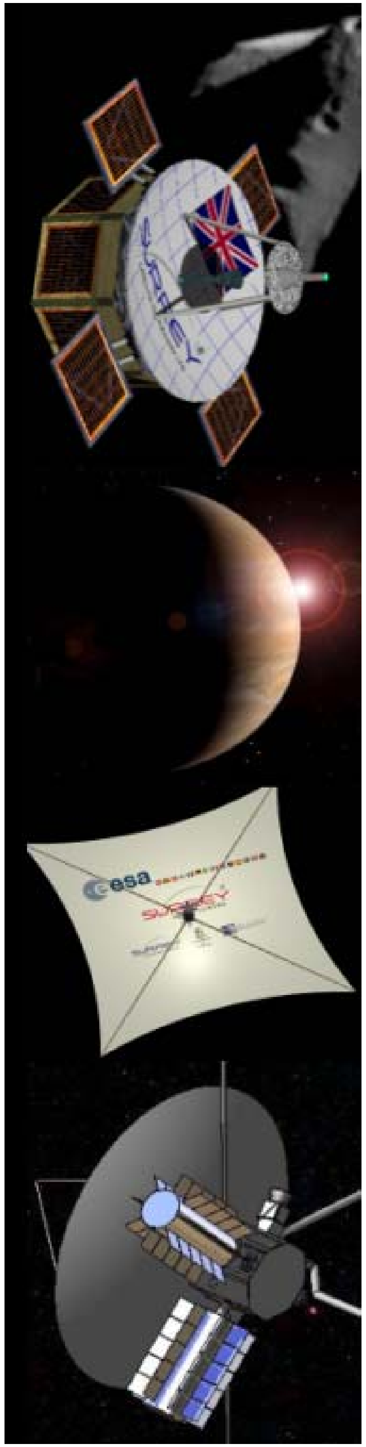


Solar Kite (Micro-Solar Sail)

- For a SRP constant of $P = 4.536 \times 10^{-6}$ N/m^2 , 5x5m sail:
- The acceleration is then:

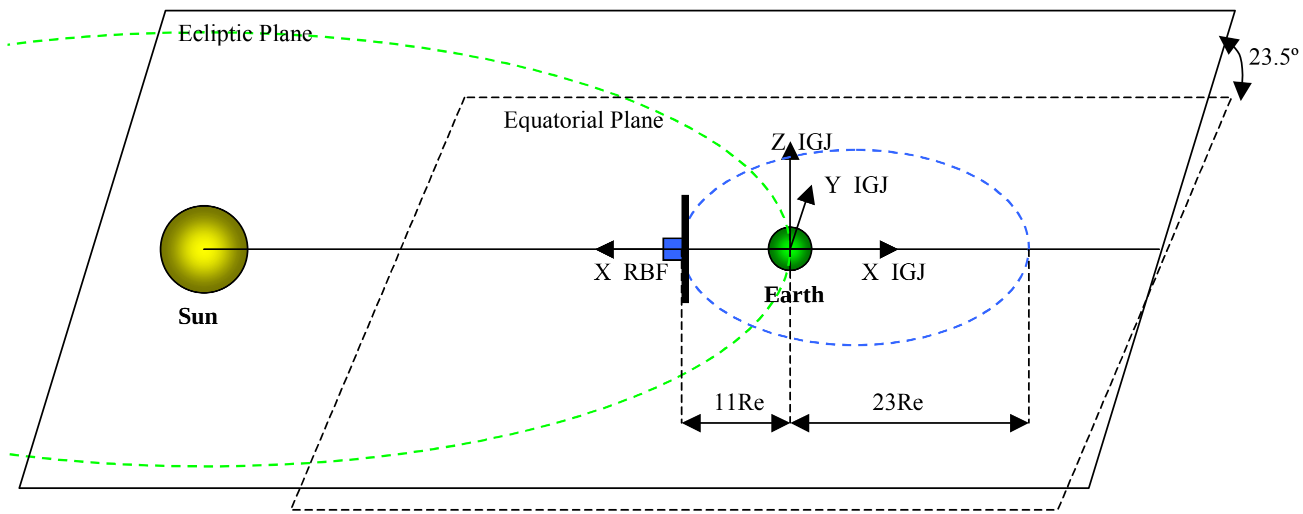
$$a_c = \frac{F_{\max}}{m} = \frac{\eta P A}{m} = \frac{\eta P}{\sigma} = 1.2 \times 10^{-4}\,\mathrm{ms}^{-2}$$

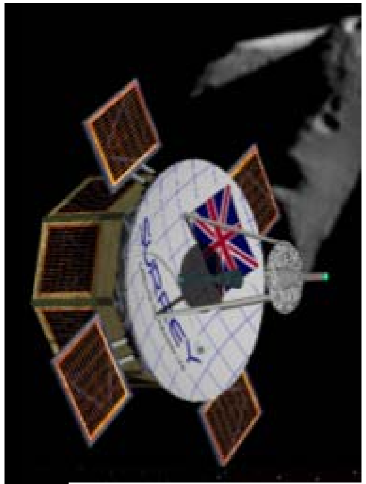
- SK's vs Large Sails: Small Satellites vs Large Satellites
  - Small Satellite Paradigm: 80% of a large mission with 20% the cost
  - Compliment large sails (> 20 m sails)
  - SK's: Easier to build, potentially less sail related challenges
  - Smaller sails, less control, dynamics, manufacturing, deployment issues, more experience available, use of inflatable technologies
  - Use MEMS, MNT, small satellite miniaturisation
  - Short design, construction turn around



A Solar Kite Mission to Study the Earth's Magneto-tail: GEOSAIL

- The geomagnetic 'tail' around Earth poses an important scientific problem related to weather conditions on Earth
- Geomagnetic tail missions require a spacecraft to be injected into a long elliptical orbit to explore the length of the geomagnetic tail.
- Orbit is inertially fixed, and the geomagnetic tail points along the Sun-Earth line, the apse line of the orbit is precisely aligned with the geomagnetic tail only once every year.





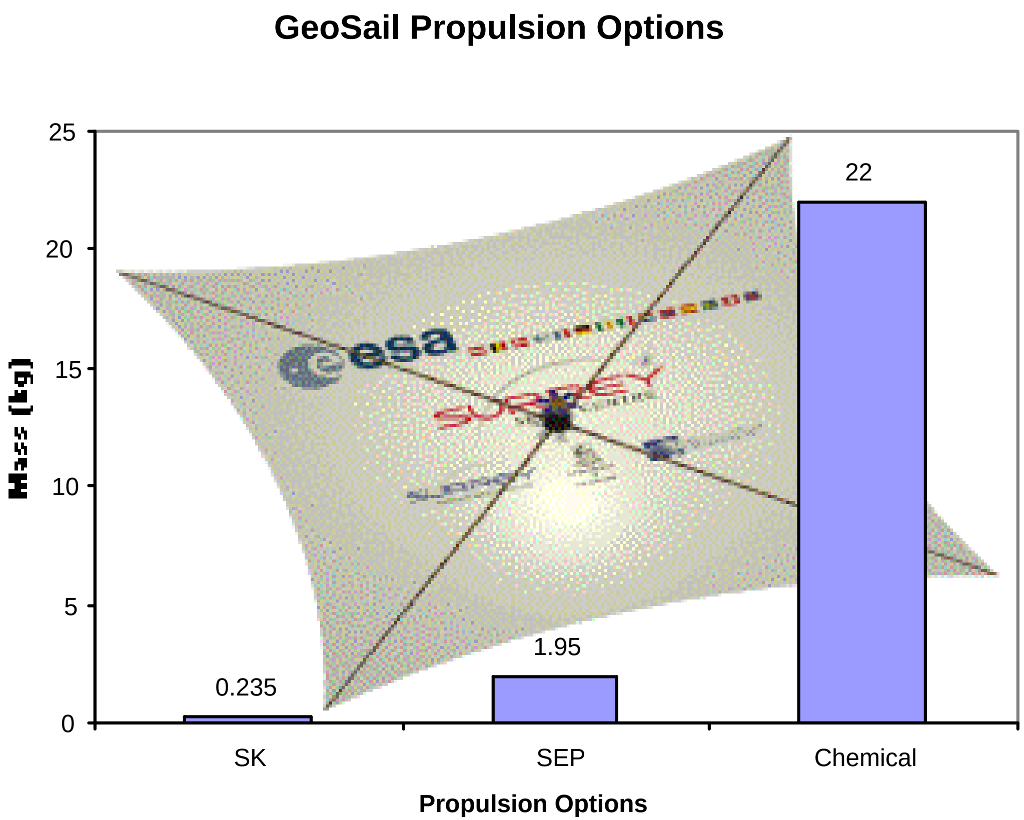
GEOSAIL Mission Analysis

- **Compare propulsion options:**
  - **Chemical, SEP, Sail**
  - **Use 1.5 kg 'bus'**

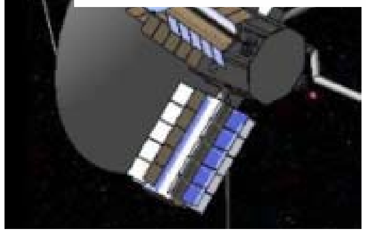
SEP Platform	
Mass of Propellant	0.354 kg
Mass of Motor	1.6 kg
Mass of Solar Panels	N/A
Total Mass	3.454 kg
Total Mass (+contingency)	4.490 kg

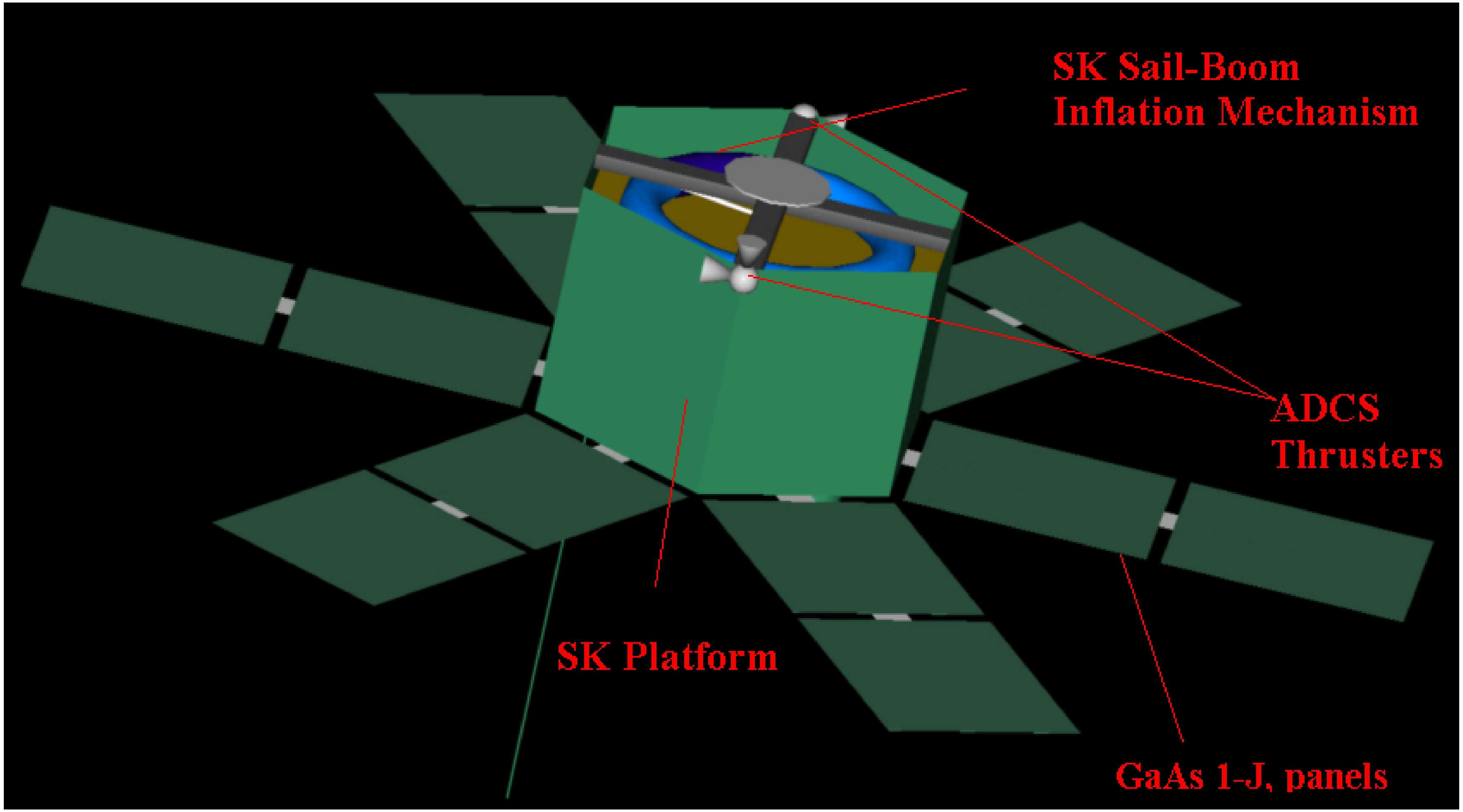
SK Desired Characteristics	
Total ΔV (km/s)	3.5
Acceleration (m/s²)	1.11E-04
Bus and P/L Mass (kg)	1.5

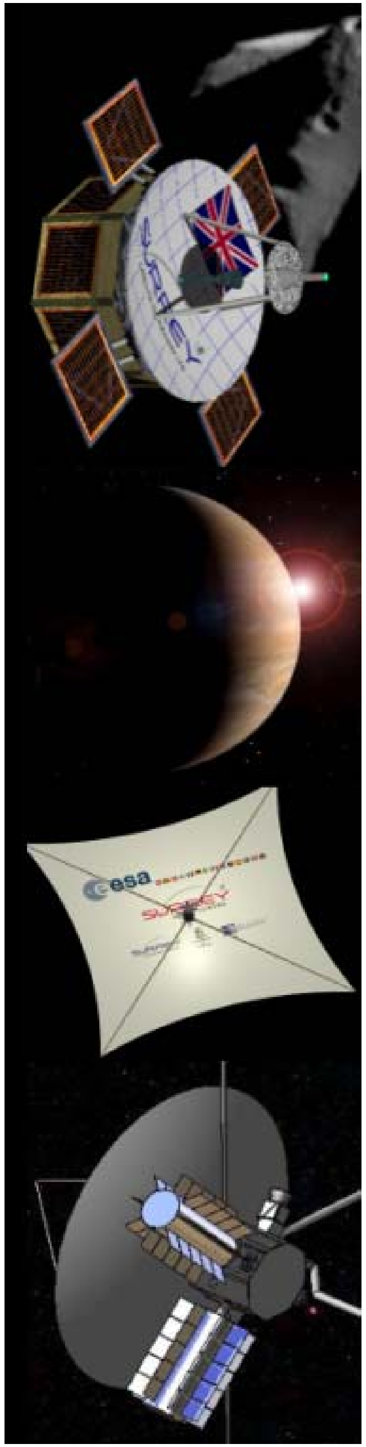
SK Sizing Parameters	
Solar Sail Mass (Ms)	0.235 kg
Total Mass	1.735 kg
Total Mass (+contingency)	2.256 kg
Sail Area	23.814 m²
Sail Side	4.88 m
Sail Film Mass (m_f)	0.071 kg
Mass of Booms	0.137 kg
Mass of Mechanisms	0.027 kg
Sail Structure Mass (m_b)	0.164 kg



Solar Kite Design



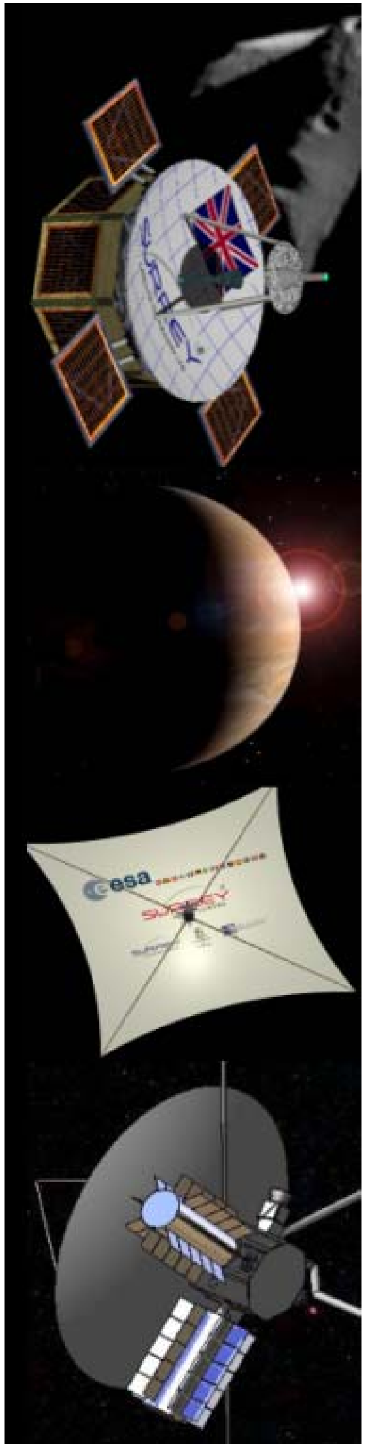




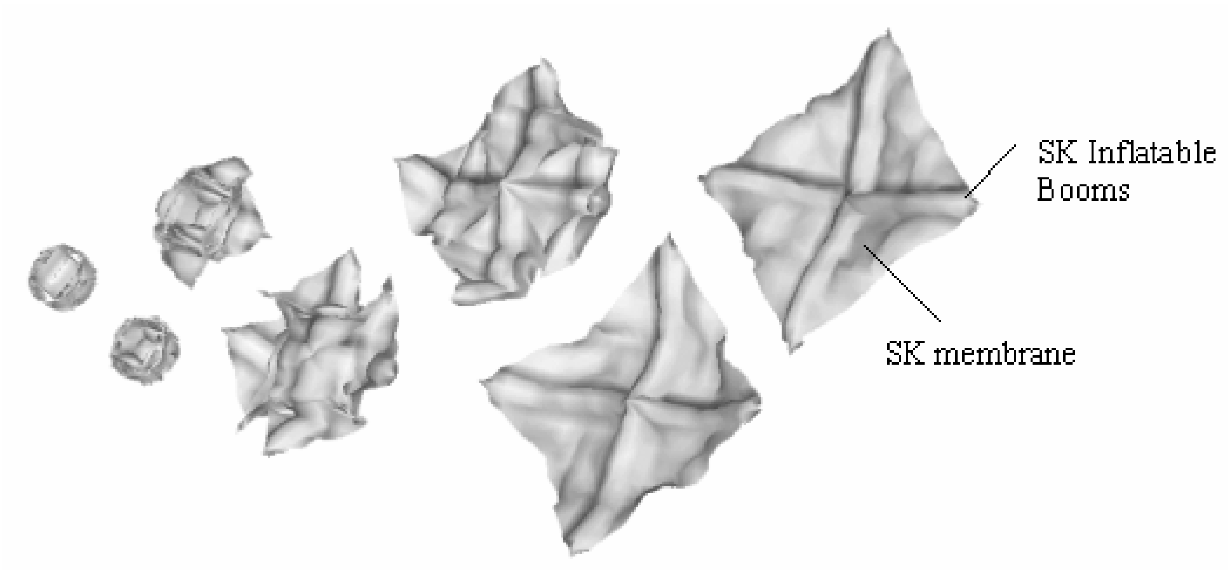
SK Boom/Sail Deployment (II)

- Deployment is achieved by two miniature valves, identical to the propulsion valves used in the SK ADCS system.
- A 9 g gas (Helium) will inflate the structure and LHZ (15 g) be able to provide continuous pressure for a minimum 2 year lifetime of the SK.
- Volume for the SK boom/sail structure is the smallest possible since storage for the integrated 'structure' is much more compact and lighter than using a traditional CFRP design

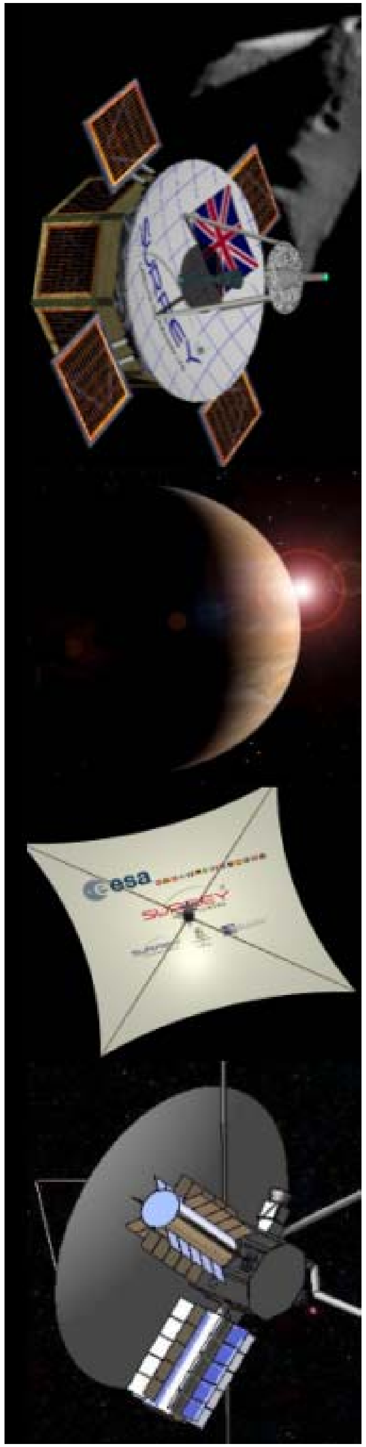
SK Sail/Boom Parameters	CFRP (kg)	Coilable (kg)	Inflatable (kg)
Sail film m_f	0.05	0.05	0.05
Booms (4) m_b	0.34	0.25	0.10
Deployment Mechanism	0.1	0.1	0.1
Total	0.49	0.4	0.25



SK Boom/Sail Deployment



SK Booms, Sail and Deployment (Nihon Concept)

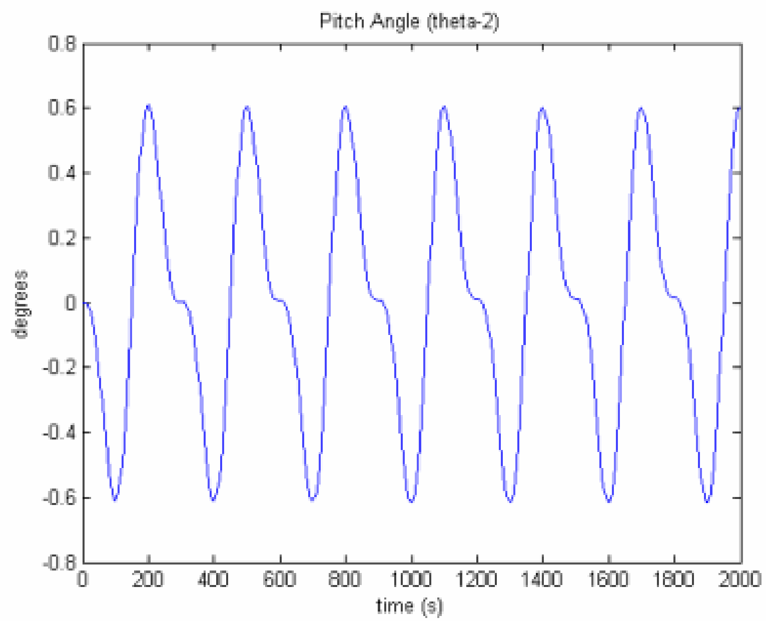


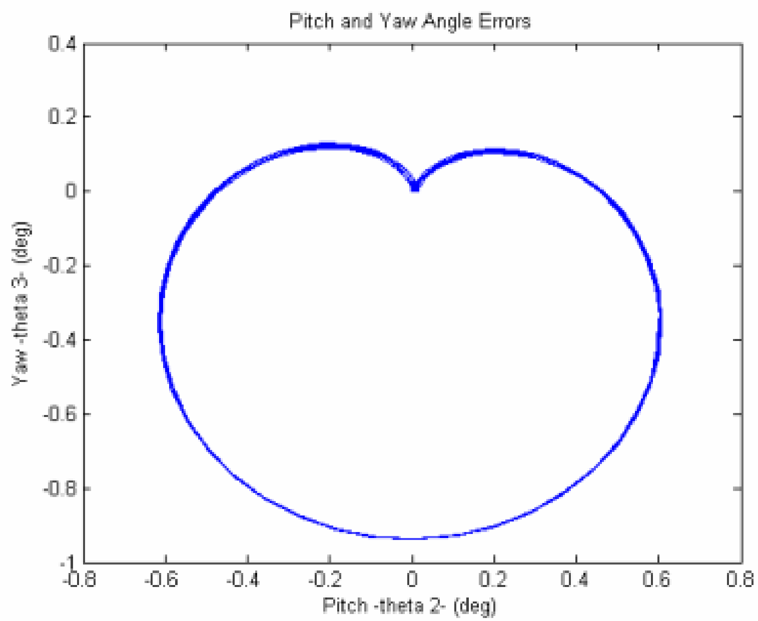
Solar Kite Attitude Control

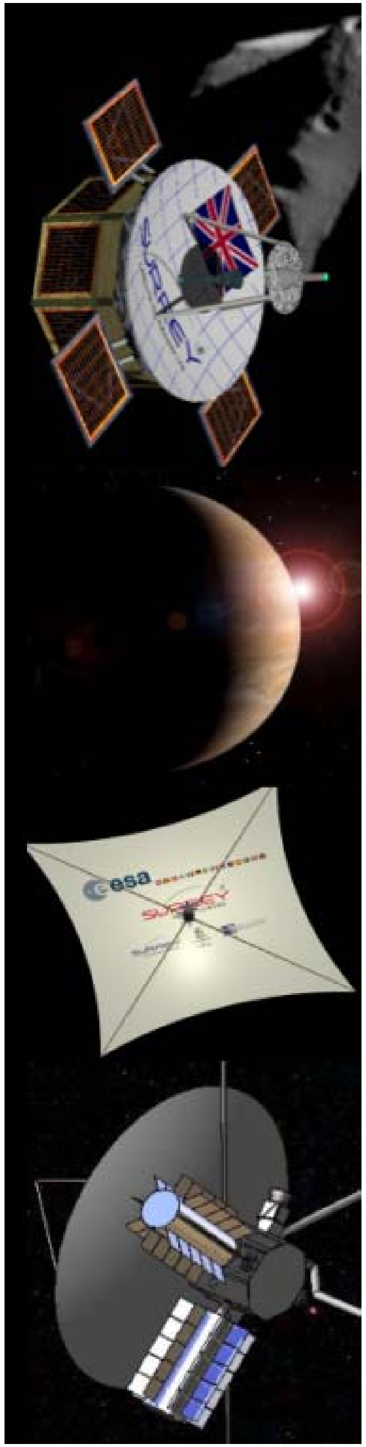
- The problem: Large inertias, little mass for ADCS...
- Large sails use cm-cp control techniques (gimballed booms etc.)
- Large sail control solutions won't be feasible for SK's
- Requirements:
  - Moments of inertia = (1.113, 0.556, 0.556) kg-m^2, cm-cp offset = 0.01 m (0.2% of 5 meter)
  - SRP Thrust = 0.2 mN, SRP Disturbance torque = 2 microN-m
  - Angular momentum storage/dumping > 0.0072 N-m-s per hour
  - Payload pointing accuracy = 1°
- Spin control scheme utilizing thrusters is selected

Solar Kite Control

- SRP Disturbance is largest disturbance: 2 micro-N-m
- For a 1 deg pointing requirement and a 0.2-mN solar pressure force, a spin rate of Ω = 1.2 deg/s is needed
- Simulations conducted for the SK indicate that the required control and stabilisation requirements are feasible







Guidance and Control for an Interstellar Heliopause Probe (IHP) Solar Sail Mission to 200 AU

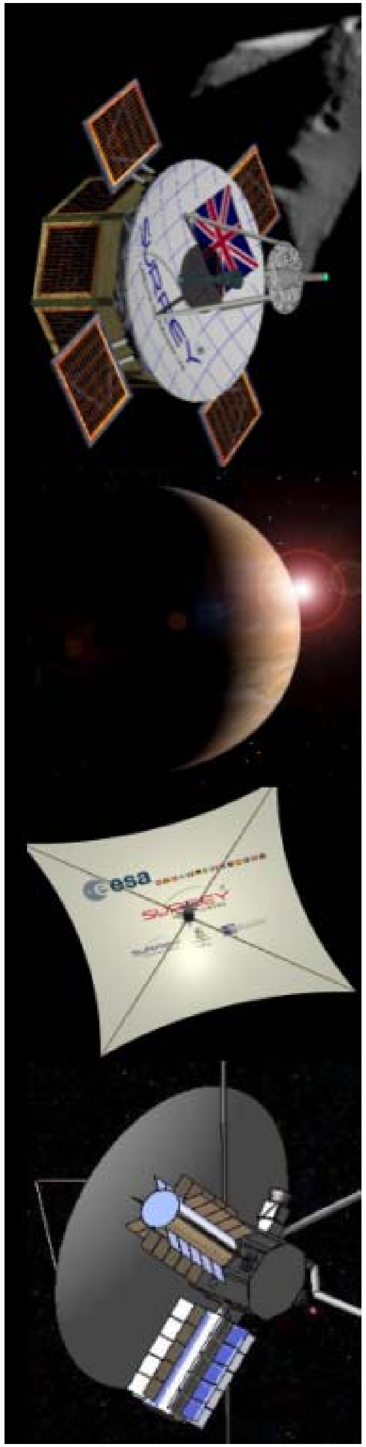
V. Lappas (1), S. Wokes (1), M. Leipold (2), A. Lyngvi (3), P. Falkner (3)

(1) University of Surrey, Surrey Space Center, UK

(2) Kayser-Threde GmbH, Wolfratshauser Str. 48, 81379 Munich, Germany

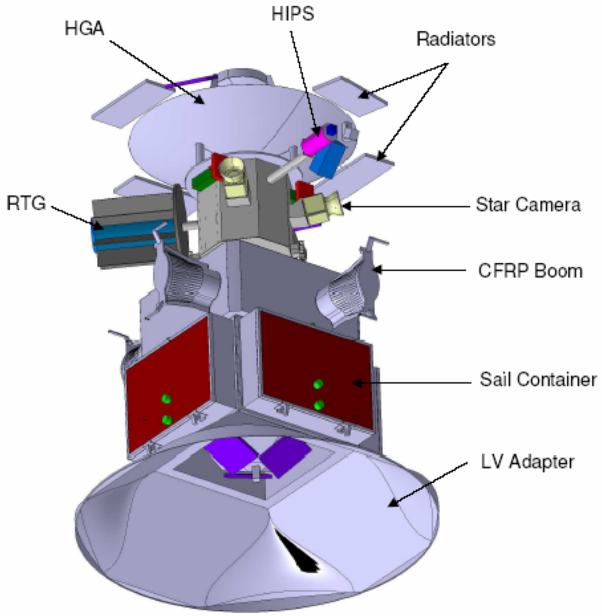
(3) Science Payload and Advanced Concepts Office, ESA, ESTEC, The Netherlands

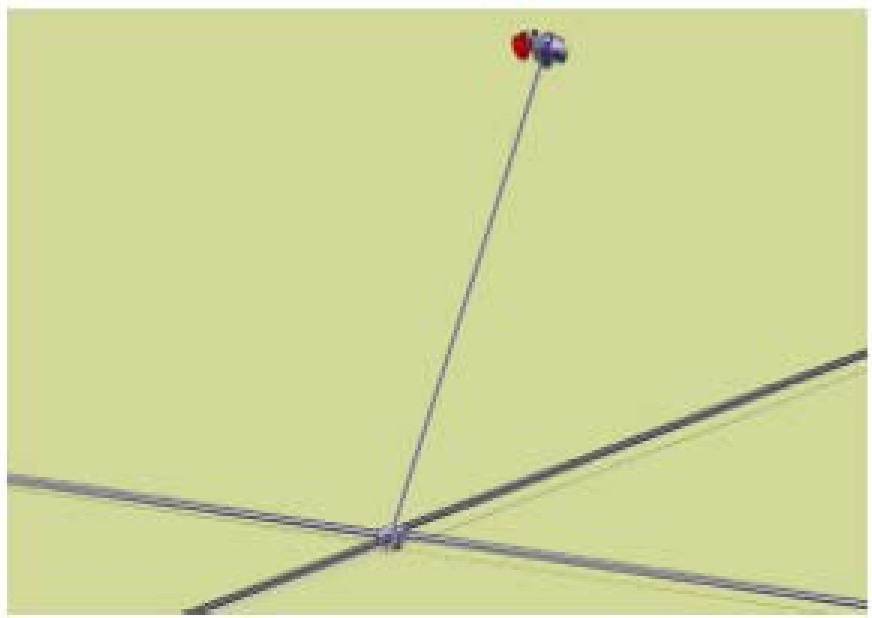
- Technology Reference Study by ESA
- The TRS studies focus on the development of strategically important technologies of likely relevance to future science missions.
- The IHP probe is a solar sail based probe.
- A ‘photonic assist’ trajectory is used in order to boost the IHP ΔV by performing two approaches close to the sun (0.25 AU).



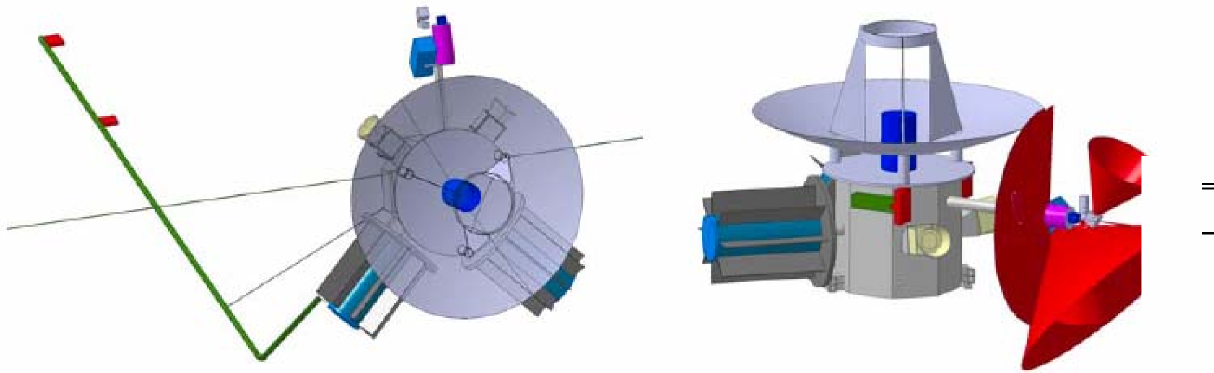
IHP Mission

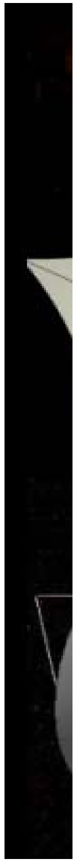
- The solar sail based IHP design will require a 245 m sail with an ejectable sail deployment structure.
- After 6.5 years of flight time the sail module of the IHP is ejected and the science platform begins its cruise phase to the Heliopause.
- Result is a 517 kg solar sail spacecraft capable of reaching 200 AU's in 30 years
- Payload: 19.2 kg, 22 W peak power

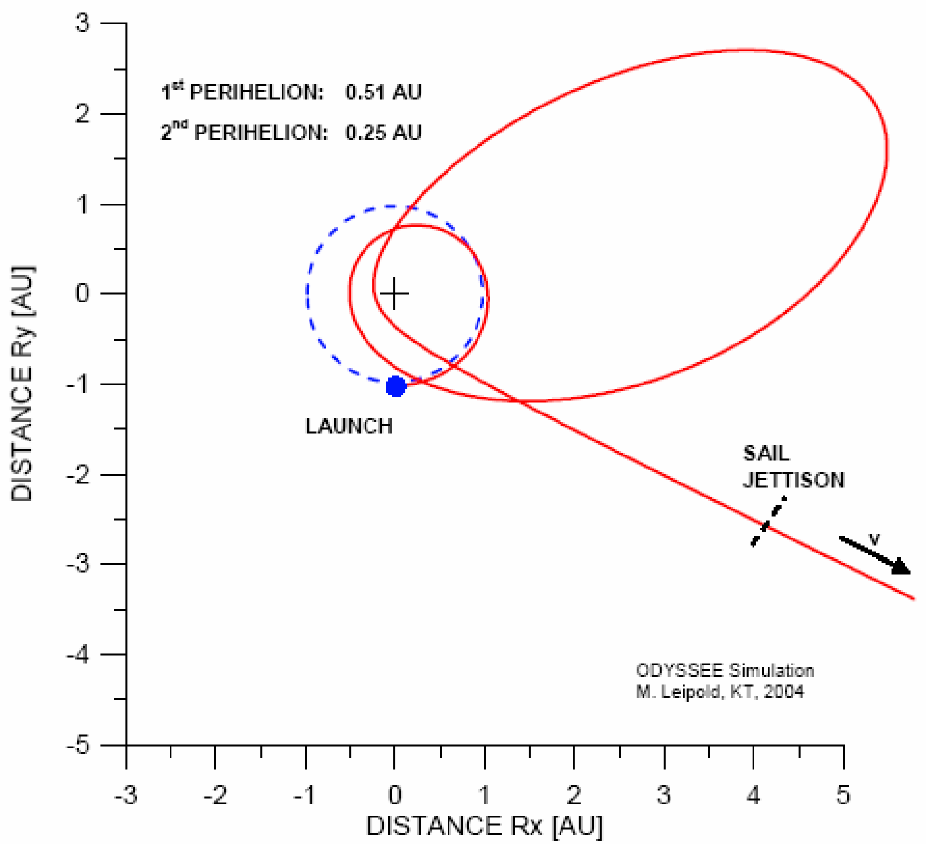




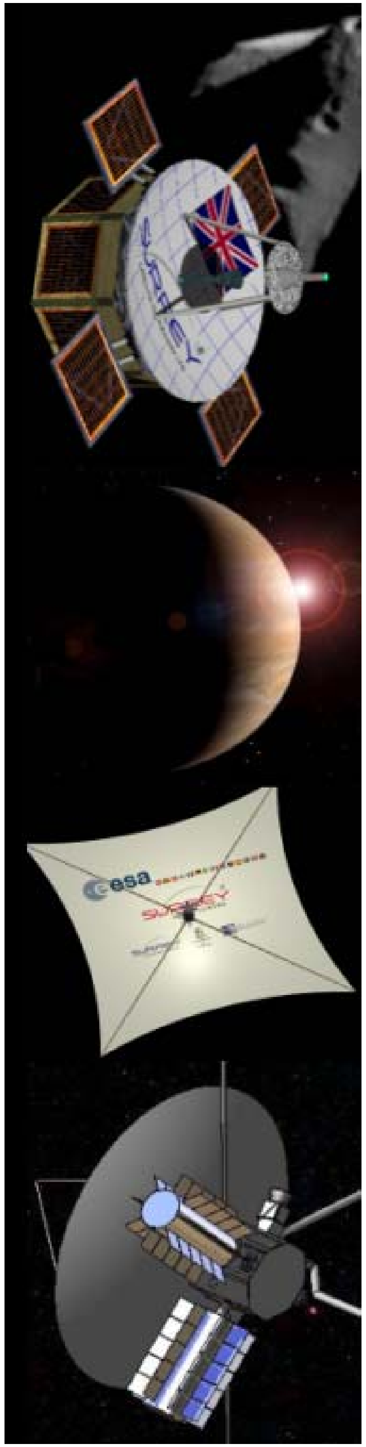
IHP





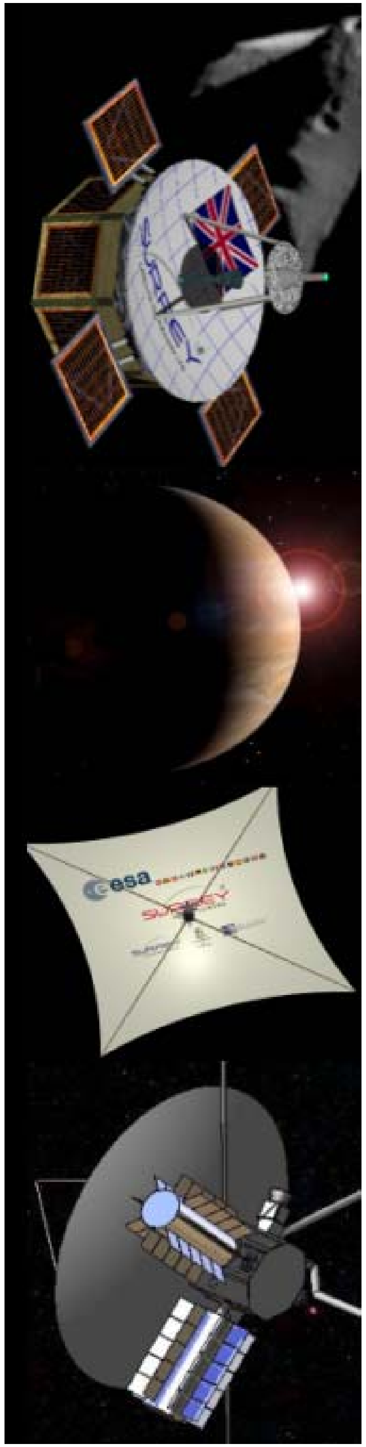


Sail Parameter	Value
Characteristic Acceleration (with 10% margin)	1.1 mm/s^2
Sail Efficiency η	0.85
Sail Assembly Loading	3.9 g/m^2
Bus Mass (with 20% margin)	181.7 kg
Sail Mass	187.6 kg
Sail Margin (10%)	18.8
Total Sail Mass	206 kg
Sail Area	60654 m^2
Sail Size (Square)	246.3 m
Boom Length	174.1 m
Boom Specific Mass	100 g/m
Total Boom Mass	70.1 kg
Sail Film CP-1 Aerial Mass	1.4 g/m^2
Total Film Mass	123.6 kg
Boom Deployment Mechanisms	25 kg
Sail Containers	20 kg
Sail Deployment Mechanism	10 kg
Sail Total Net Mass	249 kg
Jettisonable Mass	42 kg
Solar Sail Total	206 kg



Study/Mission/Attitude Control Requirements

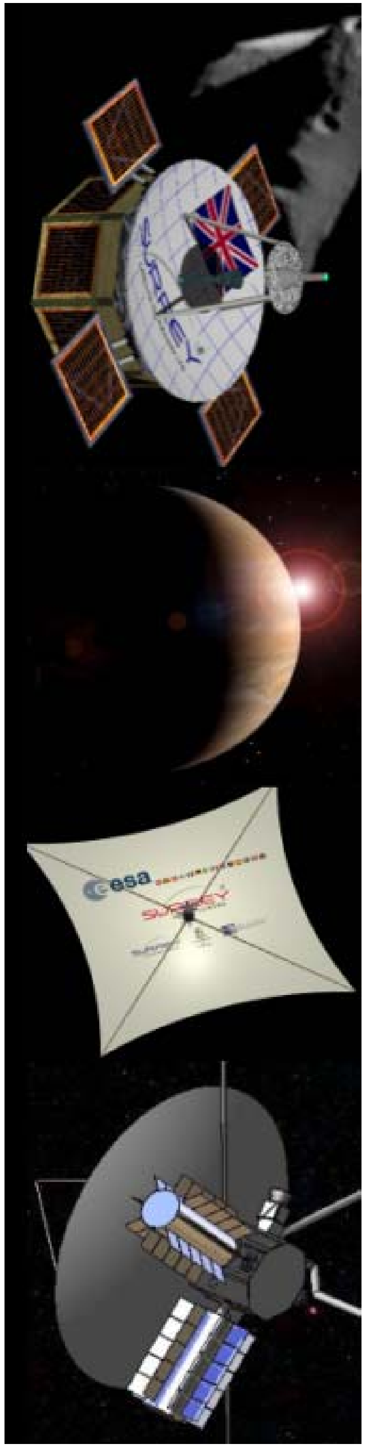
- Maximum turn rate sailing mode: 29°/day (heliocentric, near sun)
- Pointing stability science mode: 0.5°
- Life time:
  - sailing mode: ca. 6.5 years
  - science mode: ca. 19 years
- Minimum mechanical complexity
- Sailcraft controllability for first natural frequency of 0.0065 Hz
- Coherent AOCS design for sailing mode and science mode (sensors etc.)
- Need to design two different ADCS for IHP



Challenge: IHP Sail Attitude Control

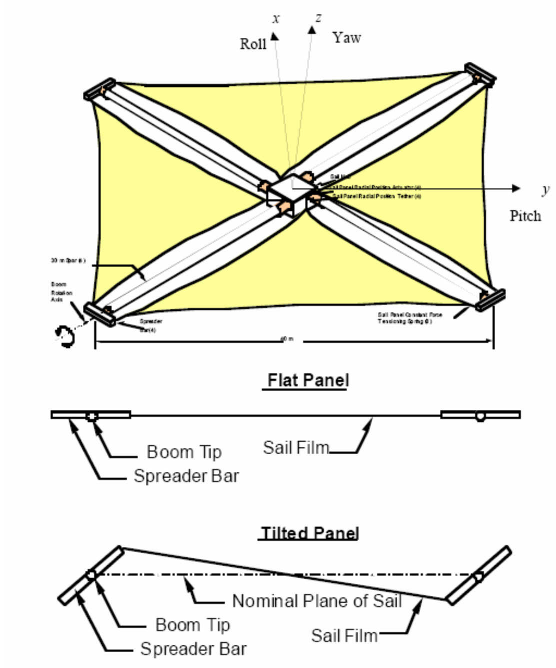
- Large inertias, small mass envelope
- A 40 x 40 m sailcraft with a nominal solar thrust force of 10 mN and a center-of mass to center-of-pressure (cm/cp) offset of ±0.1 m has an SRP disturbance torque of ±1 mN-m, which is about 100 times larger than that of typical geo-synchronous communications satellites [Wie et al.]
- Depends on sail configuration and deployment
- Solar Sail is inherently coupled to solar sail technology
- Many deployment and control schemes available:
  - Spinners
  - TVC (cm-cp methods)
  - Hybrid
- Most Sail ACS designs are towards generic 3-axis schemes

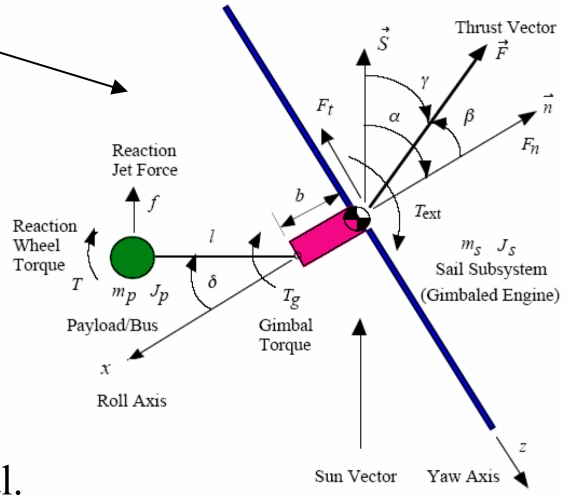
SURREY SPACE CENTRE



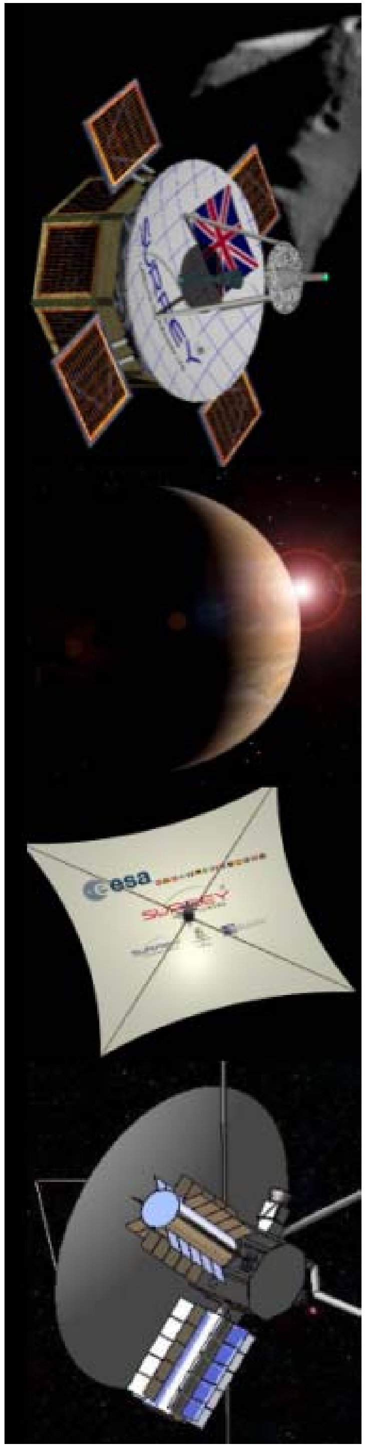
IHP Sail Control Schemes

- Spin Type
- Sail Translating/tilting panels
- Thrust Vector Control
  - Gimballed Booms
  - Tip vanes

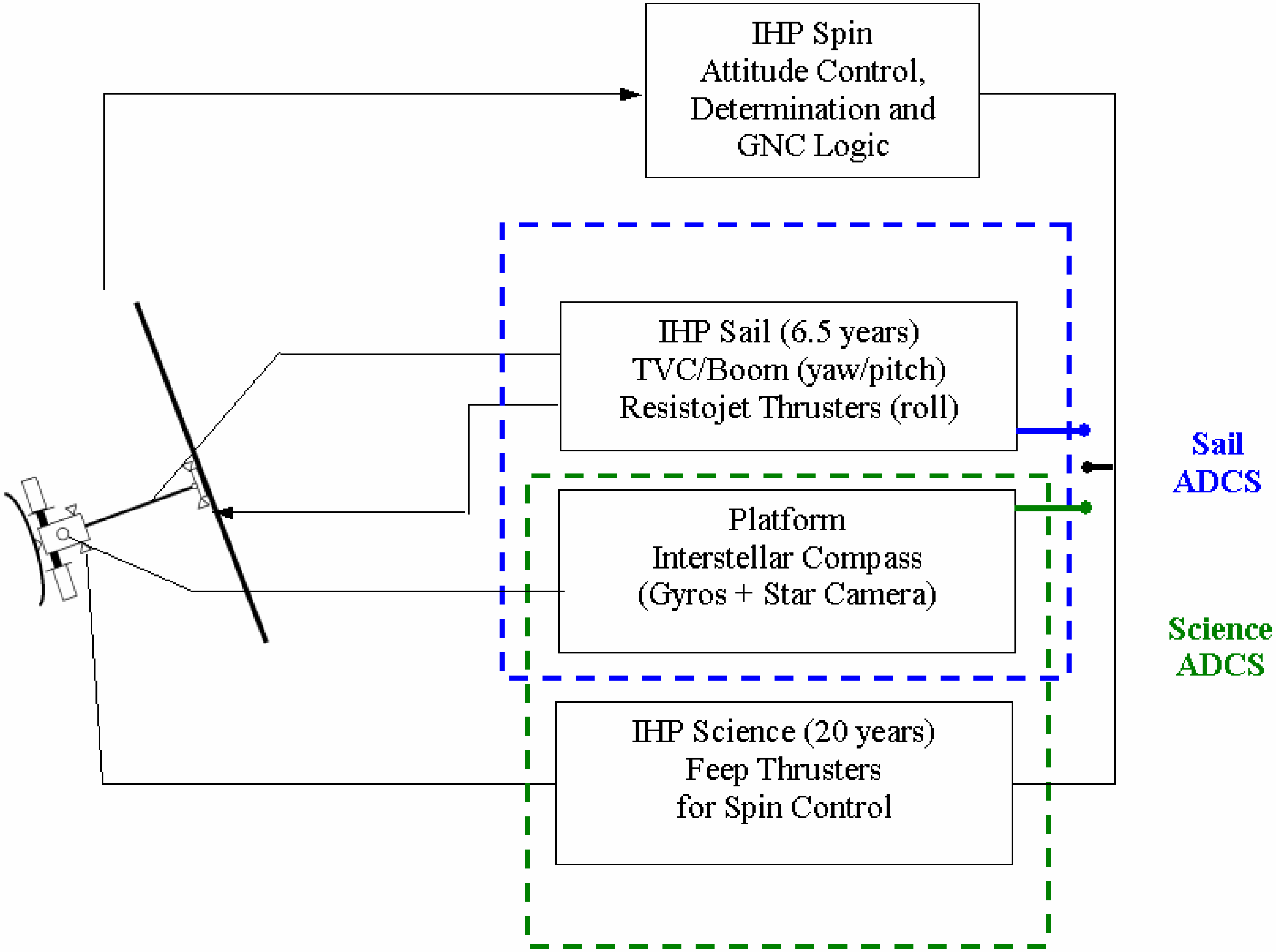


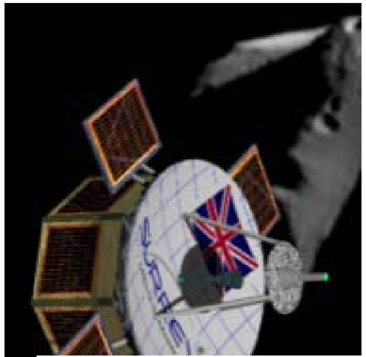


Diagrams from Wie et al.



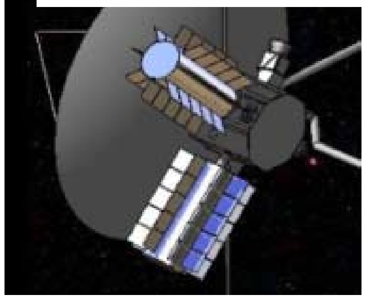
ADCS Architecture





IHP Sail Control Scheme Trade-Off

Control Schemes	Advantages	Disadvantages
Tip Vanes	3-axis, tested in orbit on GEO sats	Heavy, complex, power hungry, non redundant
Quadrant Tilt Translation	3-axis, use torque arms	No heritage, non redundant, heavy
TVC	2-axis	Needs also tip vanes or quadrant tilt, single point failure possibility, heavy
Quadrant Tilt	Single axis, easy to use	Need to combine with other schemes
Ballast	Full 3-axis control, agility	Mechanisms, failures
Tip Thrusters	Excellent for spin, need ballast for 3-axis, using large torque arms	Wireless RF/power needed



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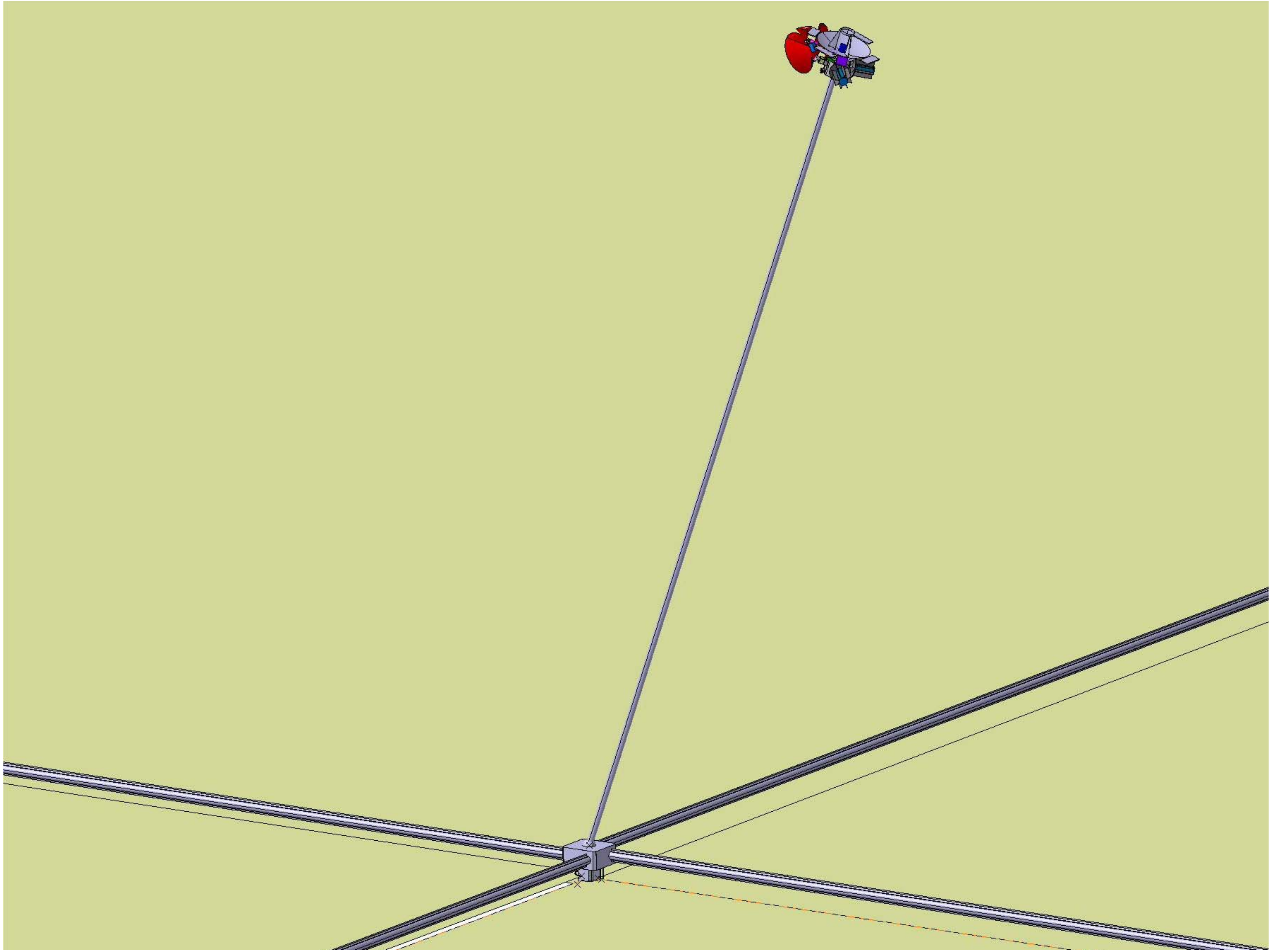
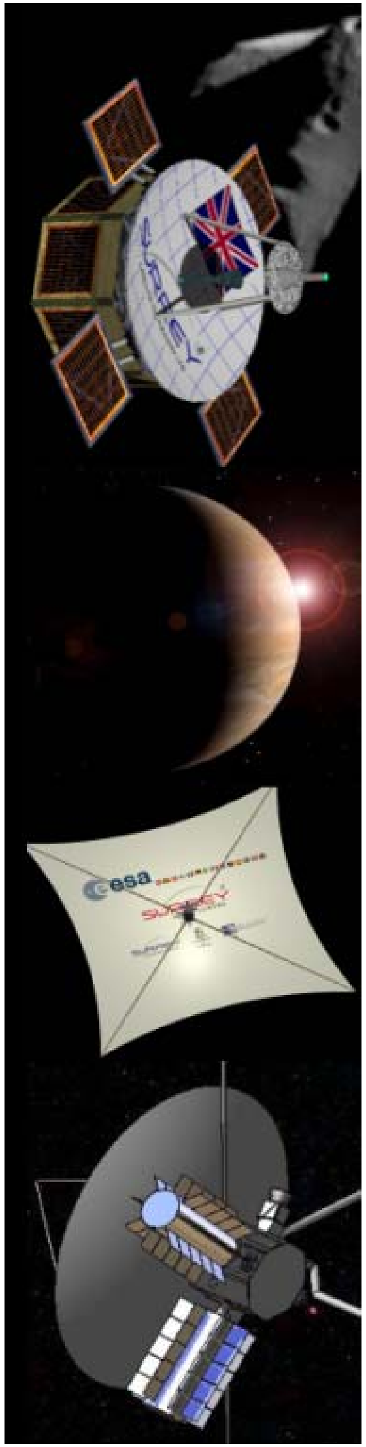
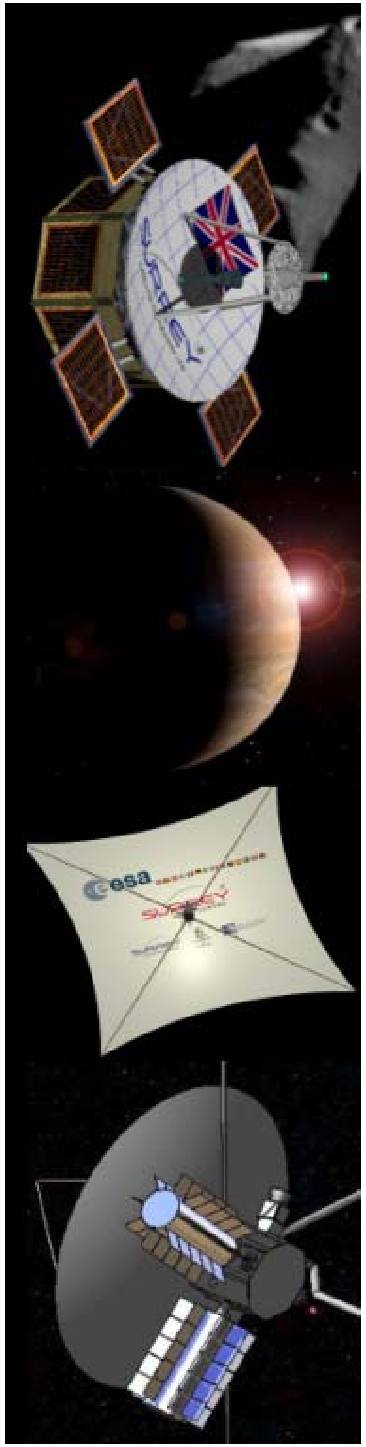


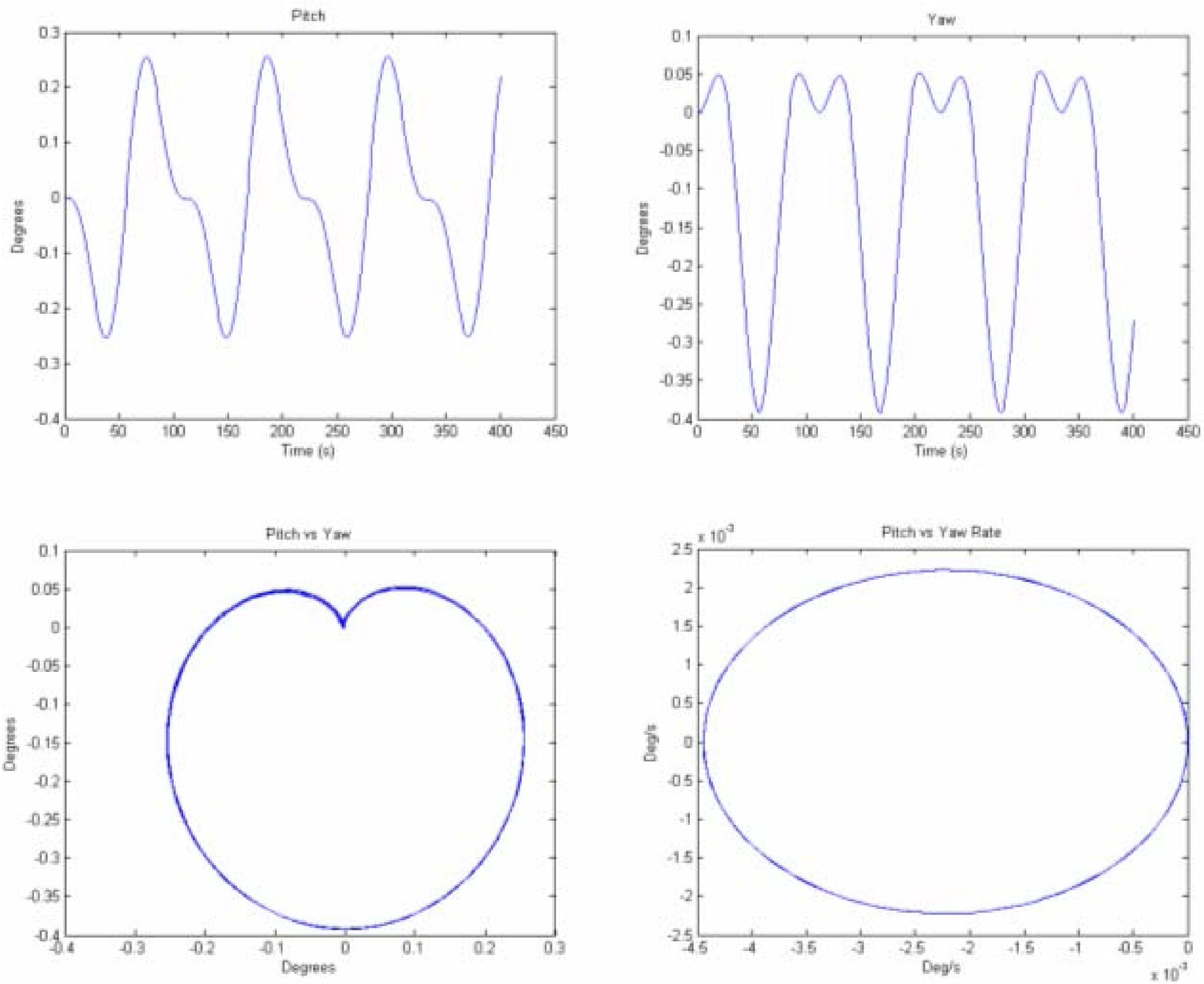


IHP Sail Control

- Moments of inertia = (433000, 433000, 865000) kg-m^2
- cm-cp offset = 0.525 m (0.2% of 245 meter sail edge)
- SRP Thrust = $F_{max} = \eta PA$ = 0.3621 N
- where, η is the sail efficiency (1.8 assumption), P is the SRP constant P = 4.536 x 10^{-6} N/m^2 at 1 AU, A is the projection area (245 x 245 - m^2)
- N_{SRP} , SRP Disturbance torque = F (cm-cp) =0.189 N-m
- Angular momentum storage/dumping > (N_{SRP})(3600 s)= 680 N-m-s per hour
- Use a 0.65 deg/s spin rate for 0.5 deg pointing accuracy, <u>1-2 rpm</u>
- Sail can also be placed in a 3-axis mode (Thrust Vector Control)

Simulation in IHP Sail Spin Mode





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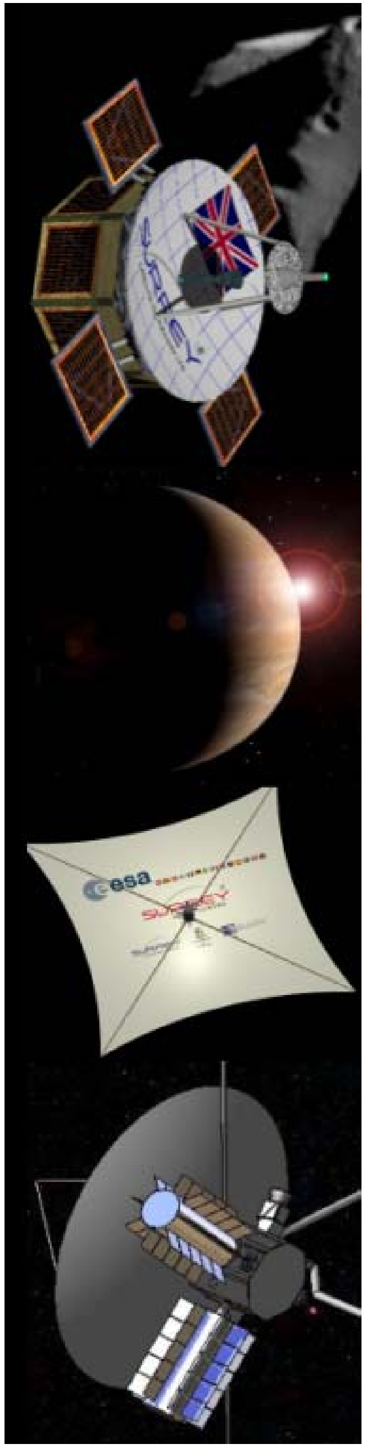
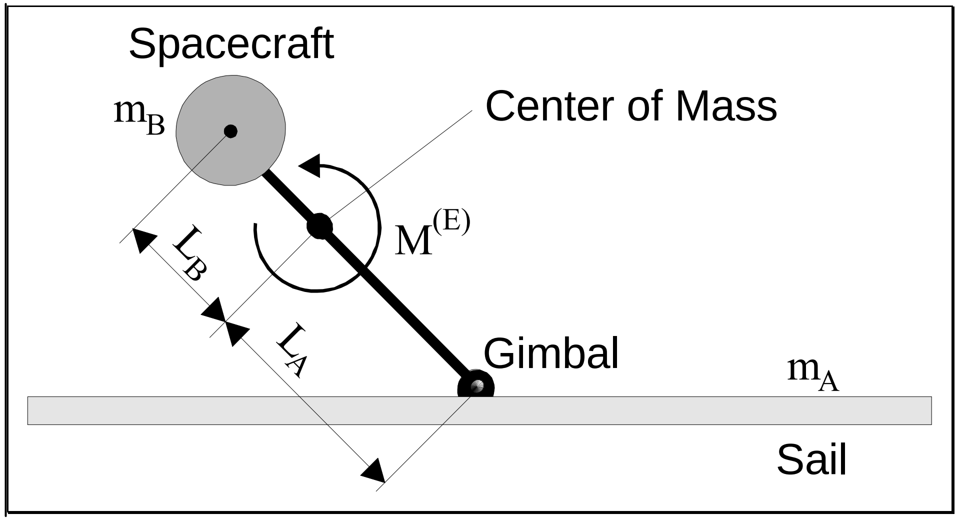
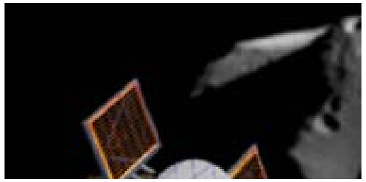


Thrust Vector Control (TVC)

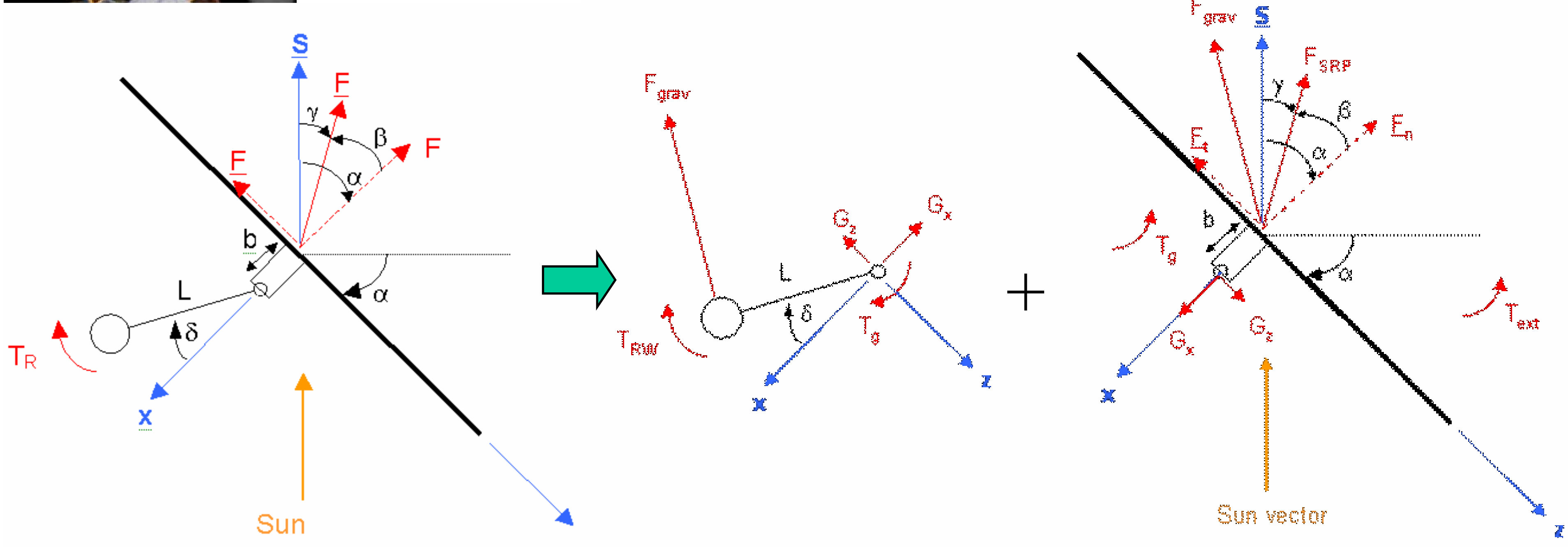
Features :

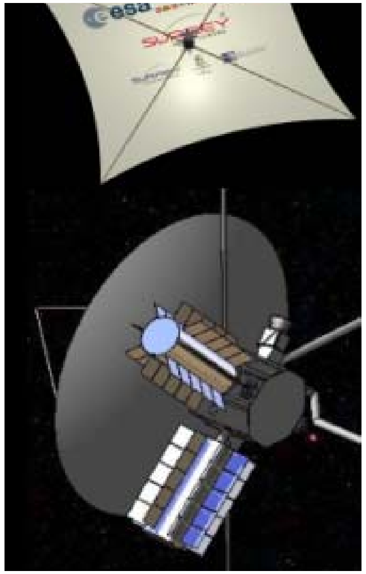
- uses 2-DOF gimbal for control about 2 axes during cruise
- keeps mechanical system central; no boom tip masses or mechanisms needed
- Actuation Range: ± 70°
- Power Level: ca. 10 W Average Power for gimbal actuation





TVC Dynamics

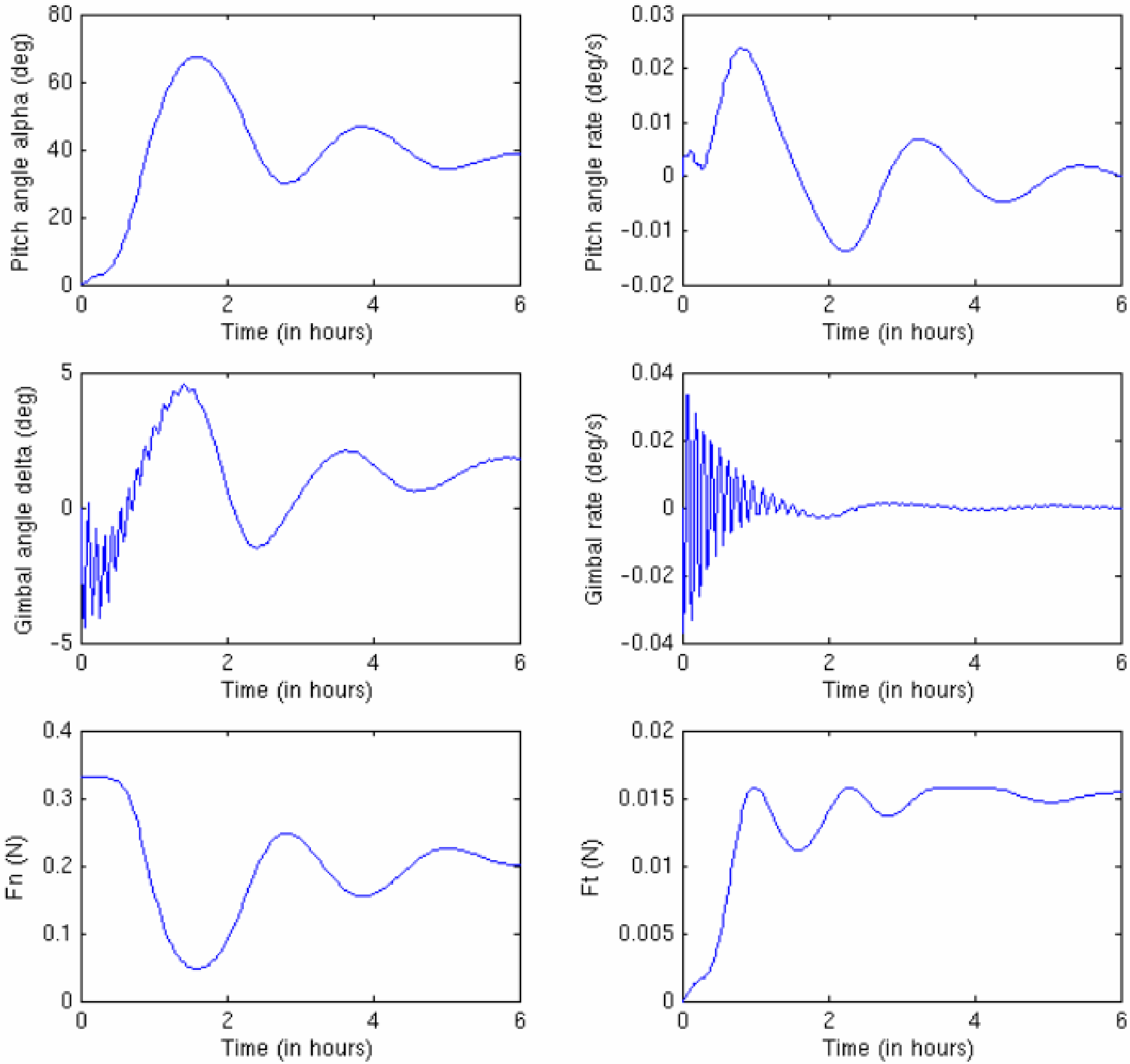




- TVC Pitch Axis:

$$\left[J_s + \frac{m_s m_p}{m} b(b+\ell)\right]\ddot{\alpha} + \frac{m_s m_p}{m} b\ell\ddot{\delta} = -\frac{m_p}{m} bF_t + \frac{m_s}{m} bf - T_g + T_{ext}$$

$$\left[J_p + \frac{m_s m_p}{m} \ell(b+\ell)\right]\ddot{\alpha} + \left[J_p + \frac{m_s m_p}{m} \ell^2\right]\ddot{\delta} = -\frac{m_p}{m} \ell F_t - \frac{m_p}{m} \ell F_n \delta + \frac{m_s}{m} \ell f + T_g + T$$



-MATLAB

-35 deg in 6 hrs

-20m Mast

-245 x 245 m

-200 kg science s/c

-500 kg total mass

-Gimbal angle < 5 deg

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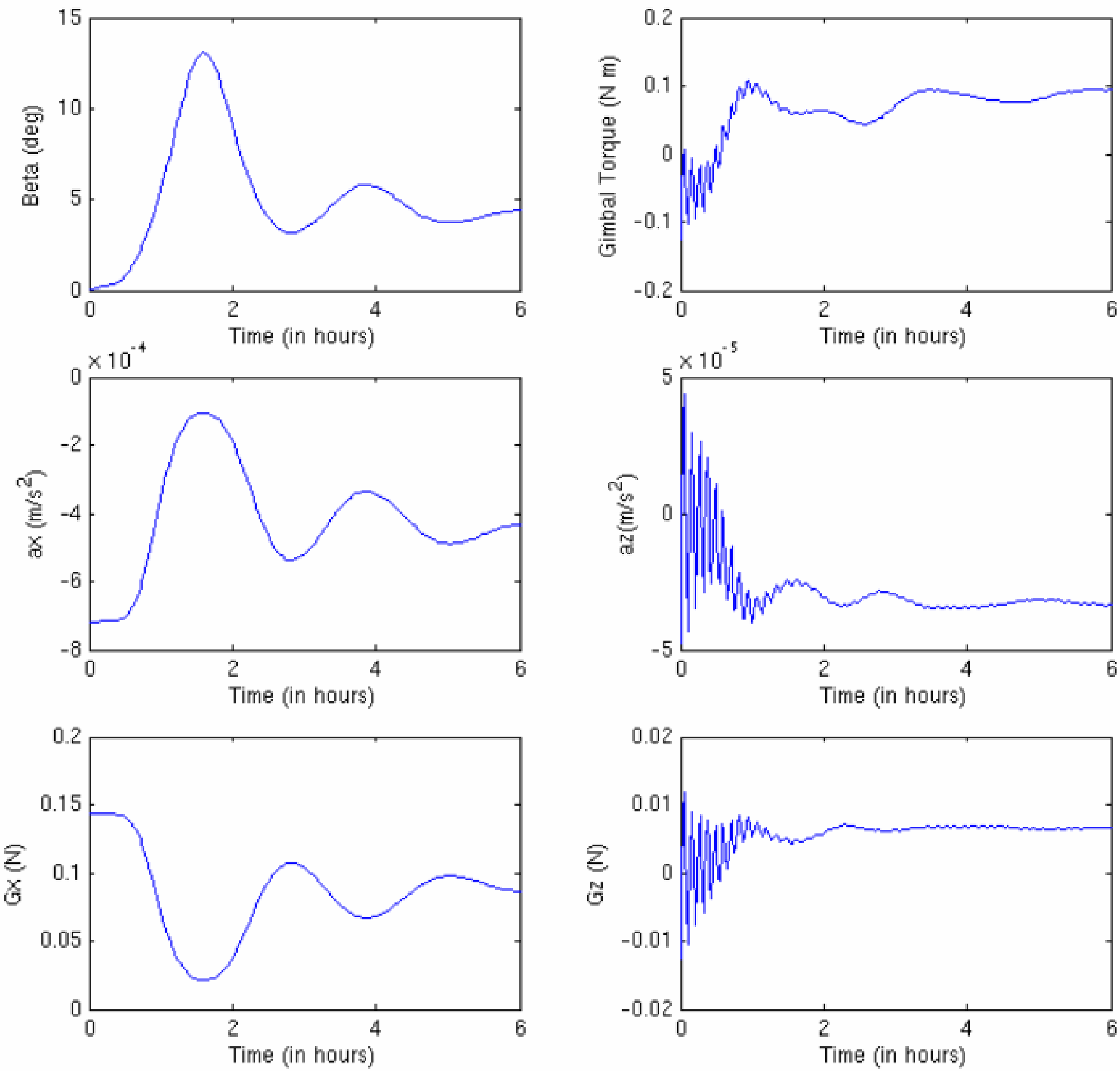

-Gimbal torques < 0.15 Nm

-Means needs robust Gimbal mechanism

-Simulations include

$\varepsilon = -0.5$ m cm/cp offset

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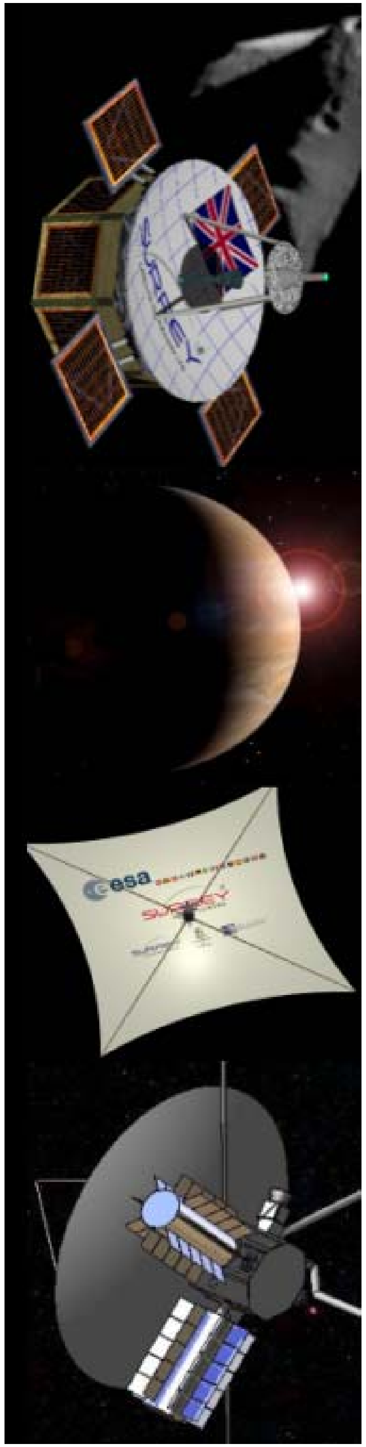
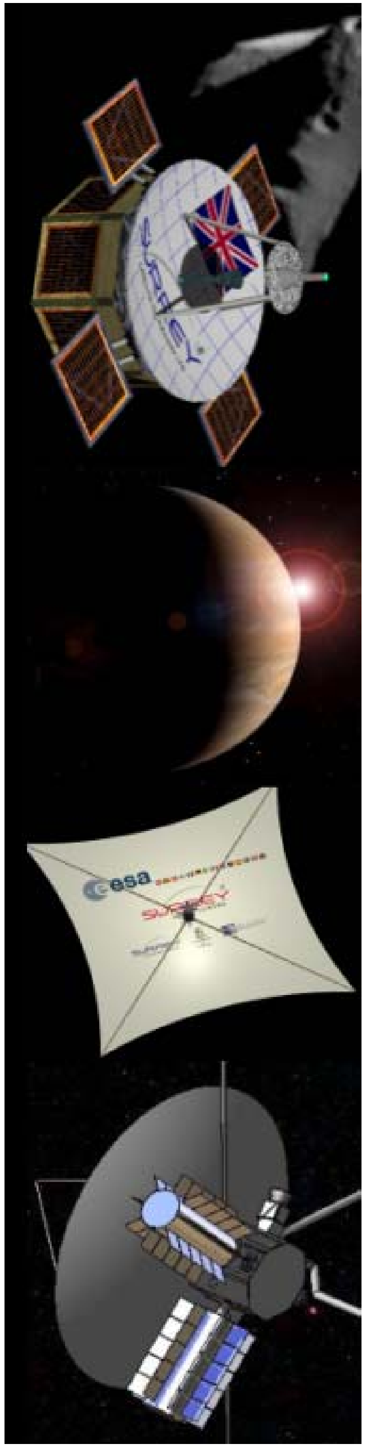


Conclusion

- Used 3 case studies to illustrate that attitude control systems (ACS) for planetary missions:
  - Have very diverse requirements
  - Physical constraints/lifetime impose multiple challenges
  - Can’t use conventional solutions
  - Robustness is a critical requirement (expensive, long term missions)
  - Need increased autonomy
- ACS is usually coupled to mission design/architecture
- Offered some low cost, innovative and versatile ACS solutions



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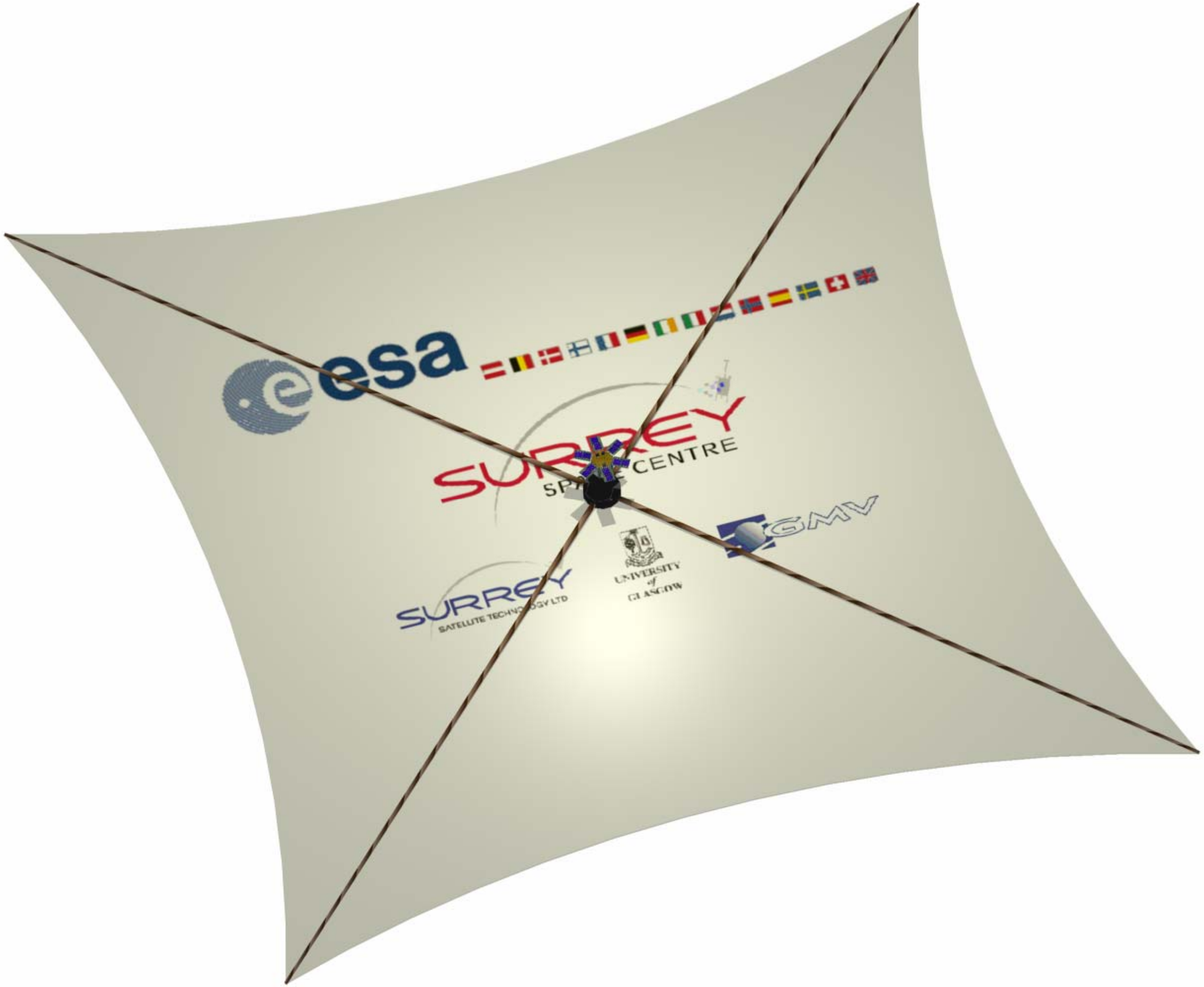
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