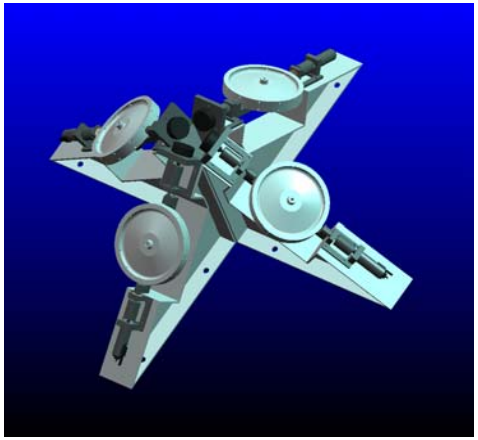
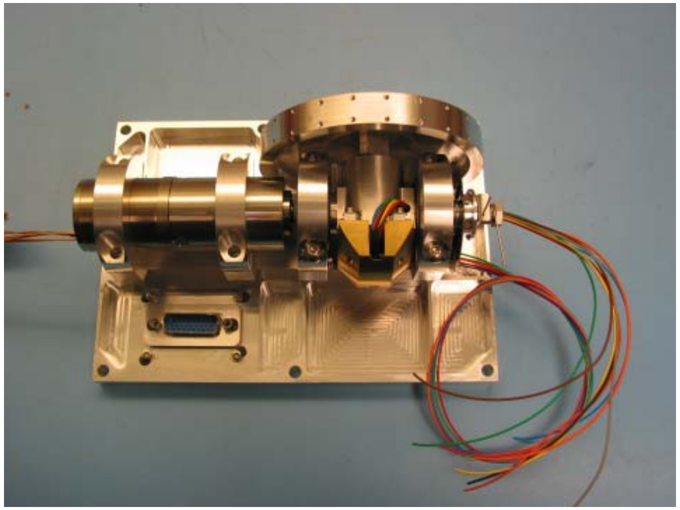
" Control Techniques for Aerospace Systems "





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May 7, 2003

METU-AERO

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SPACE AT SURREY

Minisatellites - Microsatellites - Nanosatellites

(platforms & payloads)

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

- *134 professional staff*
- *8 faculty*
- *27 PhD researchers*
- *18 visiting staff*
- *dedicated space building*

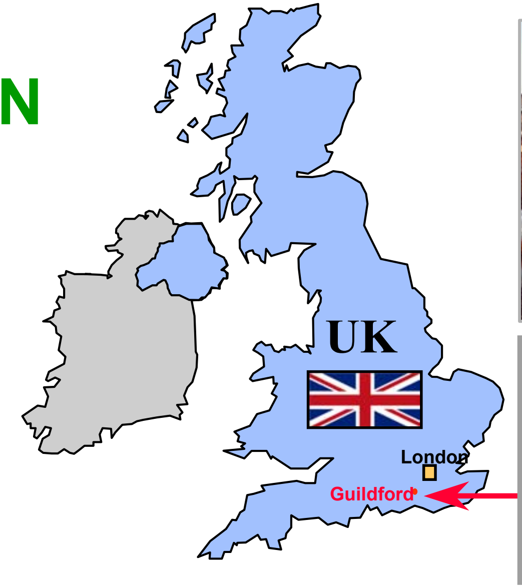
POSTGRADUATE EDUCATION

Research Degrees (MSc, PhD)

Short Courses for Industry

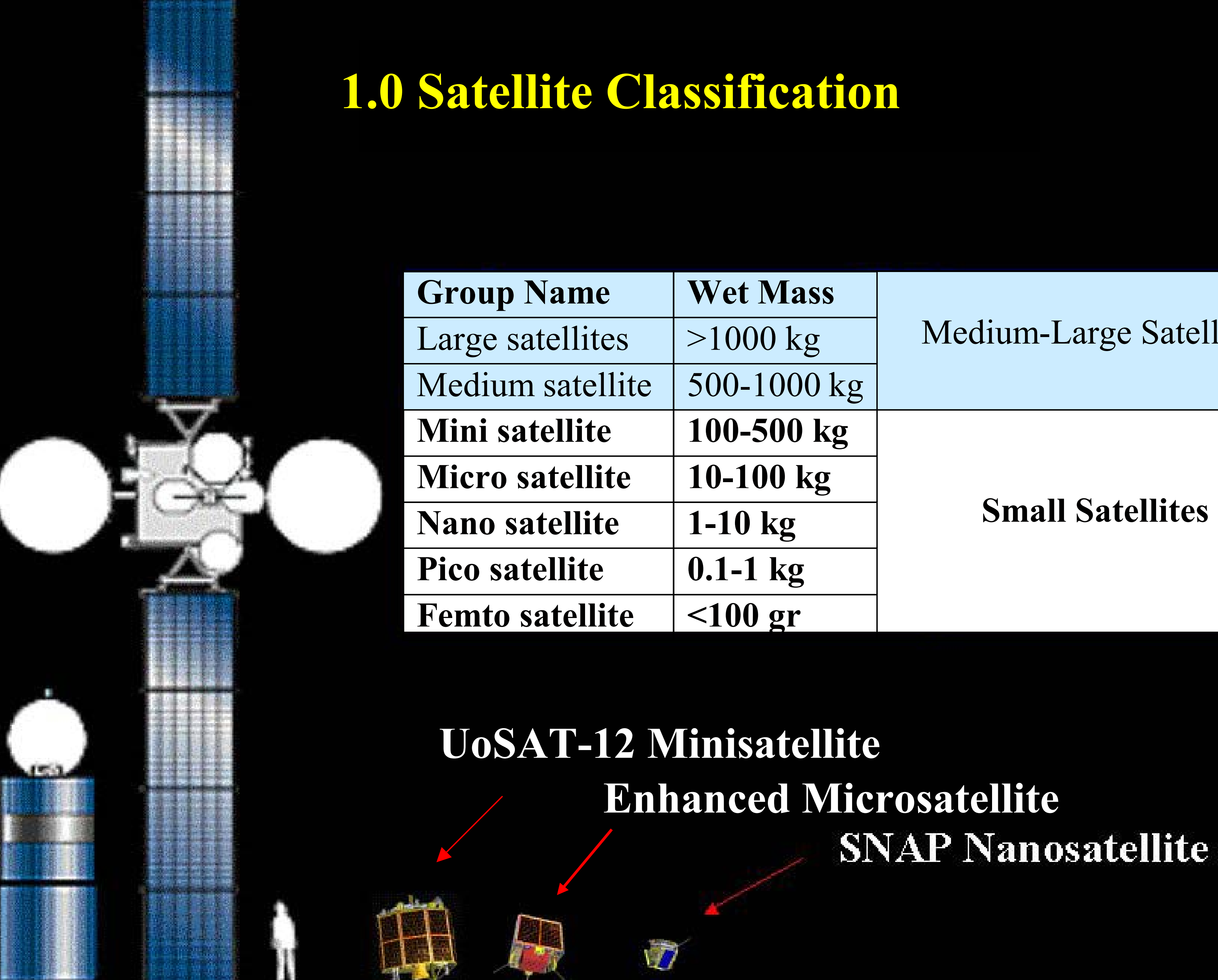
Commercial Exploitation

Surrey Satellite Technology Ltd

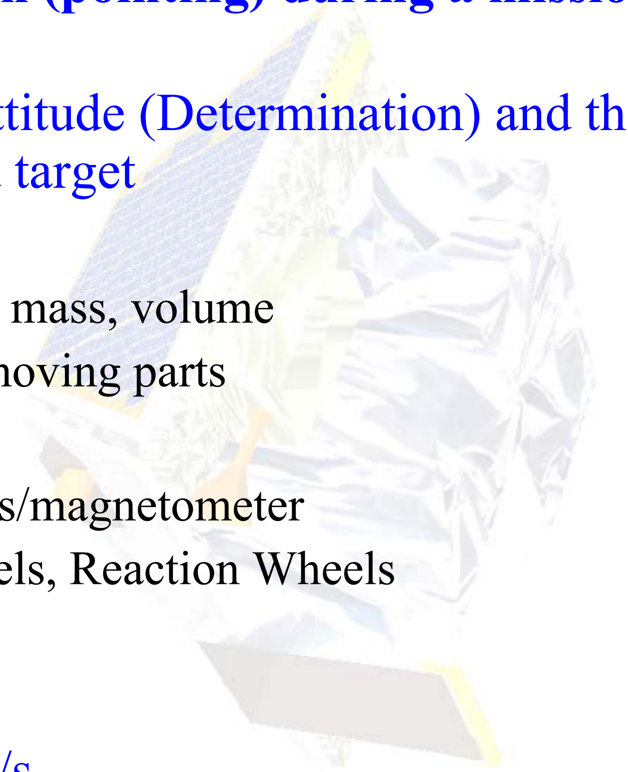


1.0 Satellite Classification

Group Name	Wet Mass	Medium-Large Satellites
Large satellites	>1000 kg	
Medium satellite	500-1000 kg	
Mini satellite	**100-500 kg**	**Small Satellites**
Micro satellite	**10-100 kg**	
Nano satellite	**1-10 kg**	
Pico satellite	**0.1-1 kg**	
Femto satellite	**<100 gr**	

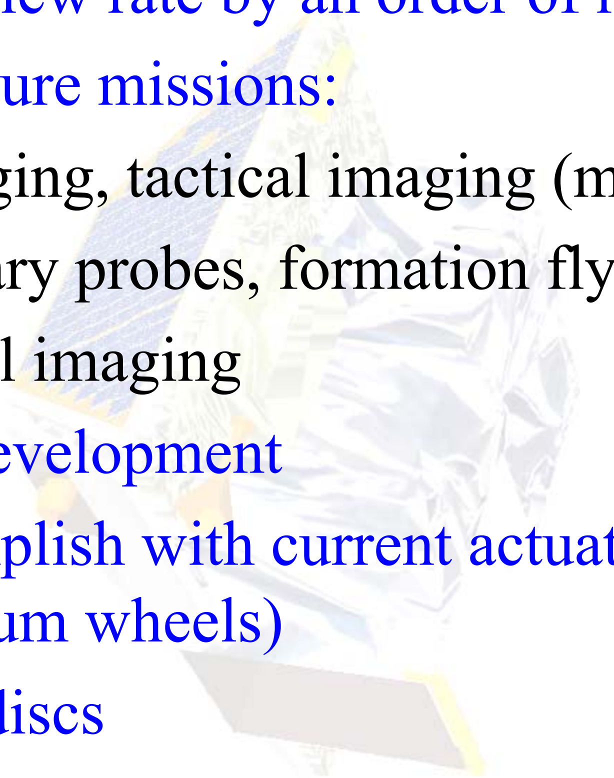


2.0 Introduction to ACS for Small Satellites



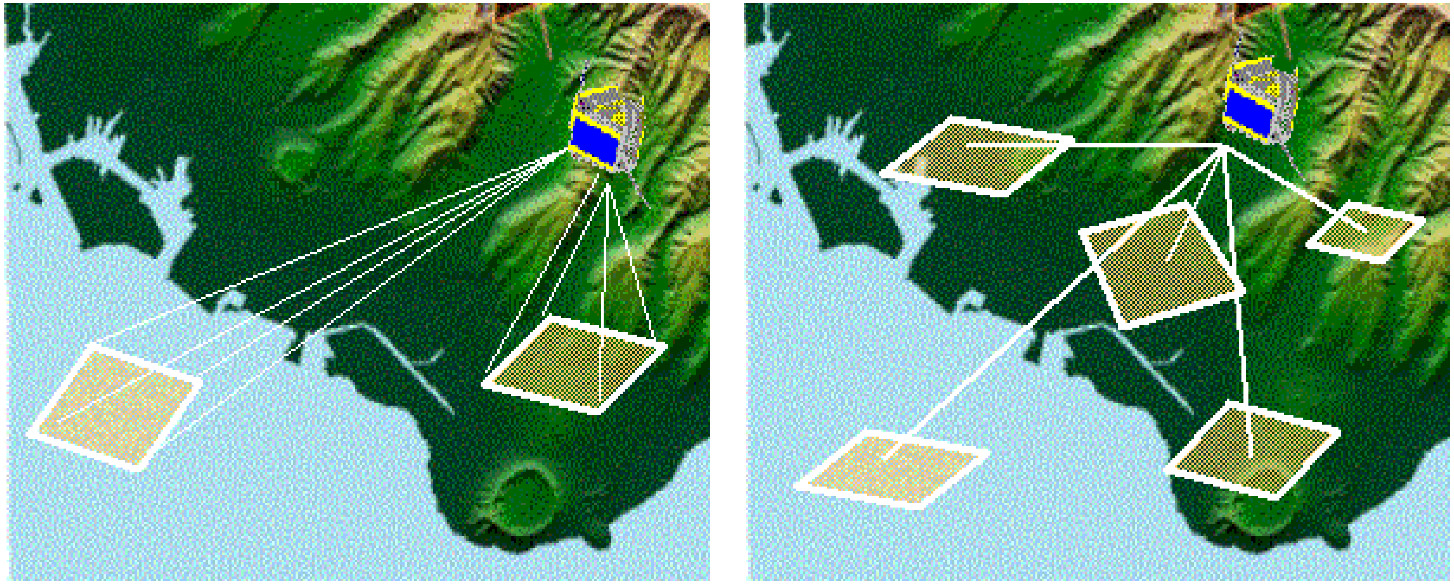
- **Attitude Control Systems (ACS): Orientation of a spacecraft in a particular direction (pointing) during a mission, despite external disturbances**
- Need to know s/c attitude (Determination) and then point using an actuator (Control) to desired target
- Focused on:
  - Low cost, power, mass, volume
  - Avoiding using moving parts
- Main actuators:
  - Magnetic torquers/magnetometer
  - Momentum Wheels, Reaction Wheels
  - Thrusters
- Accuracy: 0.1-5°
- Slew rates: 0.1-0.5°/s

3.0 Slew Rates - Agility (I)



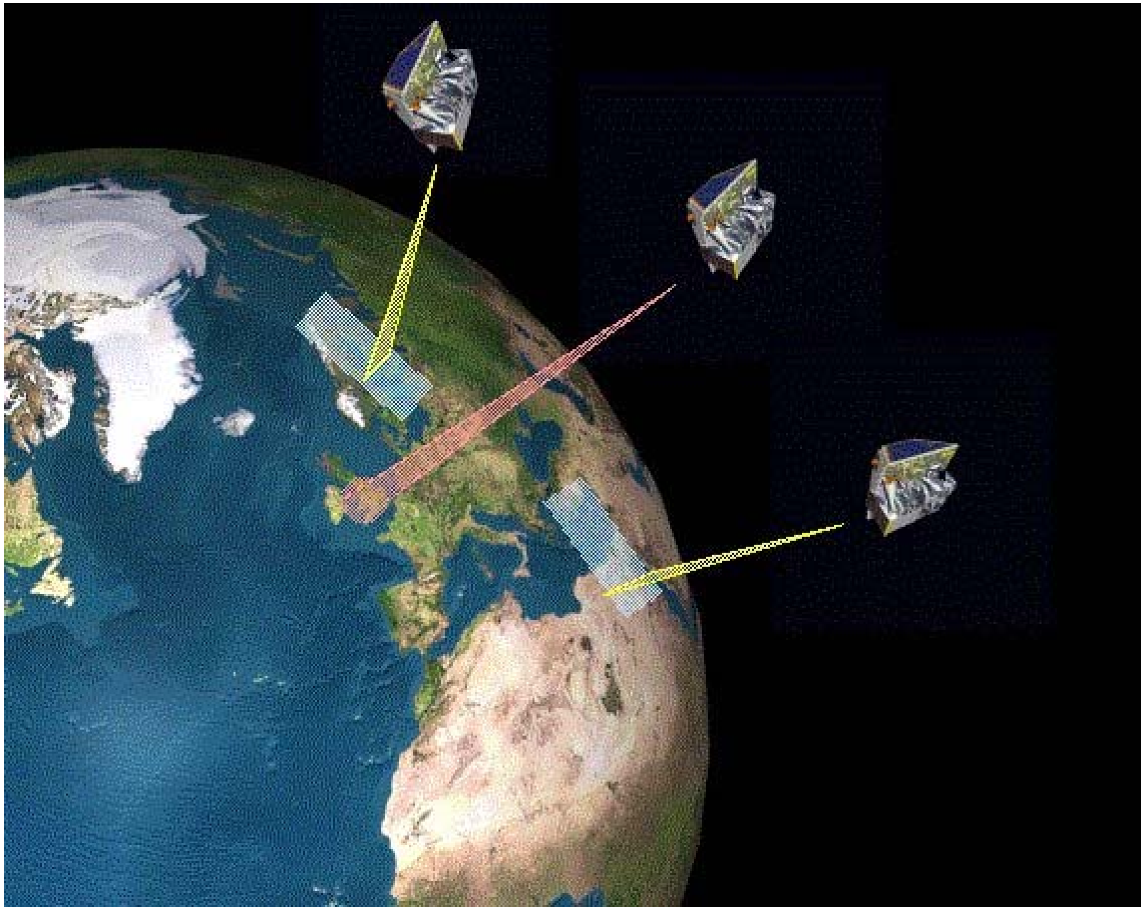
- Current Small Satellite slew rate: 0.1-1°/s
- Need to increase slew rate by an order of magnitude (1-10°/s)
  - Dictated by future missions:
    - Stereo-imaging, tactical imaging (military imaging)
    - Interplanetary probes, formation flying
    - Commercial imaging
  - Technology Development
- Difficult to accomplish with current actuators (reaction/momentum wheels)
  - Large motors/discs
  - Power, volume, mass constraints
- **Agility: High degree of spacecraft manoeuvrability**
- **Agility**: High spacecraft slew rates

3.0 Agility (II)

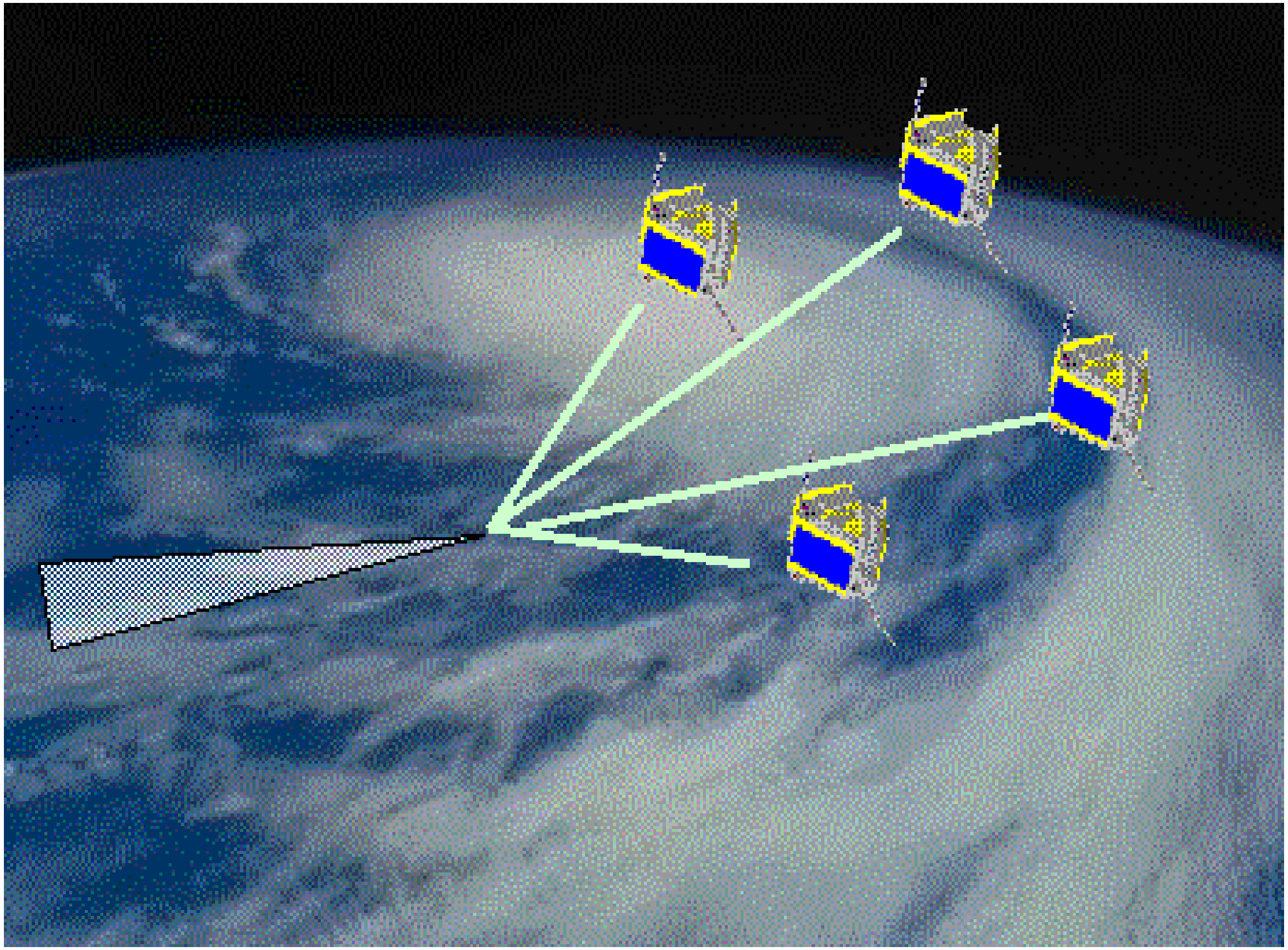


- **Agility substantially increases the operational envelope and efficiency of spacecraft**
- **Considerable increase in the return of earth and science mission data**
- **Direct increase in commercial & scientific value of mission**

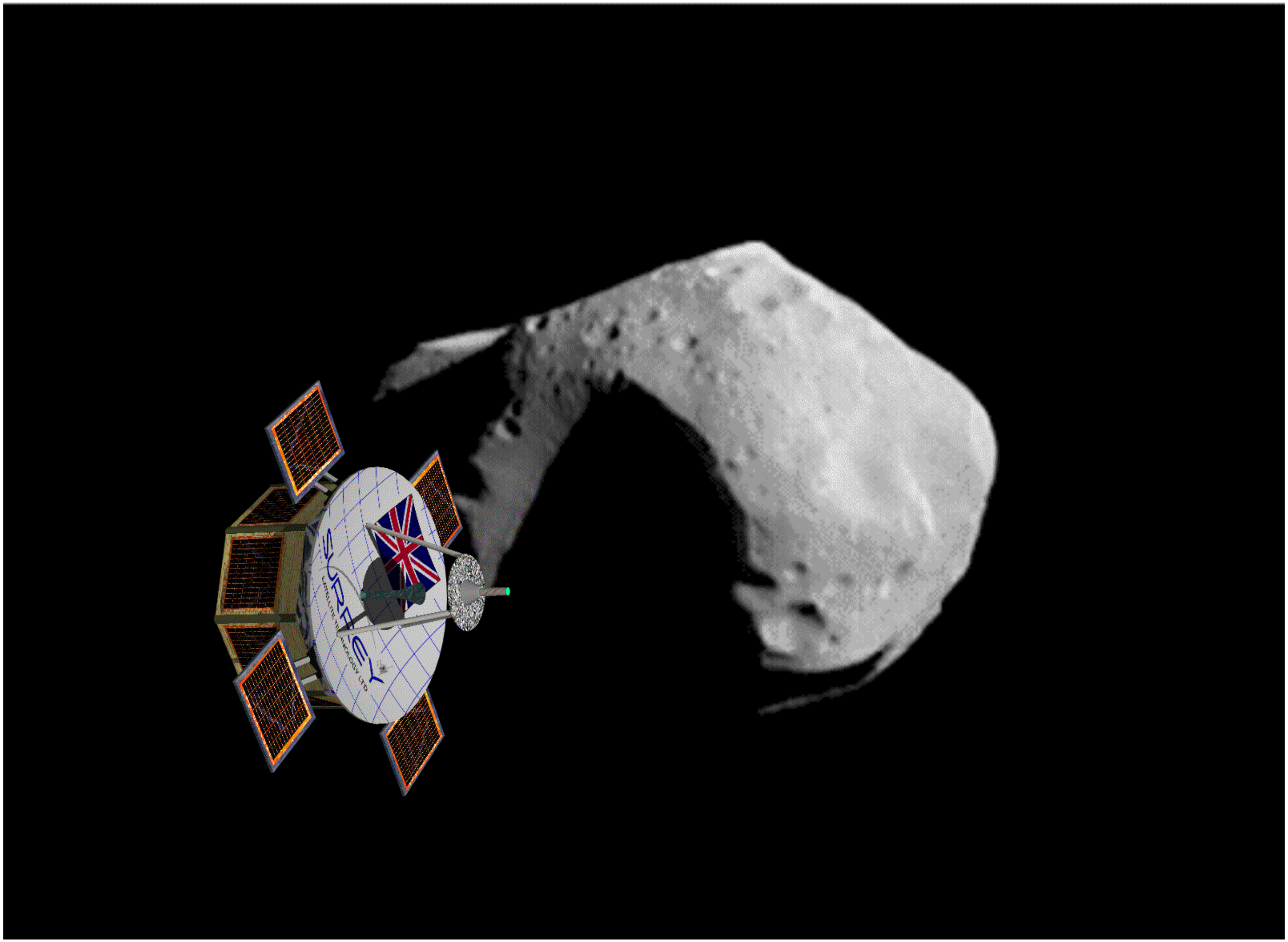
Tactical Imaging & Tracking Moving Objects, Commercial Imaging



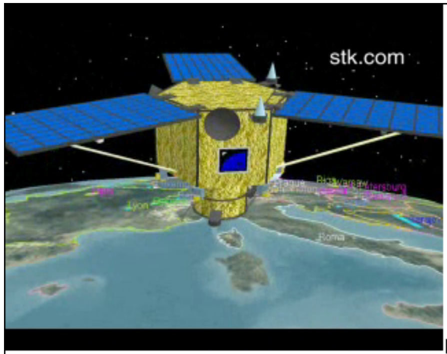
Formation Flying, Satellite/Space Station Inspection



Asteroid Missions-Agility



Agility for Small Satellites



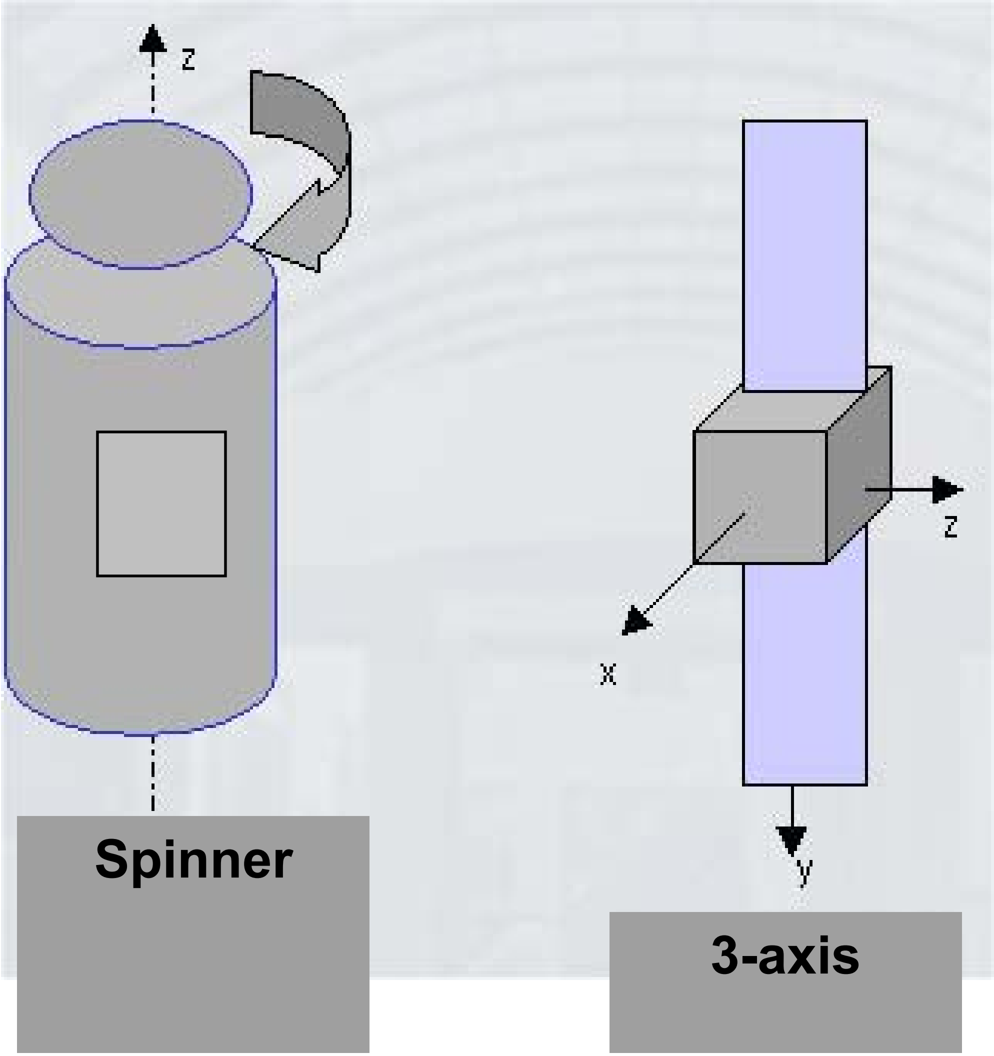
No Picture

ikonos_europe_3d[1](1)

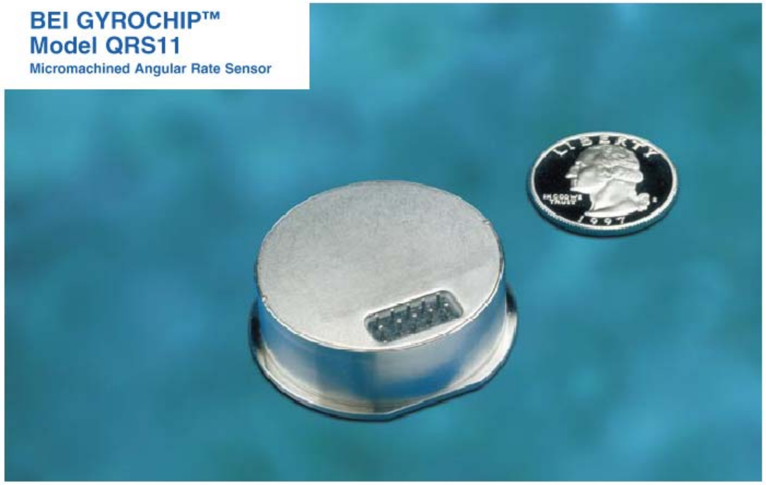
Attitude Determination and Control Systems (ADCS)

- Key Subsystem of Spacecraft
- Important for stability and pointing
- Think of a person taking a picture with a camera (blurry pictures if not stable)
- ADCS Systems are complicated:
  - Fusion of software/hardware components
  - Need electronics/aerospace/controls principles
- Brief overview of ADCS components:
  - Stabilisation
  - Sensors for attitude determination
  - Actuators

Spacecraft Stabilisation



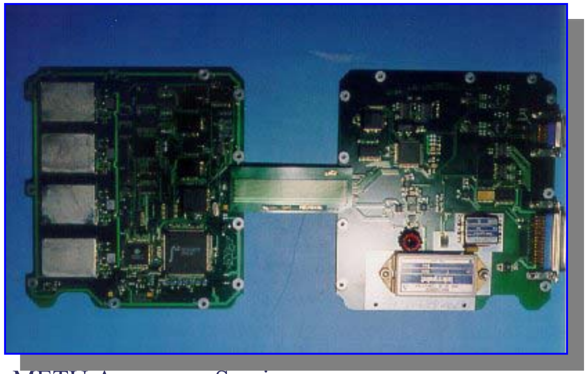
Sensors for Attitude Determination

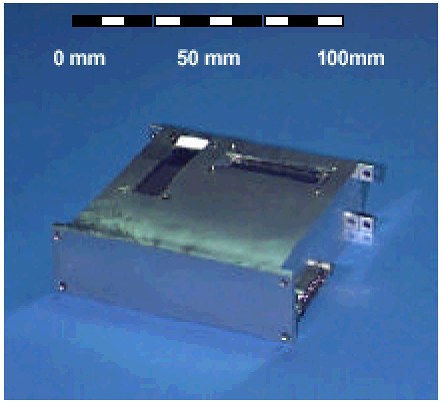


Gyros

Star Camera

GPS



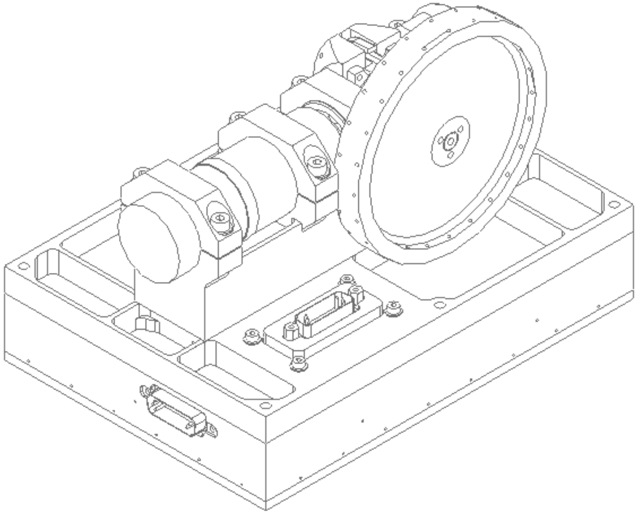


Sun Sensor

Actuators for Attitude and Orbit Control

Reaction/

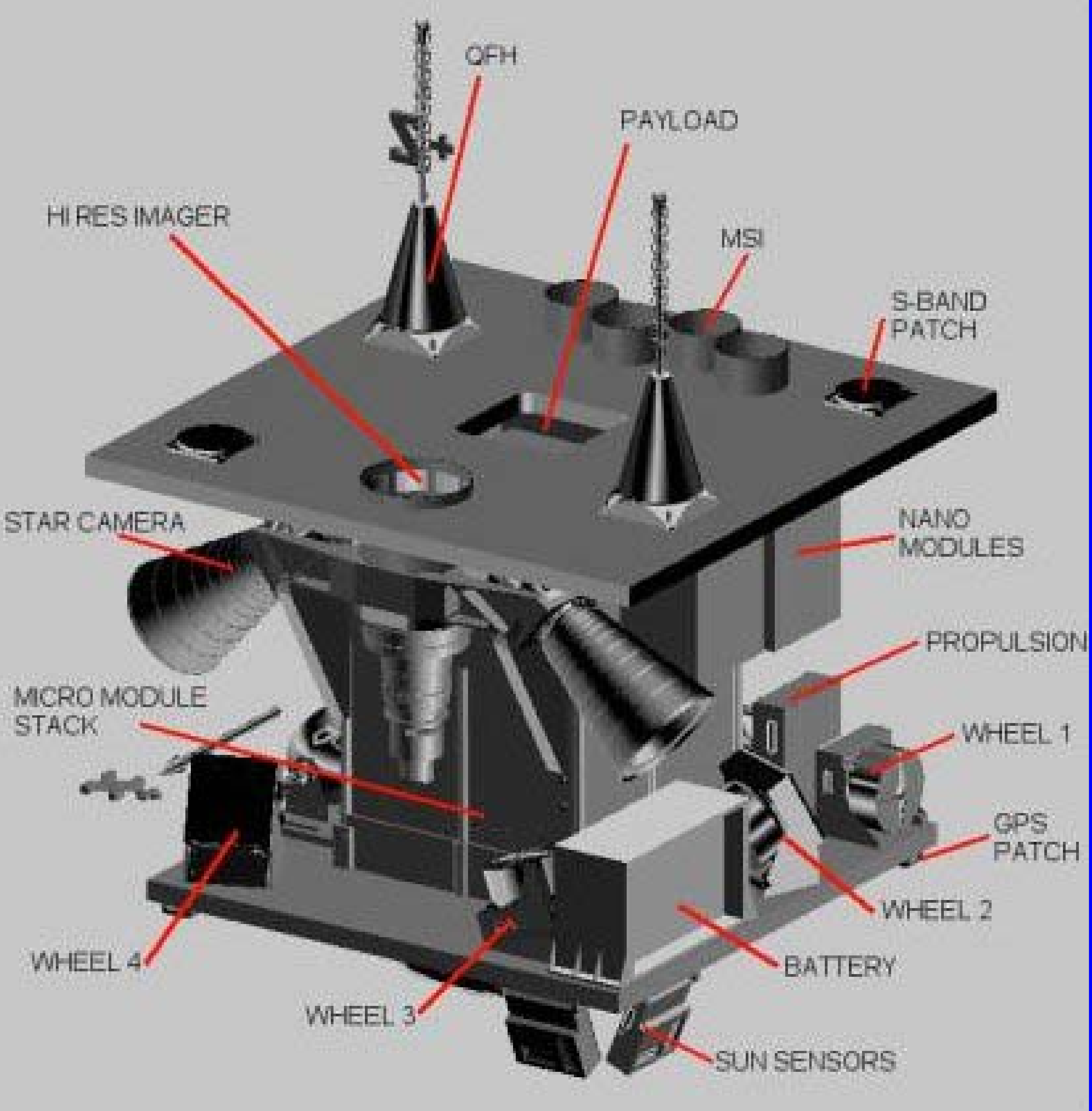
Momentum Wheels



CMGs

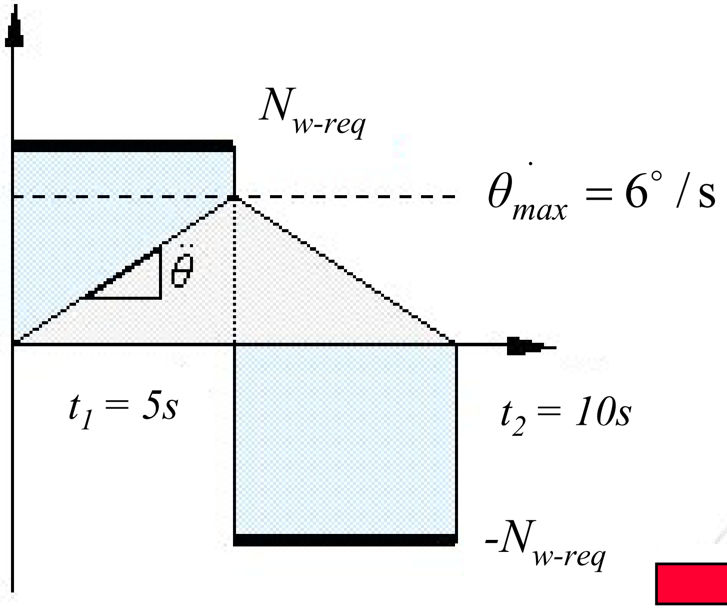
Thrusters

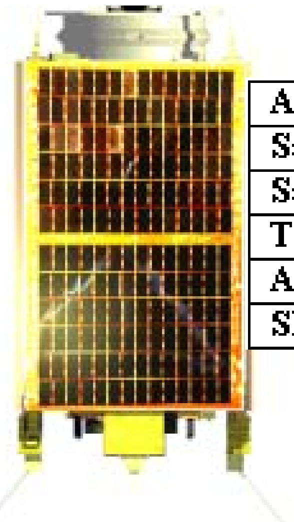
ADCS


QFH
PAYLOAD
HI RES IMAGER
MSI
S-BAND PATCH
STAR CAMERA
NANO MODULES
PROPULSION
MICRO MODULE STACK
WHEEL 1
GPS PATCH
WHEEL 2
WHEEL 4
BATTERY
WHEEL 3
SUN SENSORS

3.0 Agility-Slew Rate Requirement

- Assumptions:
  - Average 3°/s slew requirement (30° in 10s)
  - Use SSTL Microsatellite platform throughout analysis



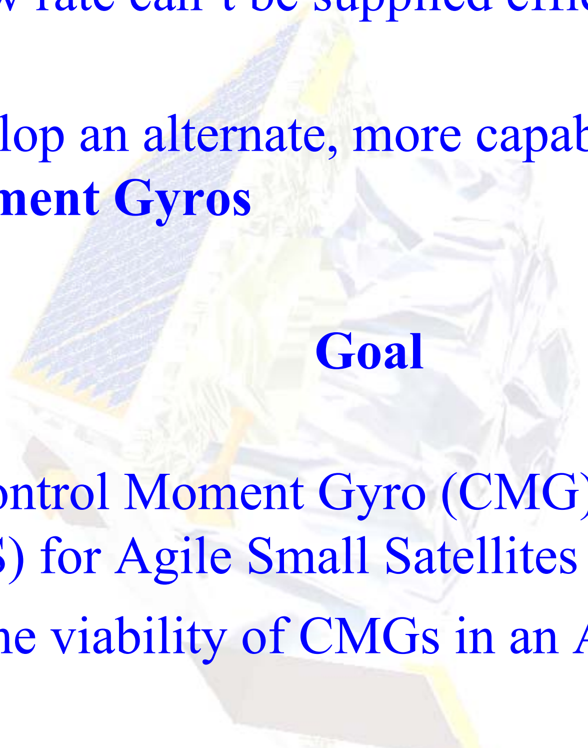


Actuator	CMG	RW
Satellite Inertias (kg-m^2)	[2.5, 2.5, 2.5]	[2.5, 2.5, 2.5]
Satellite Mass (kg)	50	50
Torque (mNm)	52.25	20
Actuator Mass (kg)	~ 1	4
Slew Rate (°/s)	3	1.85

$$N_{w\text{-}req} = 52.25 \text{ mNm}$$

- SSTL actuators: 3-20 mNm
- ACS based on RWs :
  - 10% of spacecraft mass
  - 40% of required torque

4.0 Motivation



Motivation:

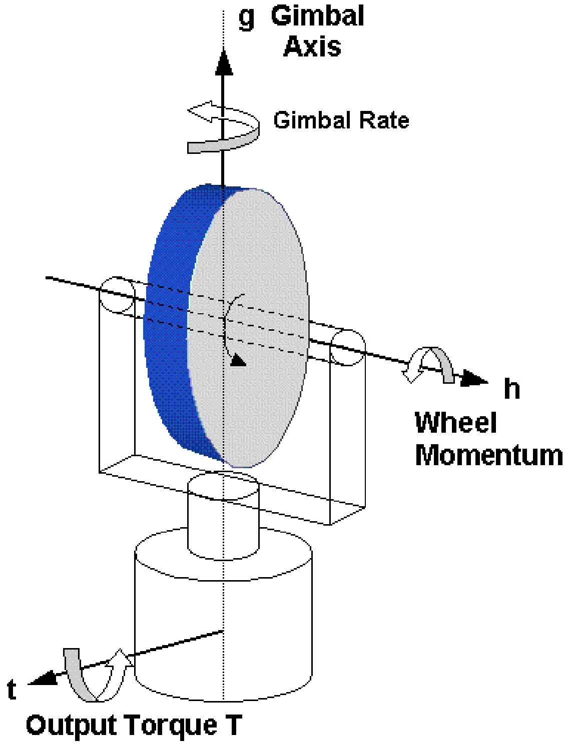
- Required slew rate can’t be supplied efficiently by current technologies
- Need to develop an alternate, more capable actuator based on **Control Moment Gyros**

Goal

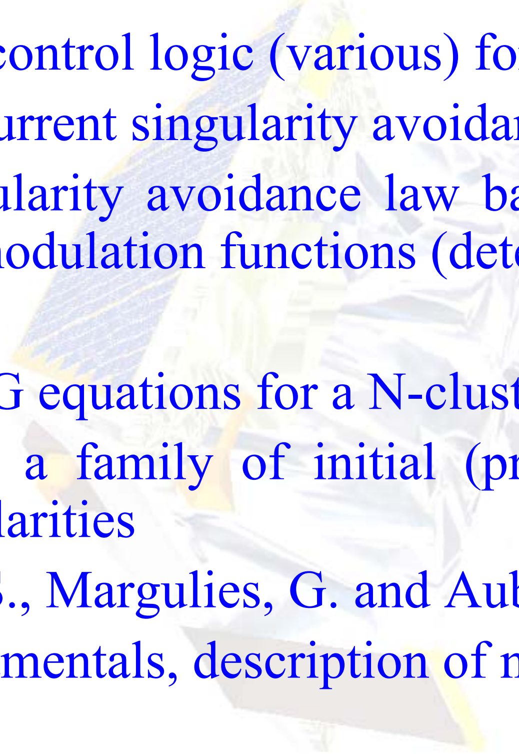
- Develop a Control Moment Gyro (CMG) based Attitude Control System (ACS) for Agile Small Satellites
    1. Proving the viability of CMGs in an ACS system for Small Satellites
    2. Developing a low-cost, miniature Single Gimbal Control Moment Gyro (SGCMG) for Small Satellites

CMG Background

- 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
  - Alcatel, Astrium (France)
  - Have not flown on commercial s/c yet

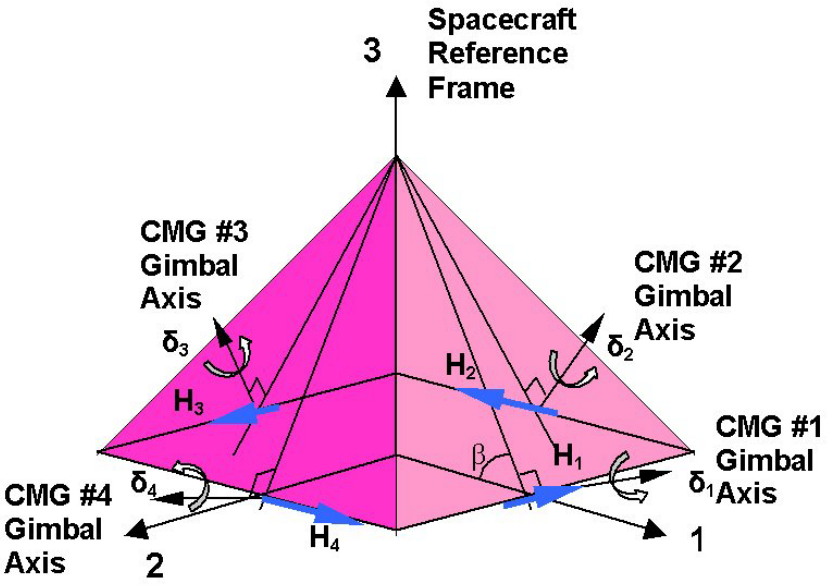


5.1 CMG Research



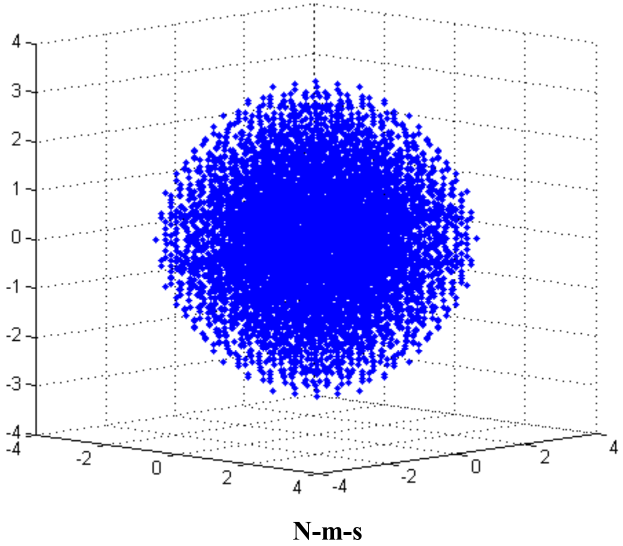
- B. Wie:
  - Provides fundamentals of CMGs
  - Using PID control logic (various) for non-linear CMG control
  - Survey of current singularity avoidance laws
  - Novel singularity avoidance law based Singularity Robust law and using modulation functions (deterministic dither)
- Vadali, S.R.:
  - Derive CMG equations for a N-cluster of SGCMGs
  - Proves that a family of initial (preferred) gimbal angles can avoid singularities
- Bedrossian, N.S., Margulies, G. and Auburn, J.N.:
  - CMG fundamentals, description of null motion & singularities

5.2 4-CMG 'pyramid' Cluster



Pyramid Arrangement of four Single-Gimbal Control Moment Gyroscope

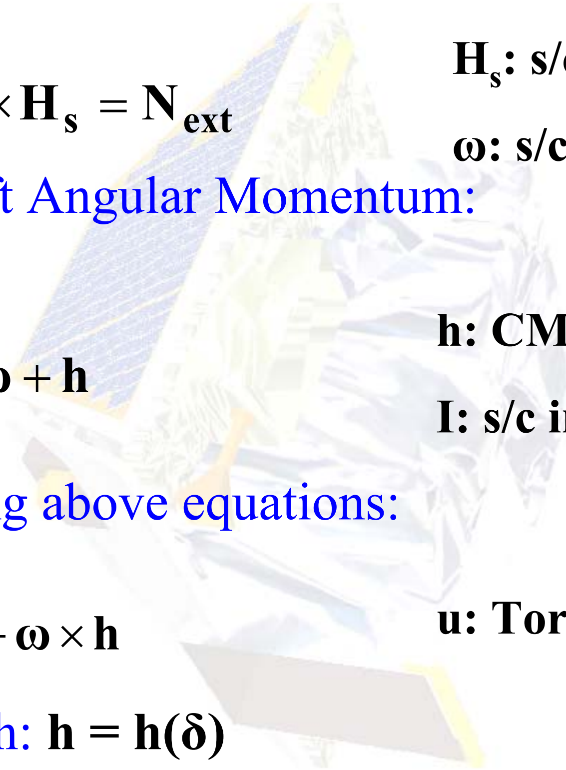
Momentum Envelope of 4-SGCMG cluster
$\beta = 54.73^0$, h = 1 N-m-s
Isometric View



4-SGCMGs-pyramid, **$\beta = 54.74°$: $h_{CMG\text{-}max} = h_0[3.15, 3.15, 3.26]^T$ N-m-s**

$$\mathbf{h} = \sum_{i=1}^{4} \mathbf{H}_i(\boldsymbol{\delta}_i) = \begin{bmatrix} -c\beta\sin\delta_1 & -\cos\delta_2 & c\beta\sin\delta_3 & \cos\delta_4 \\ \cos\delta_1 & -c\beta\sin\delta_2 & -\cos\delta_3 & c\beta\sin\delta \\ s\beta\sin\delta_1 & s\beta\sin\delta_2 & s\beta\sin\delta_3 & s\beta\sin\delta_4 \end{bmatrix}$$

5.2 Mathematical description of a 4-CMG Cluster



- Rotational Equations of Motion:

$$\dot{\mathbf{H}}_s + \boldsymbol{\omega} \times \mathbf{H}_s = \mathbf{N}_{ext}$$

H_s: s/c angular momentum

ω: s/c angular velocity

- Spacecraft Angular Momentum:

$$\mathbf{H}_s = \mathbf{I}\boldsymbol{\omega} + \mathbf{h}$$

h: CMG angular momentum

I: s/c inertia matrix

- Combining above equations:

$$\dot{\mathbf{h}} = -\mathbf{u} - \boldsymbol{\omega} \times \mathbf{h}$$

u: Torque control vector

- SGCMG h: **$\mathbf{h} = \mathbf{h}(\delta)$**
- Need 4-SGCMGs for full 3-axis control

5.3 Singularity Avoidance Steering Laws

$$\dot{\mathbf{h}} = \mathbf{A}\,\dot{\boldsymbol{\delta}}$$

- Where **A** is a 3 x 4 Jacobian Matrix

$$\mathbf{A} = \begin{bmatrix} -c\beta\cos\delta_1 & \sin\delta_2 & c\beta\cos\delta_3 & -\sin\delta_4 \\ \sin\delta_1 & -c\beta\cos\delta_2 & \sin\delta_3 & c\beta\cos\delta \\ s\beta\cos\delta_1 & s\beta\cos\delta_2 & s\beta\cos\delta_3 & s\beta\cos\delta_4 \end{bmatrix}$$

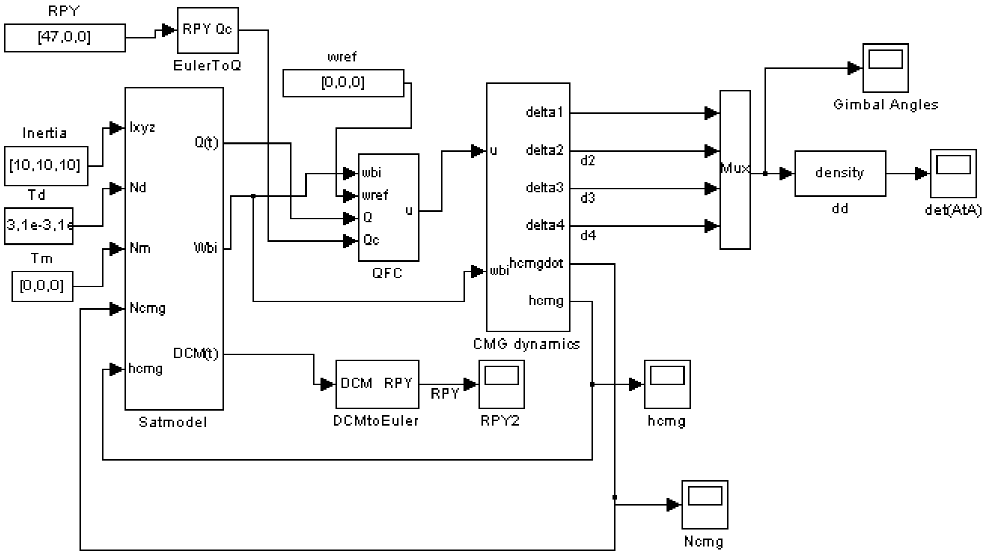
- Inverse Kinematic Solution (Pseudoinverse)

$$\dot{\boldsymbol{\delta}} = \mathbf{A}^{+}\,\dot{\mathbf{h}} = \mathbf{A}^{\mathrm{T}}(\mathbf{A}\mathbf{A}^{\mathrm{T}})^{-1}\,\dot{\mathbf{h}}$$

- Goal is to generate commanded torques and to also avoid ‘singular’ sets of gimbal angles, where no torque is produced
- ‘Steer’ angles to more favourable directions, escape, avoid or transit through singularities

5.4 CMG ACS Simulations (I)

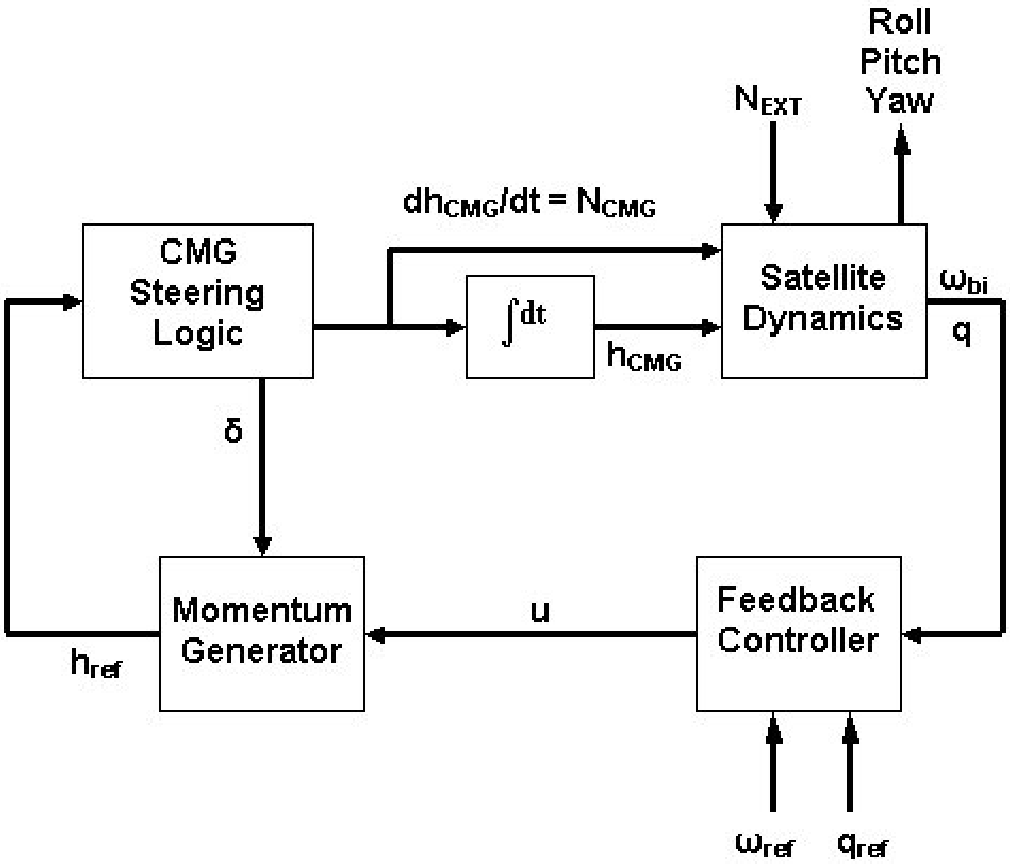
- In MATLAB® and SIMULINK®
- Satellite Model, CMG Dynamics, Quaternion Feedback Controller



- Used to study the behaviour of a CMG attitude control system
- Test Singularity Avoidance laws, try new ones
- Minisatellite, Microsatellite and Nanosatellite models used

5.4 CMG ACS Simulations (II)

Attitude Control Model



5.4 CMG ACS Simulations (III)

Microsatellite

–65^0 Roll maneuver

$[I_x, I_y, I_z]$ =

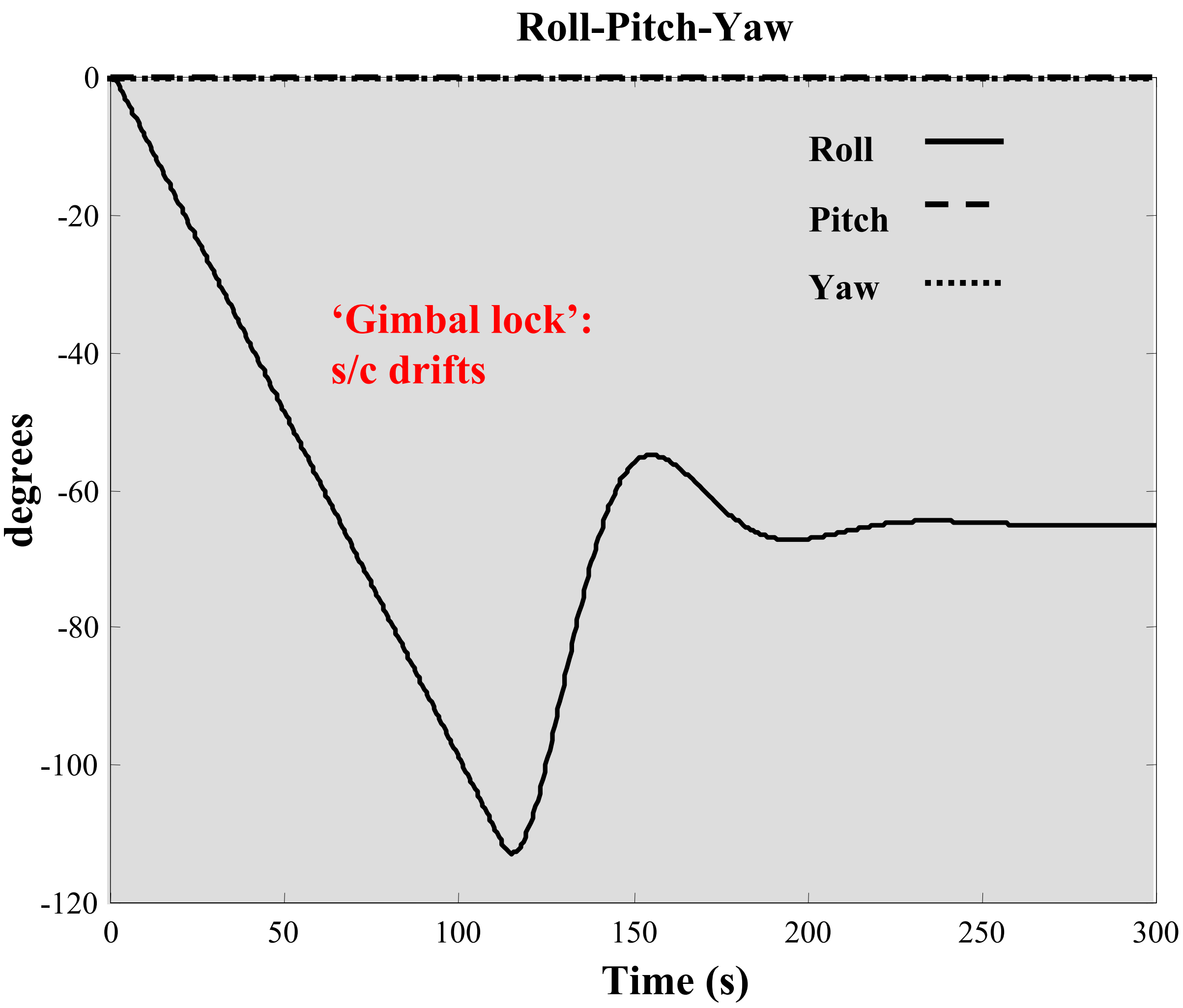
[10, 10, 10]

kg-m^{2}s

$[\delta_1, \delta_2, \delta_3, \delta_4]$ = [70, 0, -70, 0]

degrees

Replicate elliptic singularity



5.4 CMG ACS Simulations (IV)

Microsatellite

-65^0 Roll maneuver

$[I_x, I_y, I_z] =$

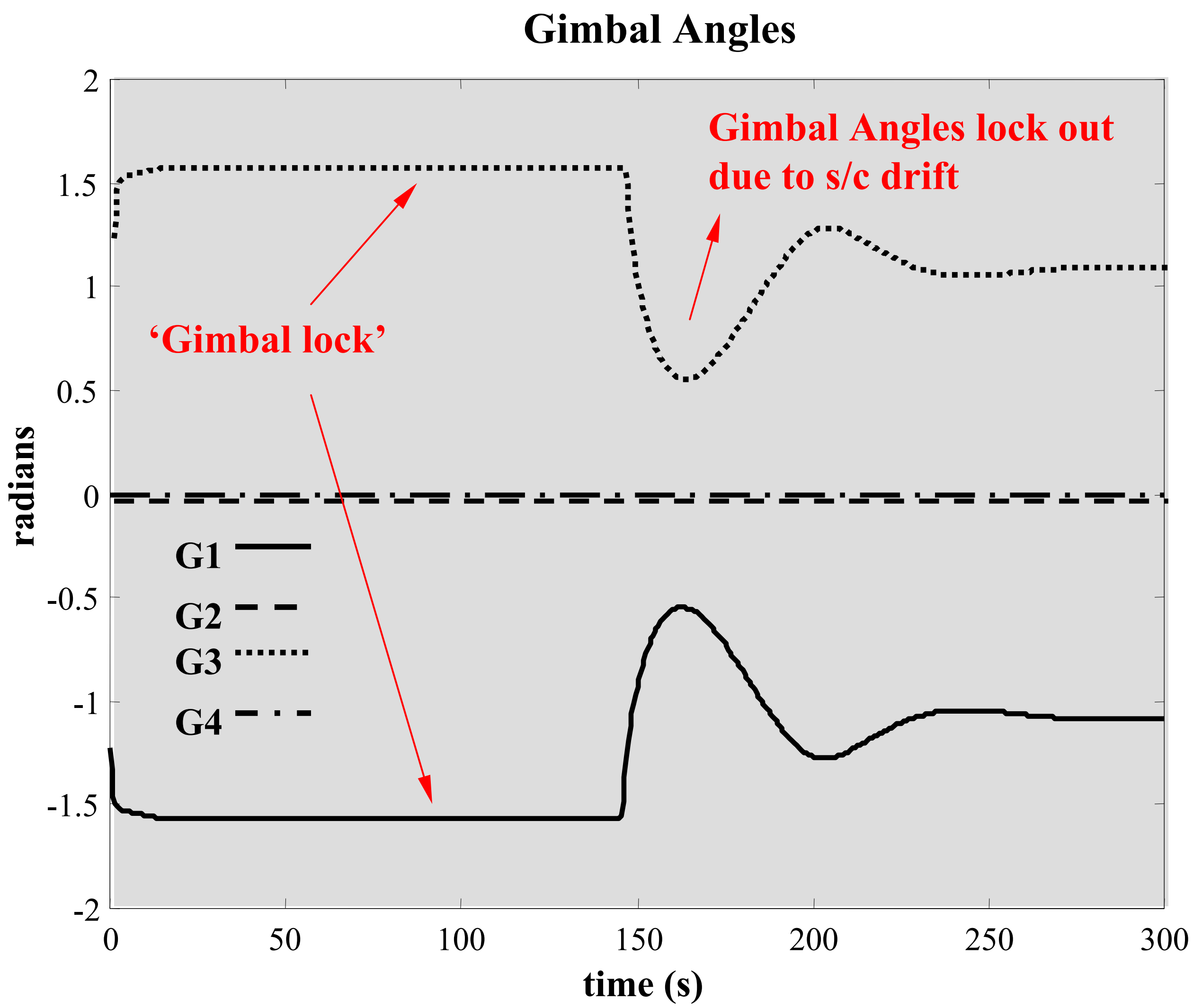
$[10, 10, 10]$

$kg\text{-}m^2s$

$[\delta_1, \delta_2, \delta_3, \delta_4] =$
$[70, 0, -70, 0]$

degrees

Replicate elliptic singularity



Gimbal Angles lock out due to s/c drift

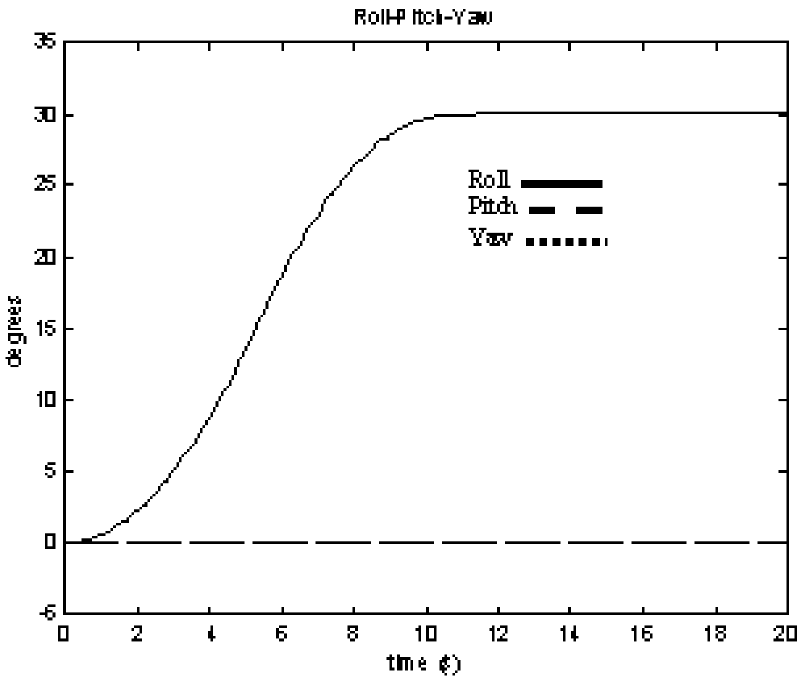
'Gimbal lock'

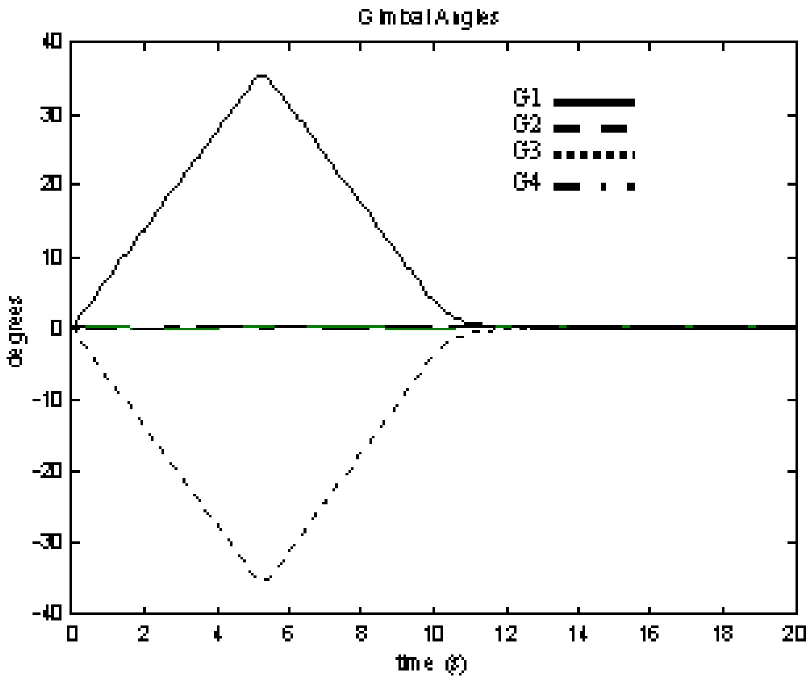
6.0 CMG Sizing for a Microsatellite

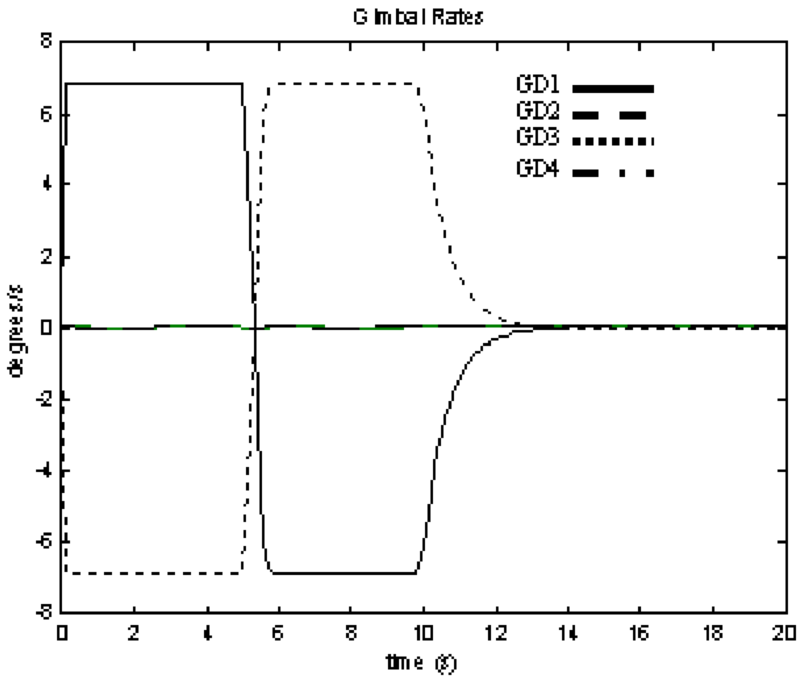
- 4-CMG cluster in pyramid configuration for full 3-axis control
- Main requirement: Generate $N_{w\text{-}req} = 52.25$ mNm (30° in 10s)

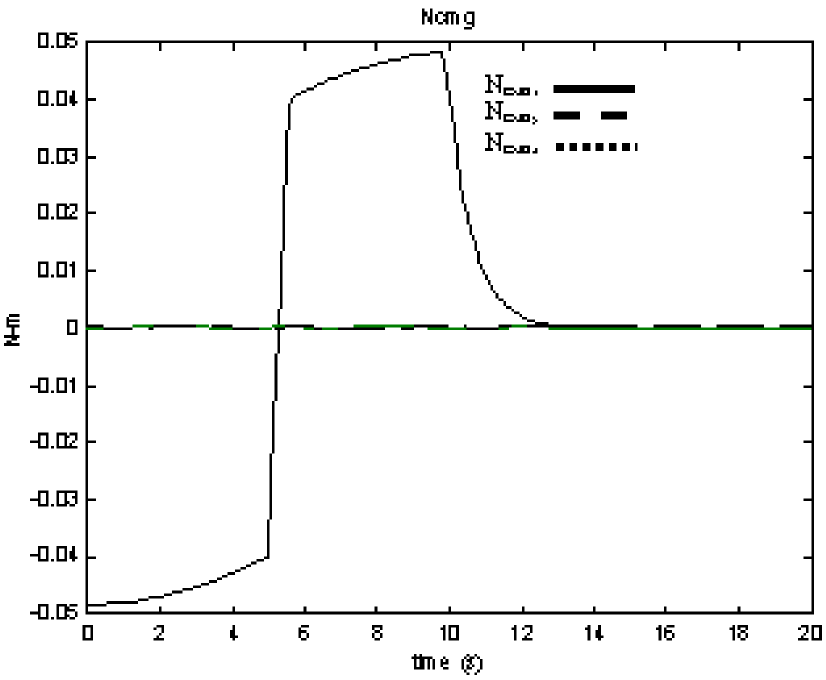
For a SGCMG: $\mathbf{N}_{\mathbf{CMG}} = \mathbf{h} \times \dot{\boldsymbol{\delta}}$

- Selection of **h** and max. gimbal rate is a trade-off between performance, size and singularity avoidance
- Keep **h** as small as possible (less mass, volume)
- Avoid using large gimbal rates leading to large gimbal angle excursions, thus singularities
- A max. gimbal rate of 7.5 °/s is used which is larger than the max. angular rate of satellite when doing a 30° maneuvre in 10s
- Ensures torque amplification throughout a maneuvre
- Simulations for a 30° maneuvre in 10s

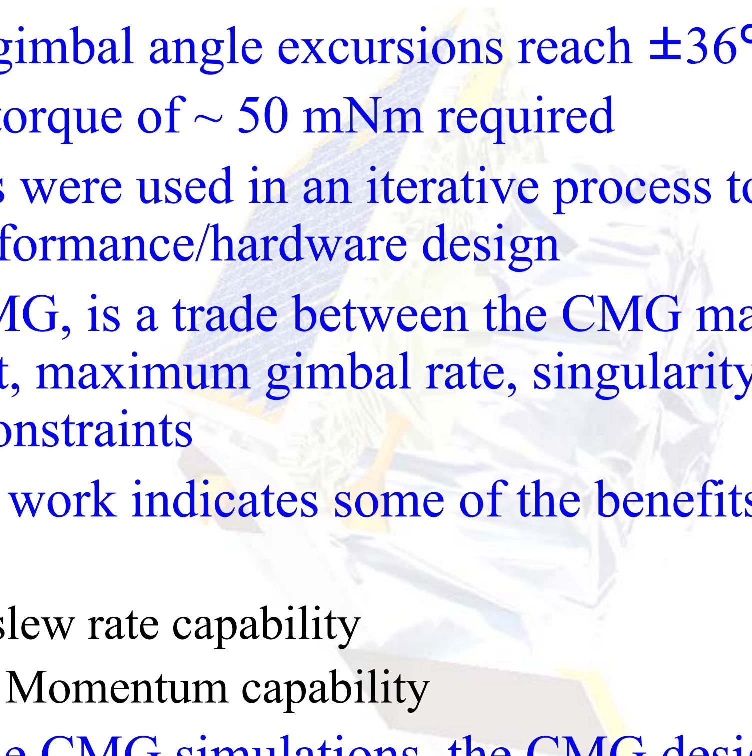

Roll-Pitch-Yaw
Roll
Pitch
Yaw
degrees
time (s)
35
30
25
20
15
10
5
0
-5
0
2
4
6
8
10
12
14
16
18
20


Gimbal Angles
G1
G2
G3
G4
degrees
time (s)
40
30
20
10
0
-10
-20
-30
-40
0
2
4
6
8
10
12
14
16
18
20


Gimbal Rates
GD1
GD2
GD3
GD4
degrees/s
time (s)
8
6
4
2
0
-2
-4
-6
-8
0
2
4
6
8
10
12
14
16
18
20


Ncmg
N-m
time (s)
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
0
2
4
6
8
10
12
14
16
18
20

6.1 CMG Simulations for a Microsatellite

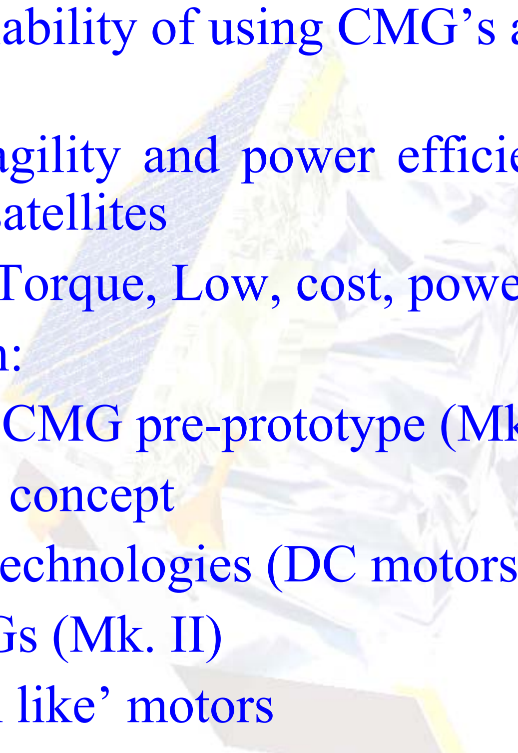


- Simulations confirm the ability of the CMGs to provide a 3 °/s average slew rate to a microsatellite
- Maximum gimbal angle excursions reach ±36°
- Maximum torque of ~ 50 mNm required
- Simulations were used in an iterative process to determine the best trade in performance/hardware design
- Sizing a CMG, is a trade between the CMG mass, average slew rate requirement, maximum gimbal rate, singularity avoidance and hardware constraints
- Theoretical work indicates some of the benefits of the CMGs for small satellites:
  - Torque/slew rate capability
  - Angular Momentum capability
- Based on the CMG simulations, the CMG design parameters are specified

6.2 CMG Cluster Characteristics

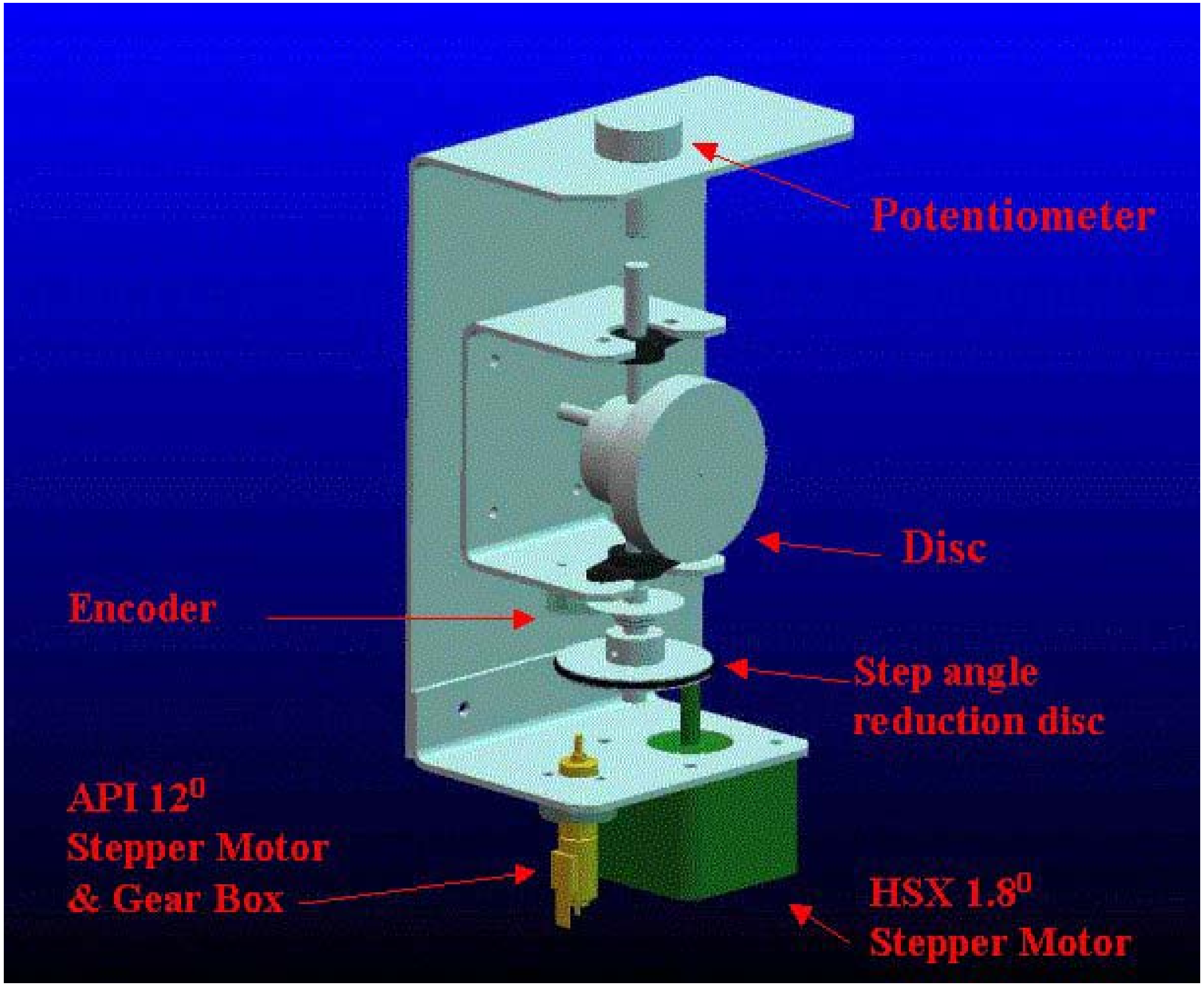
Parameter	Value
DC motor mass [Faulhaber 1525E]	30 g
Momentum Wheel	150 g
Gimbal motor mass [P10]	9 g
Gimbal Motor Gear box [R10]	6 g
Potentiometer [Sector]	10 g
Couplers (2)	10 g
Power (Min.-Max.)	TBD
Voltage	5-12 V
SGCMG Mass	200 g
SGCMG Ang. Mom. h_0 **(**ω_w **= 20,000 rpm)**	0.35 Nms
CMG avionics	50 g
CMG Total Mass	~ 1000 g
CMG Output Torque	52.25 mNm

7.0 Developing a Low-Cost, Miniature CMG for Small Satellites

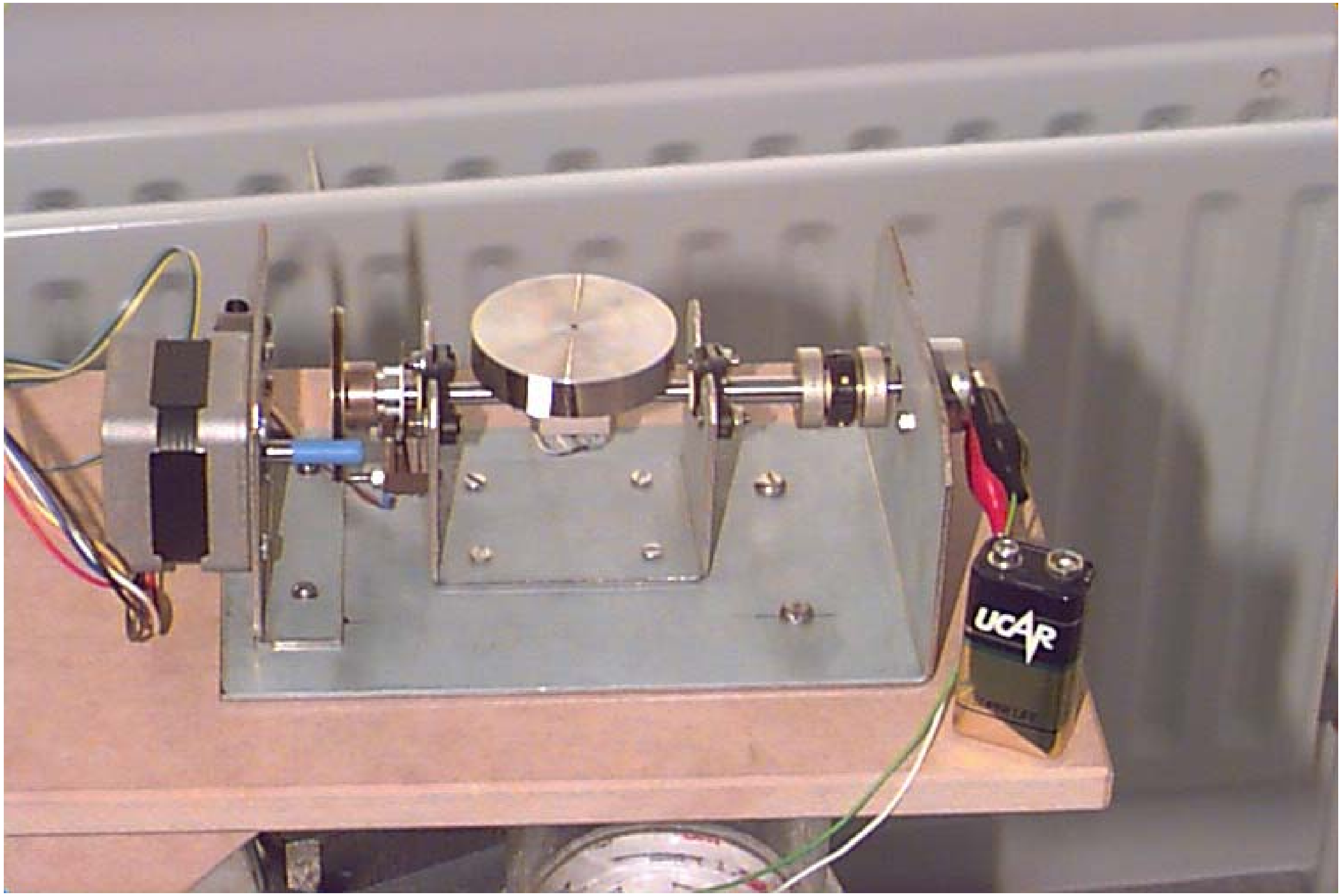


- The main aims are :
  1. To **practically** confirm the theoretical work (simulations) performed
  2. To validate the viability of using CMG's as actuators on a microsatellite in a practical way
  3. To confirm the agility and power efficiency that CMGs can potentially provide to microsatellites
- Achieve 52.25 mNm Torque, Low, cost, power, size, mass, use COTS
- Use a staged approach:
  1. A Single Gimbal CMG pre-prototype (Mk.I)
     - Demonstrate concept
     - Try various technologies (DC motors, stepper motors)
  2. Cluster of 4-CMGs (Mk. II)
     - Use 'mission like' motors
     - Demonstrate CMG benefits (torque, ang. momentum, power, mass)
     - Sized for a SSTL 50 kg microsatellite (e.g. PICOSAT)

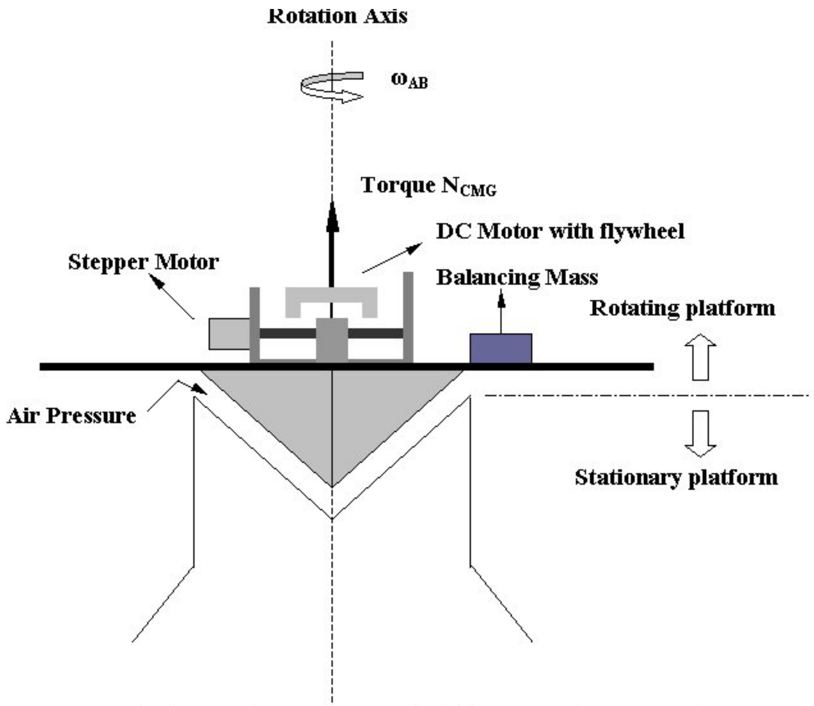
7.1 CMG Mk.I Testbed



7.2 CMG Mk.I

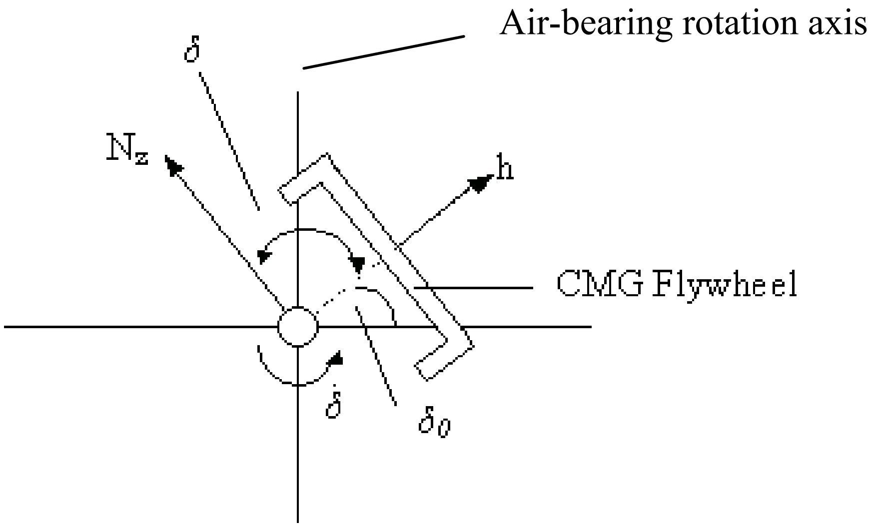


7.3 Air Bearing Experiments



- Air-bearing table provides the capability of rotation without significant friction
- Used to test the dynamic characteristics and performance of a model satellite control system during the pre-launch experimental testing campaign on the ground
- Suspended by air, allows nearly frictionless rotation

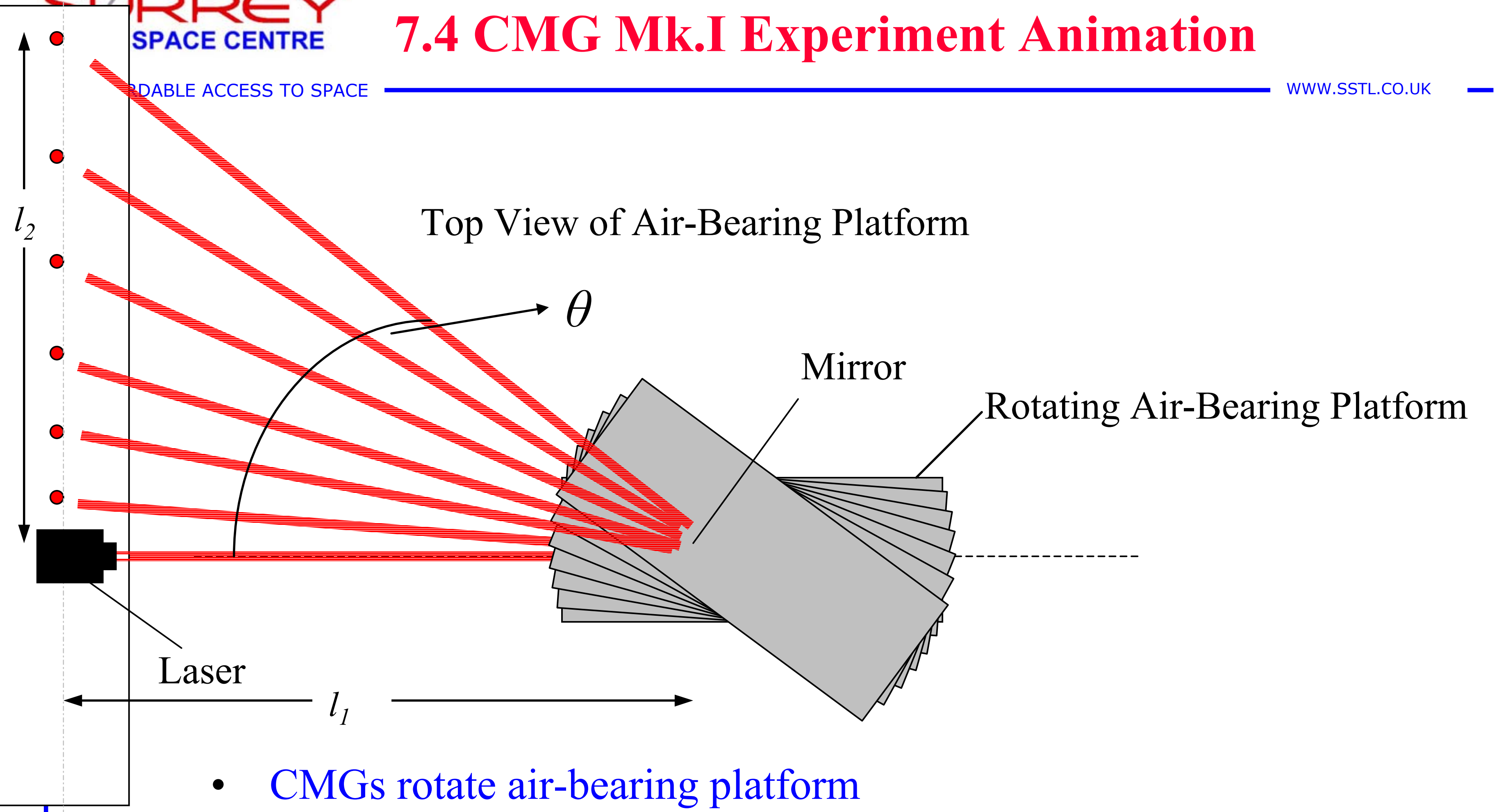
7.4 CMG Mk.I Experiment (I)



Side view of air-bearing

- Operate CMG from a known angle θ_0 of 25° between the spin axis and the horizontal
- Perform a 50° excursion and return to its initial position
- This will generate a rotation about the air-bearing rotation axis

7.4 CMG Mk.I Experiment Animation

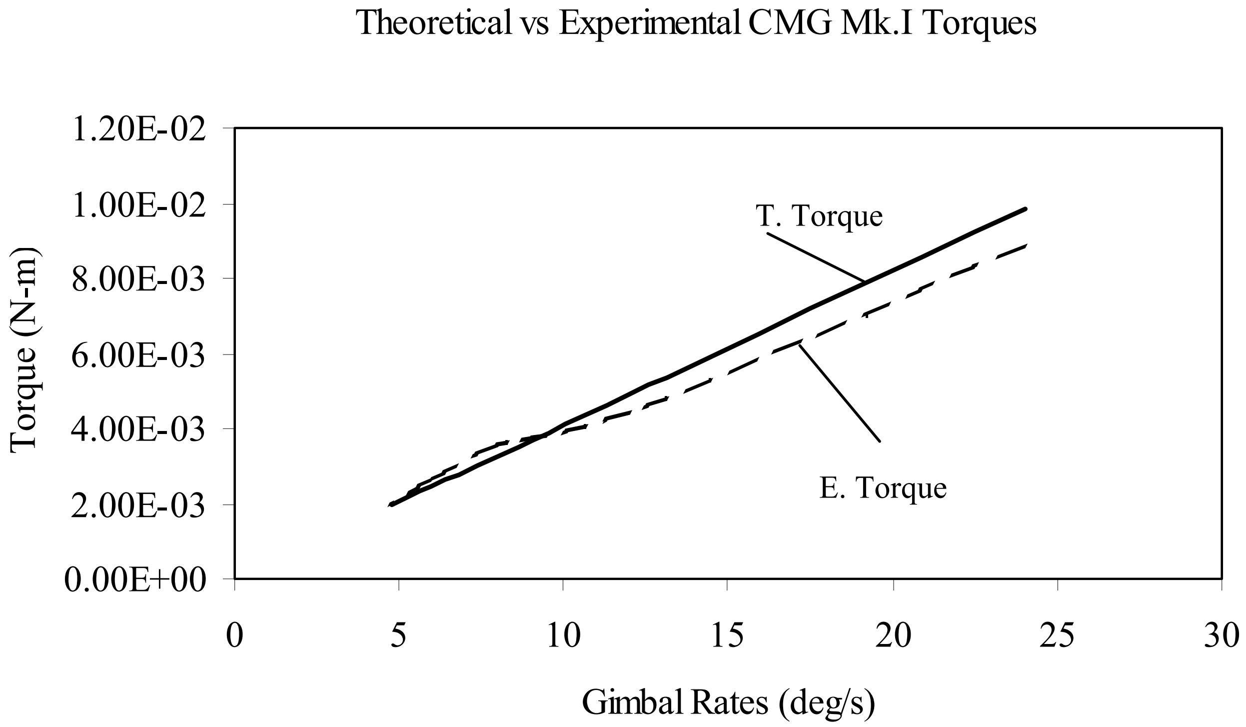


- CMGs rotate air-bearing platform
- Use stopwatch to time angular displacements
- Measure laser beam dot distance
- Use trigonometry to calculate the angular rate of rotating platform

7.4 CMG Mk.I Testing (IV)

Rotation of CMG & rotation platform (N_{CMG}=8.84 mNm)

7.4 CMG Mk.I Testing (IV)



- Theoretical Torque: $N_z = h\dot{\delta}\cos\delta_0$

- Experimental Torque: $N_{CMG} + N_d = -I_{AB}\,\dot{\omega}_{AB}$

7.4 CMG Mk.I Testing (V)

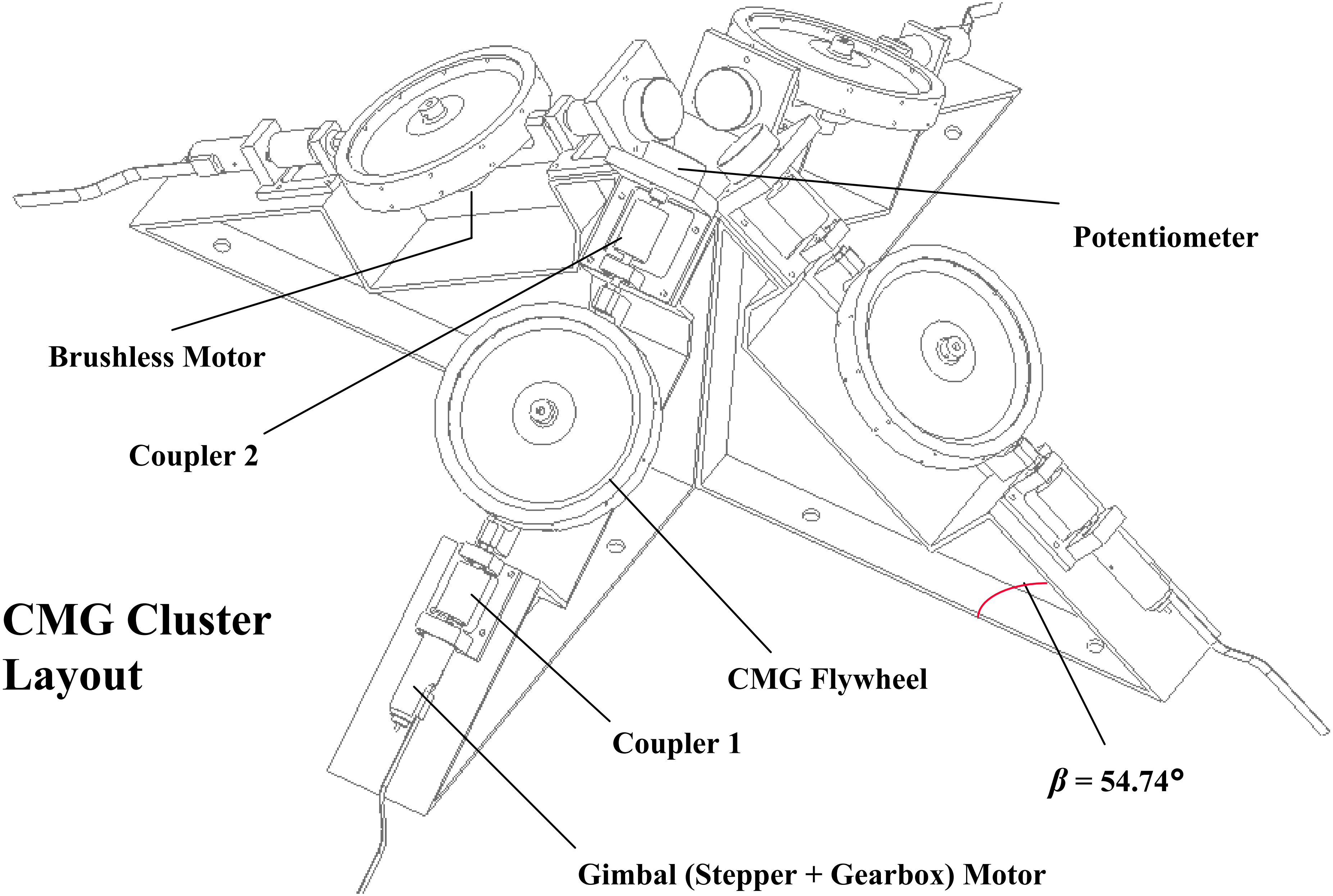
- Theoretical CMG Torque value expected for a gimbal rate of 24°/s is 9.82 mNm
- Experimental value of 8.84 mNm and results to a difference (error) of 9.97%
- Errors due to air-bearing table bias, flywheel imbalances, flexing of the wires, aerodynamics friction
- Maximum angular speed is 11,200 rpm (maximum speed 16,000 rpm) due to aerodynamics friction, less angular momentum

Parameter	**CMG E. Microsat**	**RW E. Microsat**
Mass of s/c (kg)	50	50
Type of actuator	1 CMG	1 RW
Mass (g)	~320	1000
Power Av. Per actuator (W)	0.1-1.2	0.8-3.5
Voltage (V)	5-12	12-16
Max.Ang. Mom. (Nms)	0.0235	0.36
Max. Torque (mNm)	8.84	10
Sat. Inertias (kg-m^2)	[2.5, 2.5, 2.5]	[2.5, 2.5, 2.5]
Average slew rate (°/s)	1.23	1.31
Min. time for 30° (s)	24.45	22.876

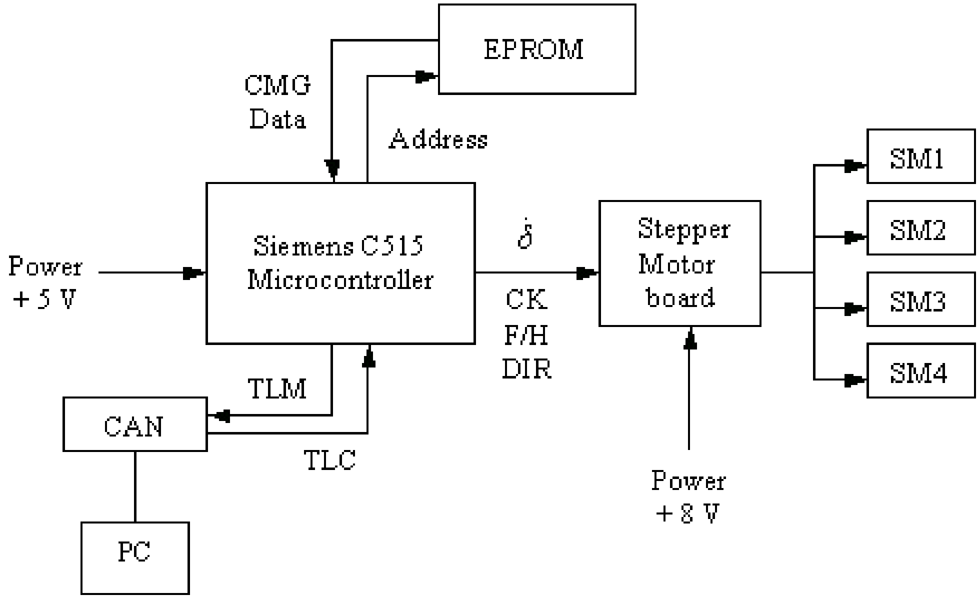
7.5 CMG Mk.II

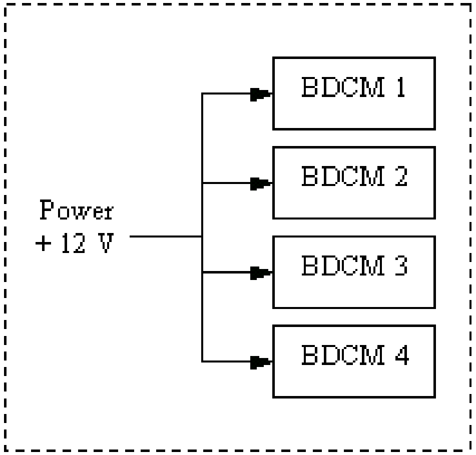
- Having tested the capability of the Mk.I CMG, another CMG is designed as part of a 4-CMG cluster, the CMG Mk.II. The CMG Mk.II utilizes:
  - A different and more powerful BLDC motor with integrated electronics (Faulhaber 1525 BRE)
  - A larger flywheel (angular momentum), properly sized to generate the required torque on the Mk.II CMG ($I_{CMG} = 1.7 \times 10^{-4}$ kg-m^2)
  - The same stepper/gimbal motor (Escap P010/R10) as in the Mk.I
  - New electronics based on a C515 Microcontroller
- Components (motors etc.) can be space graded
- CMG Cluster performance is evaluated through air-bearing experiments

CMG Cluster Layout



7.5 CMG Mk.II Electronics

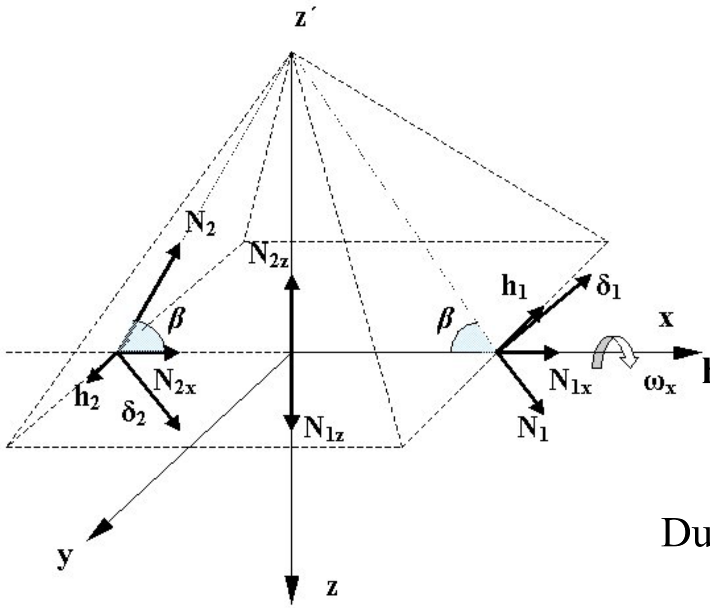




EPROM: Erasable Programmable ROM
SM: Stepper Motor
BDCM: Brushless DC Motor
CK: Clock
F/H: Full/Half step mode
TLC: Telecommand
TLM: Telemetry
DIR: Direction

$\dot{\delta}$: Stepper Motor gimbal rate

7.6 Single-axis maneuvre with two CMGs



$$\mathbf{h}_1 = h_0 \begin{bmatrix} -\sin\delta_1 \cos\beta \\ -\cos\delta_1 \\ \sin\delta_1 \sin\beta \end{bmatrix} \qquad \dot{\boldsymbol{\delta}}_1 = \begin{bmatrix} -\dot{\delta}_1 \sin\beta \\ 0 \\ -\dot{\delta}_1 \cos\beta \end{bmatrix} \Rightarrow N_{1x} = h_0\, \dot{\delta}_1 \cos\beta \cos\delta_1$$

$$\mathbf{h}_2 = h_0 \begin{bmatrix} -\sin\delta_2 \cos\beta \\ \cos\delta_2 \\ -\sin\delta_2 \sin\beta \end{bmatrix} \qquad \dot{\boldsymbol{\delta}}_2 = \begin{bmatrix} -\dot{\delta}_2 \sin\beta \\ 0 \\ \dot{\delta}_2 \cos\beta \end{bmatrix} \Rightarrow N_{2x} = h_0\, \dot{\delta}_2 \cos\beta \cos\delta_2$$

Due to symmetric rotation $\delta_1 = \delta_2$ and $\dot{\delta}_1 = \dot{\delta}_2 = \dot{\delta}$

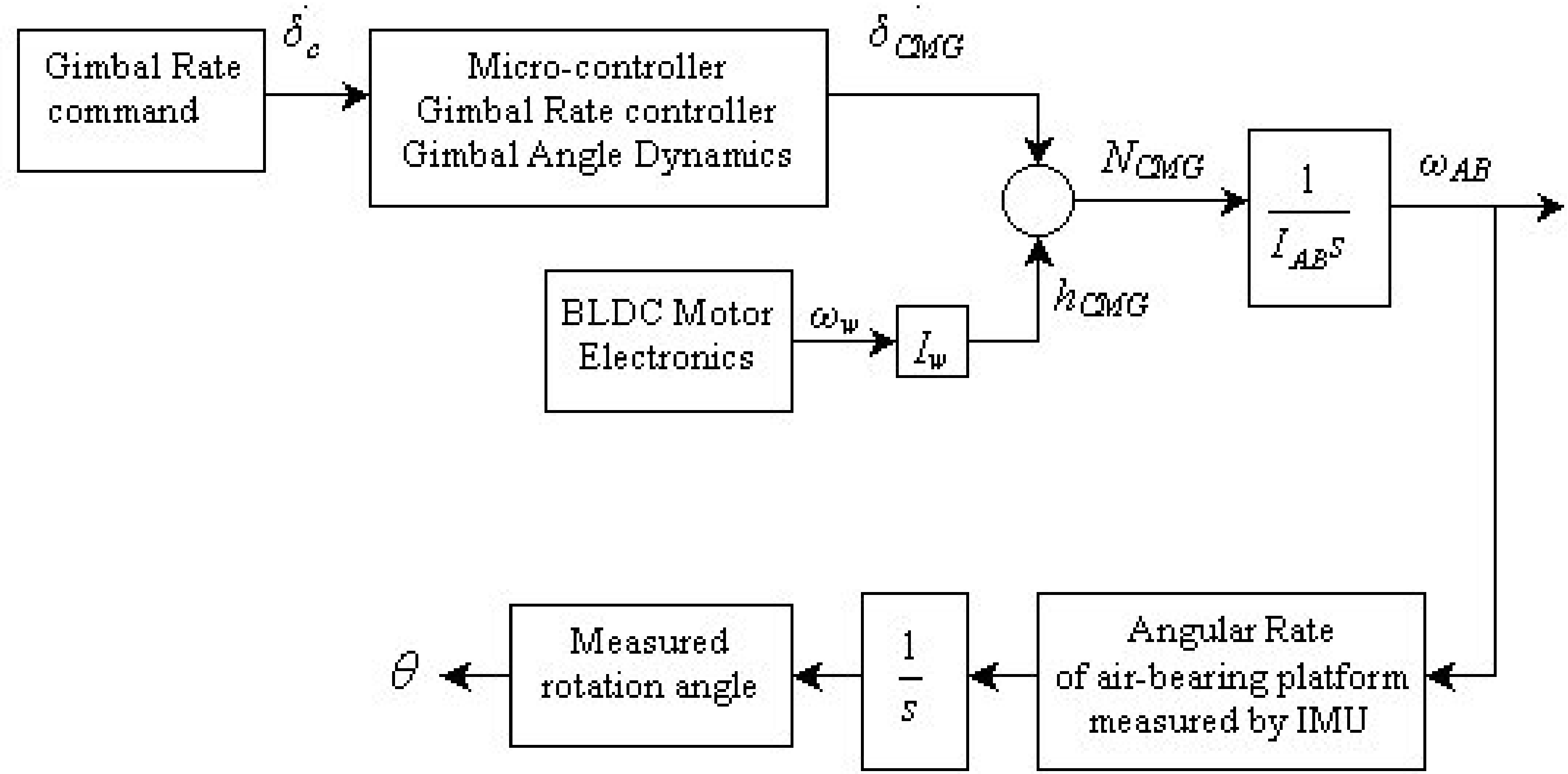
$$\Rightarrow N_x = 2h_0\, \dot{\delta} \cos\beta \cos\delta$$

Theoretical CMG Torque = $N_x = 2h_0\, \dot{\delta} \cos\beta \cos\delta$

Experimental CMG Torque = $N_{CMG} + N_d = -I_{AB}\, \dot{\omega}_{AB}$

- $I_{AB} = 0.8$ kg-m^2

7.7 Experimental Set-up Block Diagram



Gimbal Rate command

$\dot{\delta}_c$

Micro-controller
Gimbal Rate controller
Gimbal Angle Dynamics

$\dot{\delta}_{CMG}$

N_{CMG}

$\frac{1}{I_{AB}s}$

ω_{AB}

BLDC Motor Electronics

ω_w

I_w

h_{CMG}

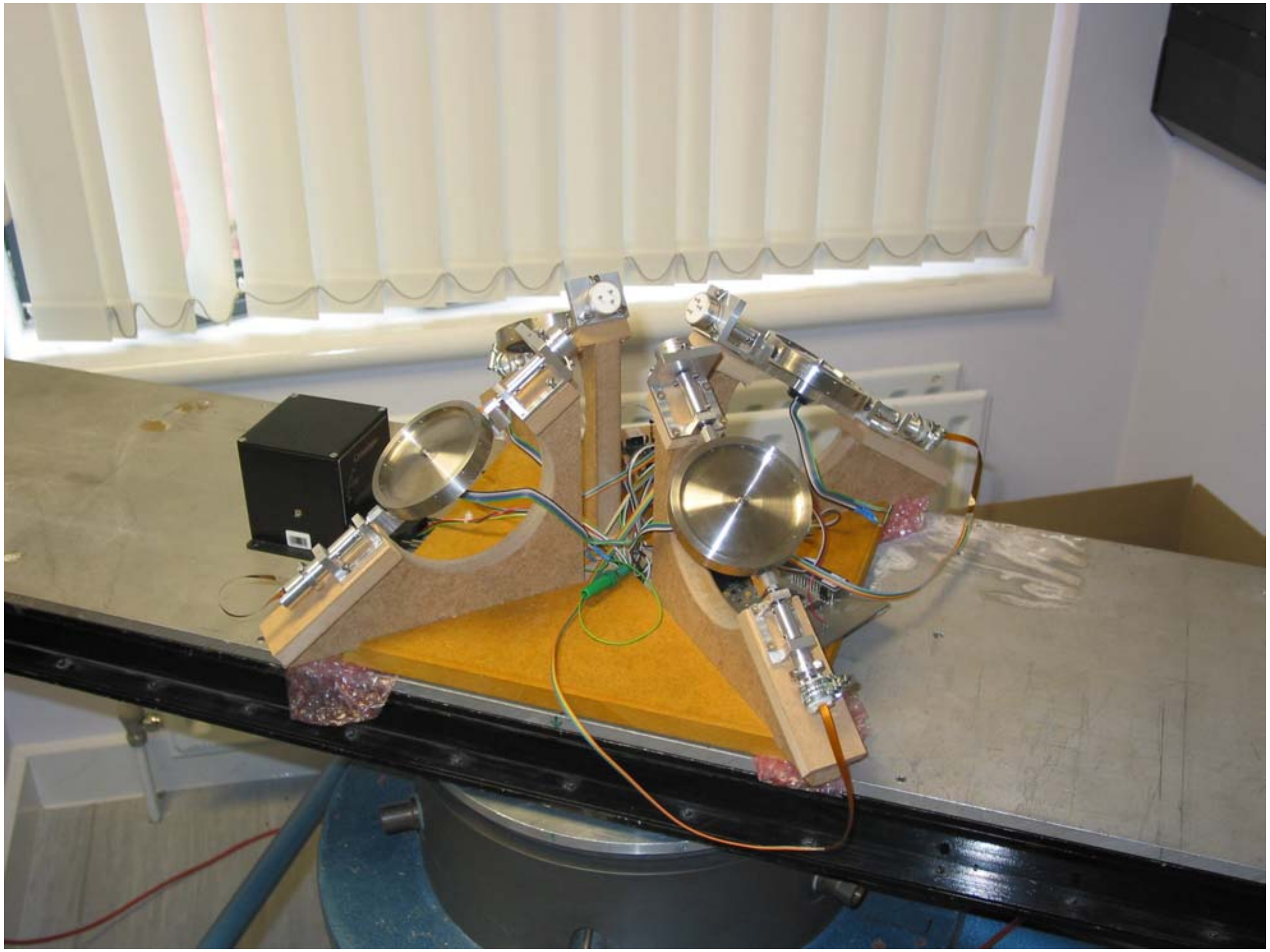
Angular Rate
of air-bearing platform
measured by IMU

$\frac{1}{s}$

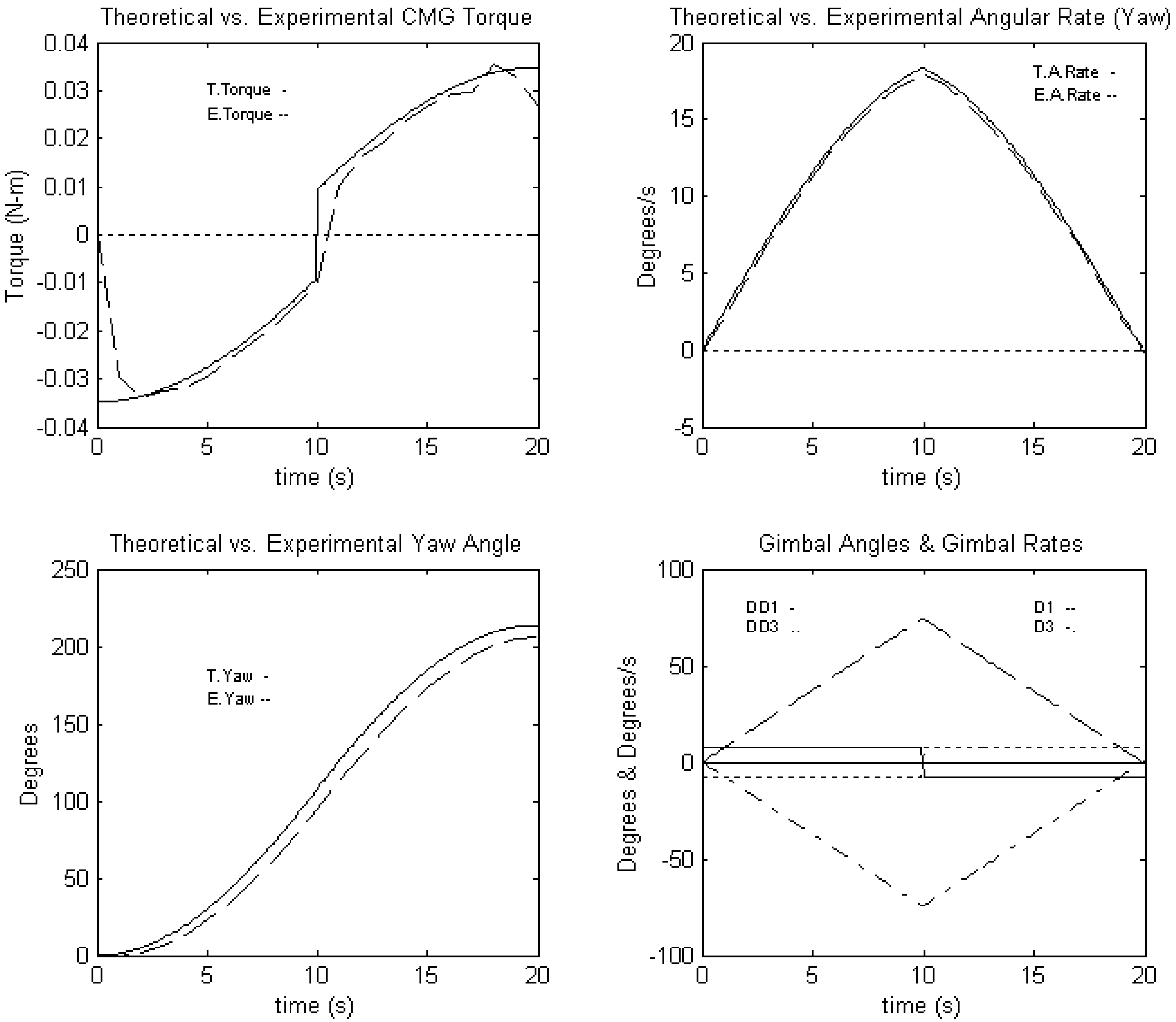
Measured rotation angle

θ

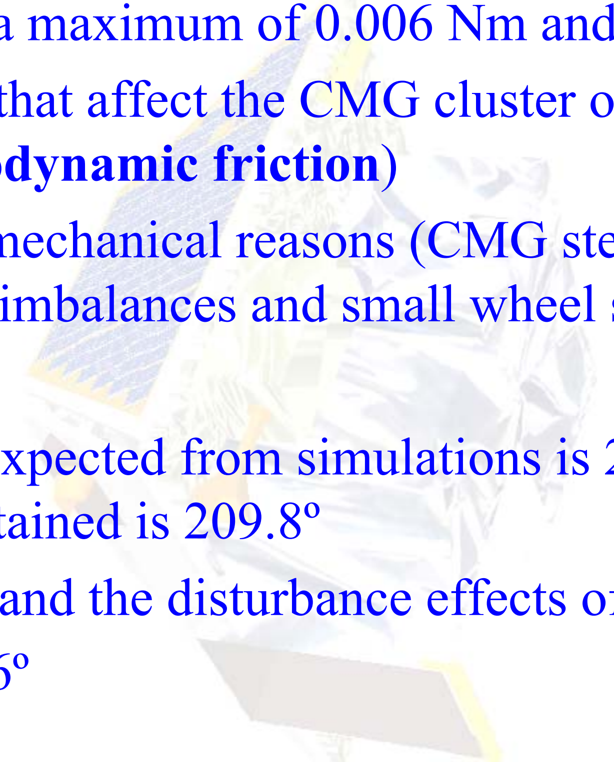
7.8 Experimental Set-up



7.9 CMG Mk.II Experiment

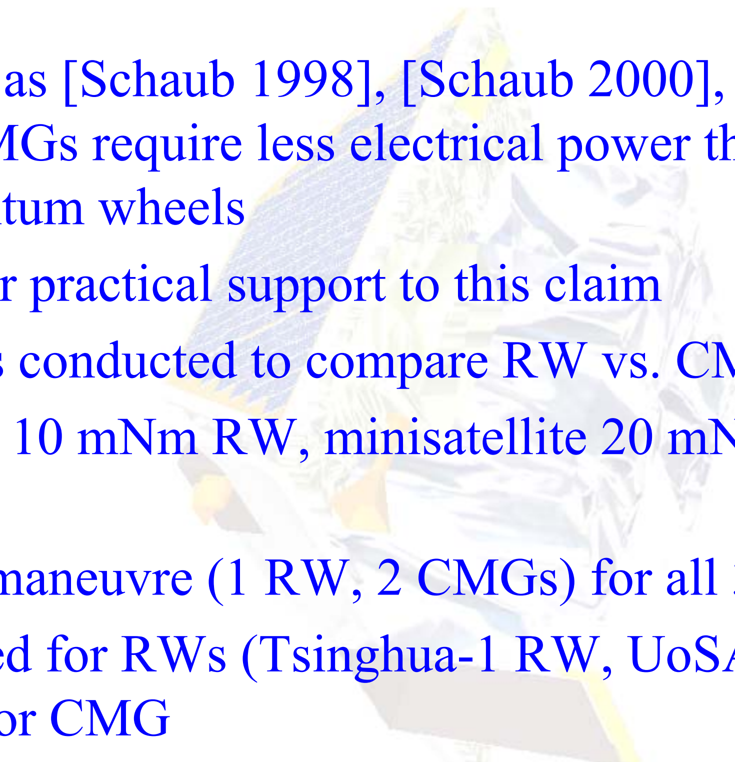

Theoretical vs. Experimental CMG Torque
Torque (N-m)
time (s)
T.Torque -
E.Torque --
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
0
5
10
15
20
Theoretical vs. Experimental Angular Rate (Yaw)
Degrees/s
time (s)
T.A.Rate -
E.A.Rate --
20
15
10
5
0
-5
0
5
10
15
20
Theoretical vs. Experimental Yaw Angle
Degrees
time (s)
T.Yaw -
E.Yaw --
250
200
150
100
50
0
0
5
10
15
20
Gimbal Angles & Gimbal Rates
Degrees & Degrees/s
time (s)
DD1 -
DD3 :
D1 --
D3 -.
100
50
0
-50
-100
0
5
10
15
20

7.9 CMG Mk.II Results



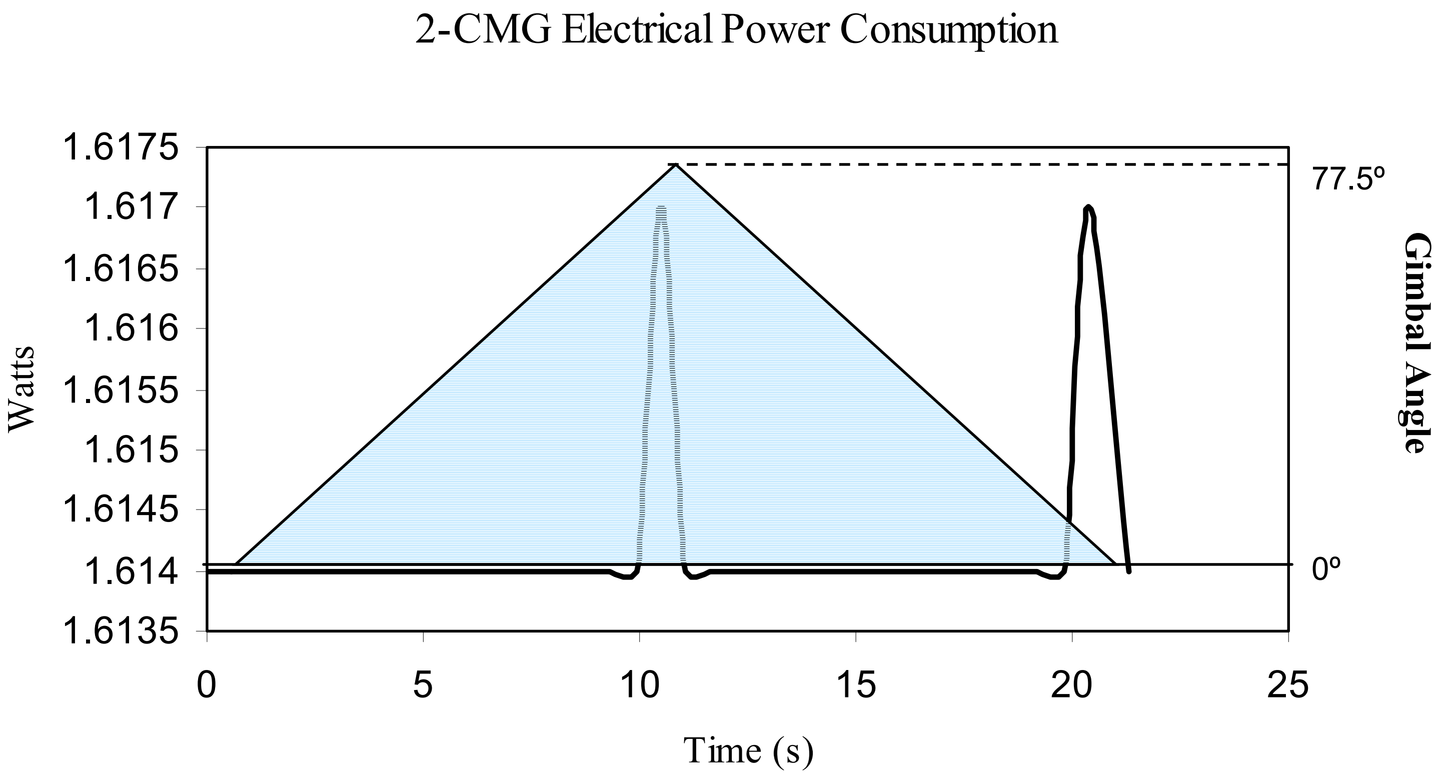
- Do not take under consideration the wheel and gimbal motor dynamics, or any other internal disturbances such as motor cogging or torque ripple effects
- Torque error reaches a maximum of 0.006 Nm and this is mainly due to:
  - The disturbances that affect the CMG cluster on the air-bearing (air-bearing bias, **aerodynamic friction**)
  - High bandwidth-mechanical reasons (CMG stepper motor backlash, micro vibrations, wheel imbalances and small wheel speed variations)
  - IMU-Gyro noise
- The rotation angle θ expected from simulations is 218.4° whereas the experimental value attained is 209.8°
- Open-loop maneuver and the disturbance effects of the air-bearing result to an acceptable error of 8.6°

7.10 Electrical Power Consumption



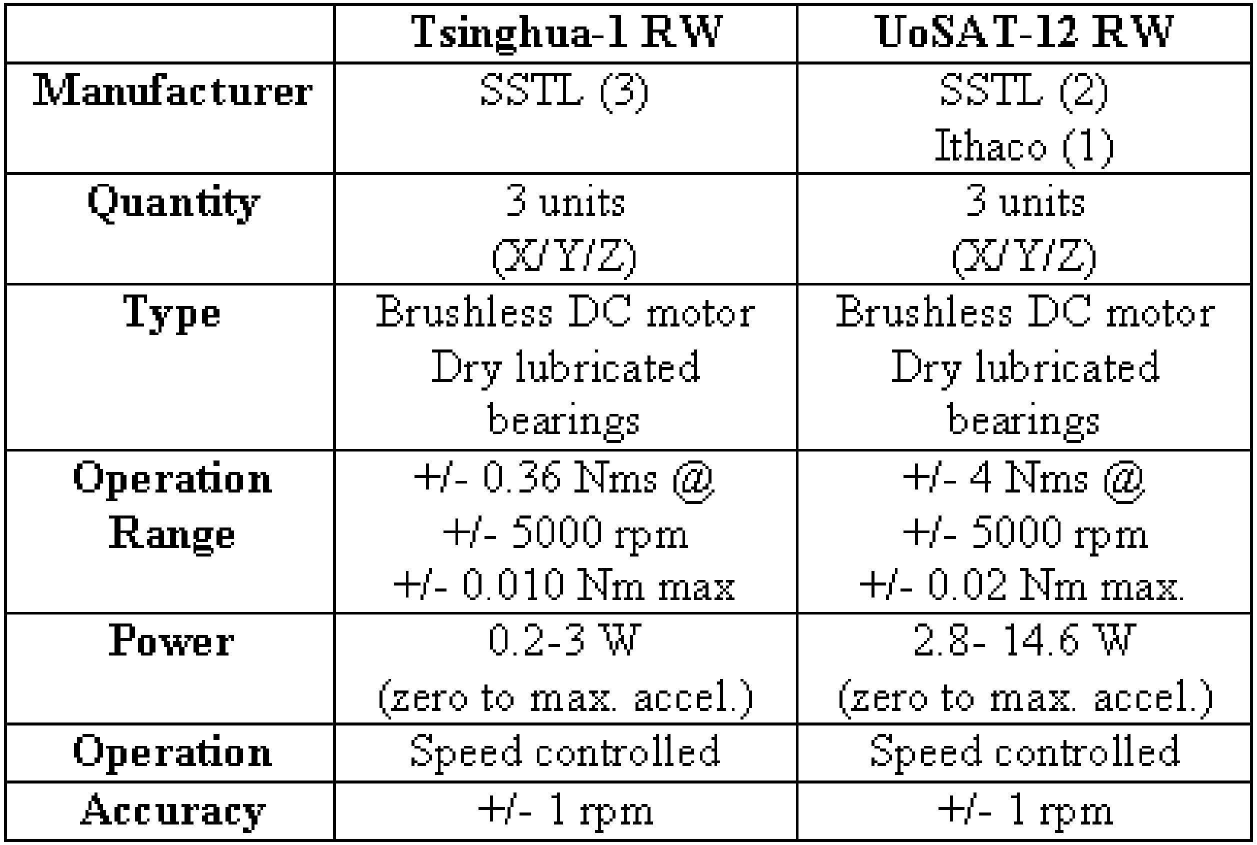
- Electrical power consumption is important small satellite development and operations
- Literature, such as [Schaub 1998], [Schaub 2000], [Roser 1997], [Salenc 2000] mention that CMGs require less electrical power than other actuators such as reaction/momentum wheels
- No theoretical or practical support to this claim
- A comparison is conducted to compare RW vs. CMG power consumption
- A microsatellite 10 mNm RW, minisatellite 20 mNm RW and 52.25 mNm CMG (2)
- 40º single-axis maneuvre (1 RW, 2 CMGs) for all 3 actuators/platforms
- In-orbit data used for RWs (Tsinghua-1 RW, UoSAT-12 RW) and vacuum power measurements for CMG
- Measurements are normalised to a 1 kg-m^2 MOI
- Energy index is introduced to compare actuators

7.11 CMG Electrical Power Consumption



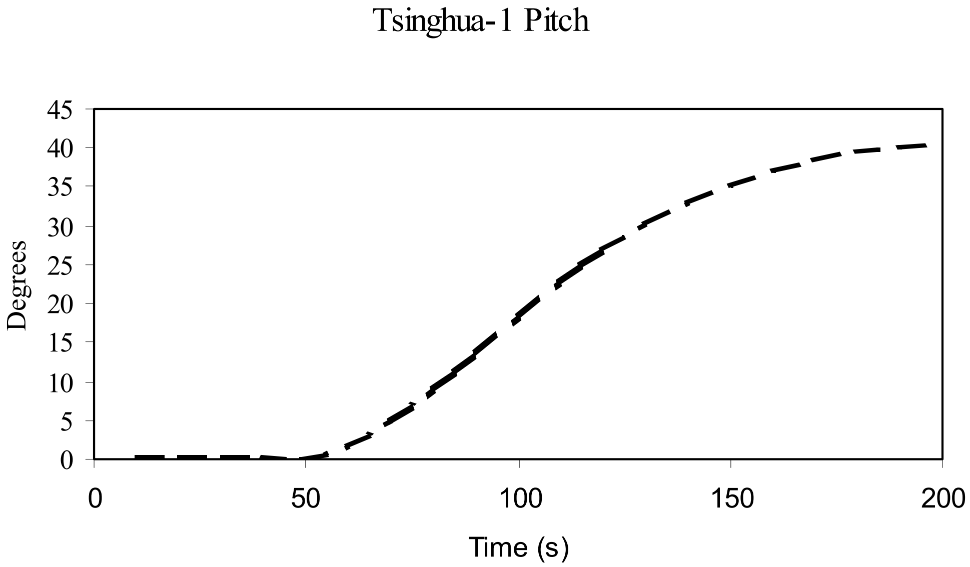
- CMGs perform the 40º maneuvre in 20s
- Identical to previous experiments
- Measurement is for all 4 stepper/gimbal motors + BDCM

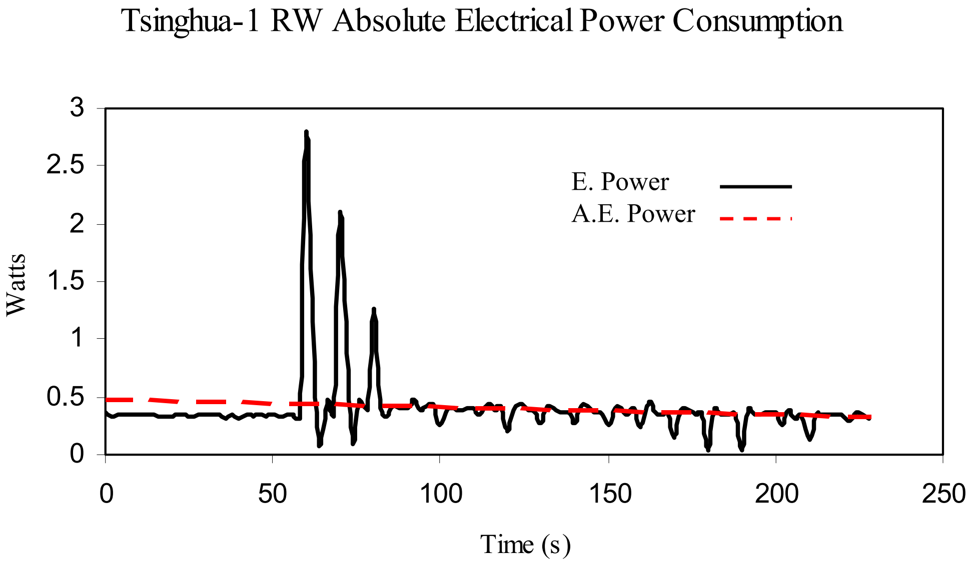
7.12 RW Electrical Power Consumption



	Tsinghua-1 RW	**UoSAT-12 RW**
Manufacturer	SSTL (3)	SSTL (2) Ithaco (1)
Quantity	3 units (X/Y/Z)	3 units (X/Y/Z)
Type	Brushless DC motor Dry lubricated bearings	Brushless DC motor Dry lubricated bearings
Operation Range	+/- 0.36 Nms @ +/- 5000 rpm +/- 0.010 Nm max	+/- 4 Nms @ +/- 5000 rpm +/- 0.02 Nm max.
Power	0.2-3 W (zero to max. accel.)	2.8- 14.6 W (zero to max. accel.)
Operation	Speed controlled	Speed controlled
Accuracy	+/- 1 rpm	+/- 1 rpm

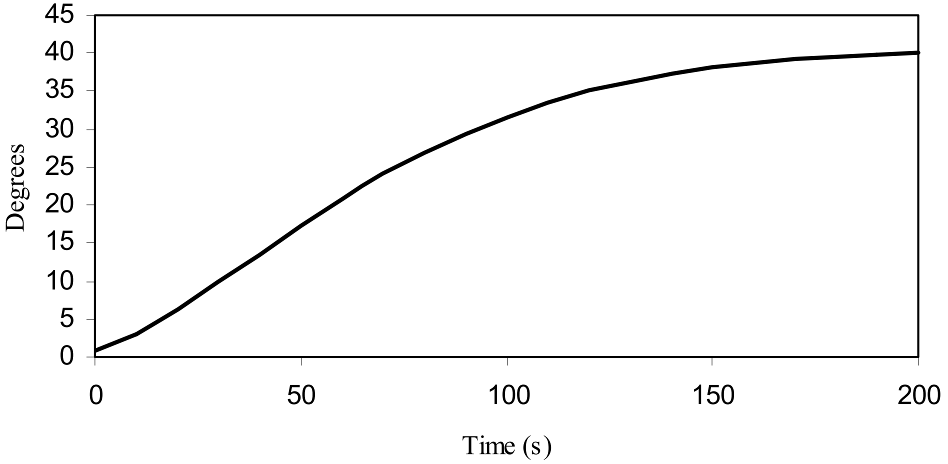
7.13 Tsinghua-1 RW Maneuvre & Electrical Power Consumption



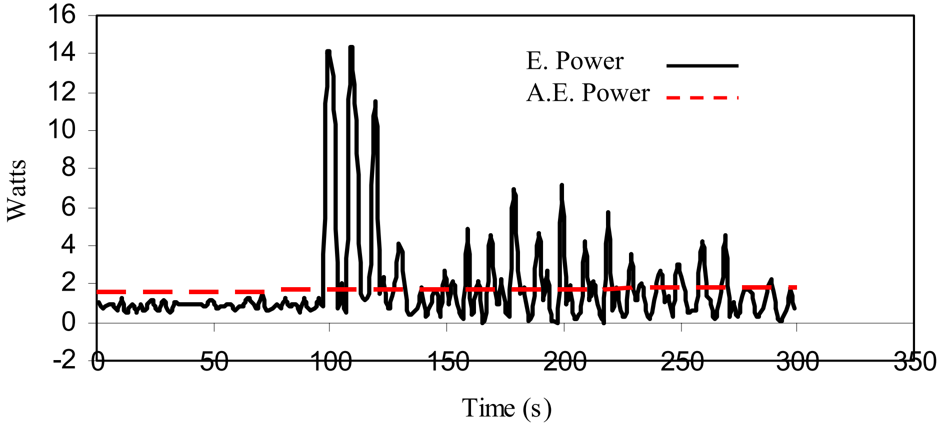


7.14 UoSAT-12 RW Maneuvre & Electrical Power Consumption

UoSAT-12 Roll



UoSAT-12 RW Absolute Electrical Power Consumption



7.15 Electrical Power Consumption Experimental Data

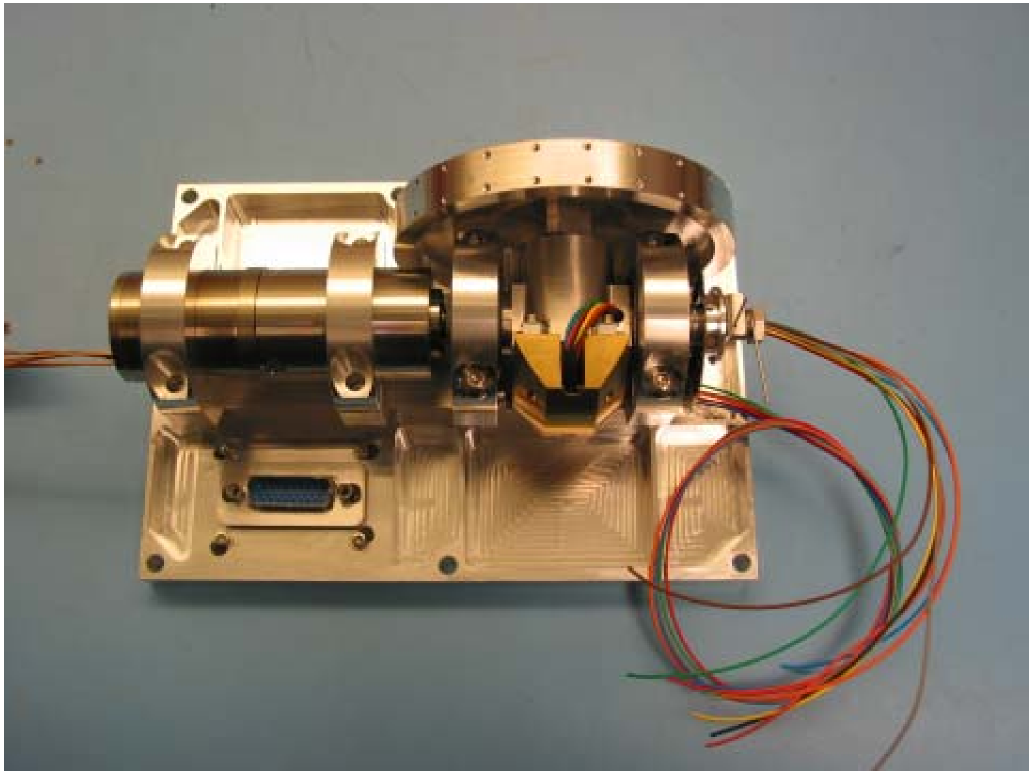
Parameter	UoSAT-12	Tsinghua-1	CMG
MOI (kg-m^2)	40	2.5	4.1
Time (s)	200	150	20
Torque (mN-m)	20	10	52.25
Mass (kg)	3.2	1	0.585[1]
Avg. Power (W)	2	0.45	1.61
Scaled Power (W-kg-m^2)	0.05	0.16	0.39
Scaled Energy (J/kg-m^2)	10	27	7.85

- [1] Mass for two CMGs, unpackaged
- Single axis 40° maneuvre
- Energy index reflects the energy accumulated during a maneuvre on a normalized 1 kg-m^2 MOI platform
- CMGs prove to be the least power consuming actuator with an energy index of 7.85
- 21.5 % more efficient than the UoSAT-12 RW power consumption and 70.9 % more efficient than the Tsinghua-1 RW

7.16 CMG Experiments – Some Conclusions

- Practical work confirms the theoretical findings on the advantageous use and performance of CMGs for agile small satellites
- Two CMGs designed (Mk.I, Mk.II)
- CMGs were evaluated in air-bearing experiments replicating single-axis maneuvers
- CMG Mk.I generated a max.torque of 8.84 mNm, CMG Mk.II a max. torque of 38 mNm, during air-bearing experiments
- Experiments indicate the better electrical power consumption when utilizing a CMG cluster when compared to a RW system
- CMG Mk.II maximum power was found to be 1.614 W
- CMGs are shown to be more power efficient by at least 21.5 % from reaction wheels, with a mass saving of 41.5 % to the smallest (Tsinghua-1) RW
- With a mass of about 1.17 kg CMGs were shown in a practical way to potentially be an efficient and highly capable means of controlling agile microsatellites

8. Application: BILSAT CMG



CMGs for BILSAT-1

- TUBITAK-BILTEN initiated a call for Turkish and SSTL payloads for BILSAT-1
- Numerous payloads suggested
- Payloads selected:
  - Turkish: Coban, Gezgin
  - SSTL: Propulsion, GPS Attitude Determination
  - SSC/SSTL: CMGs…
- Payload Selection: September 2001
- Unofficial approval for CMGs: June 2002
- Time to design CMGs: 6 months ! (not…!)
- Payload: A twin (2)-CMG cluster for rapid pitch axis control

BILSAT Payloads

Primary mission: imaging

- **Multi spectral**
  - **RED** 26 m ground sampling distance
  - **BLUE** 26 m ground sampling distance
  - **GREEN** 26 m ground sampling distance
  - **NIR** 26 m ground sampling distance
- **Panchromatic**
  - 12 m ground sampling distance

Secondary mission: Store and forward communications

BILSAT Additional Payloads (I)

Additional payloads

Maximize the profit gained from this technology transfer programme

COBAN

Multi band camera;

80 m resolution;

9 channels;

SQM model of coban

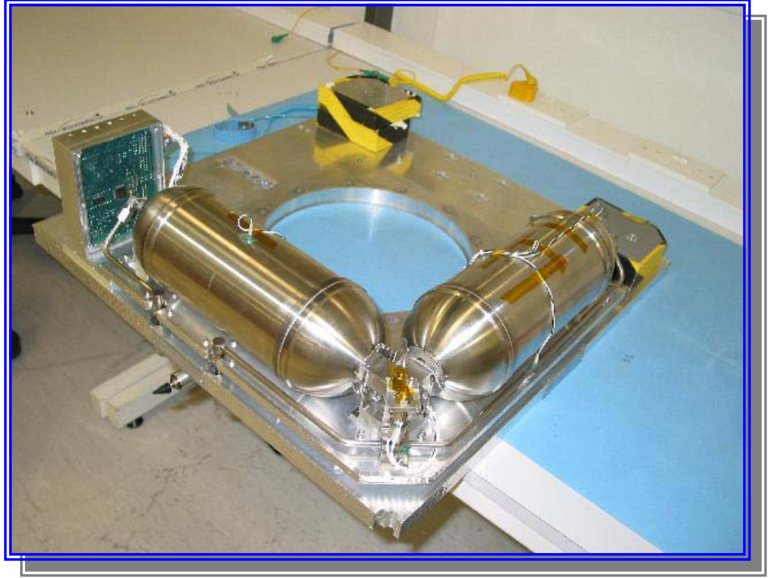
GEZGIN

JPEG2000 DSP Card;

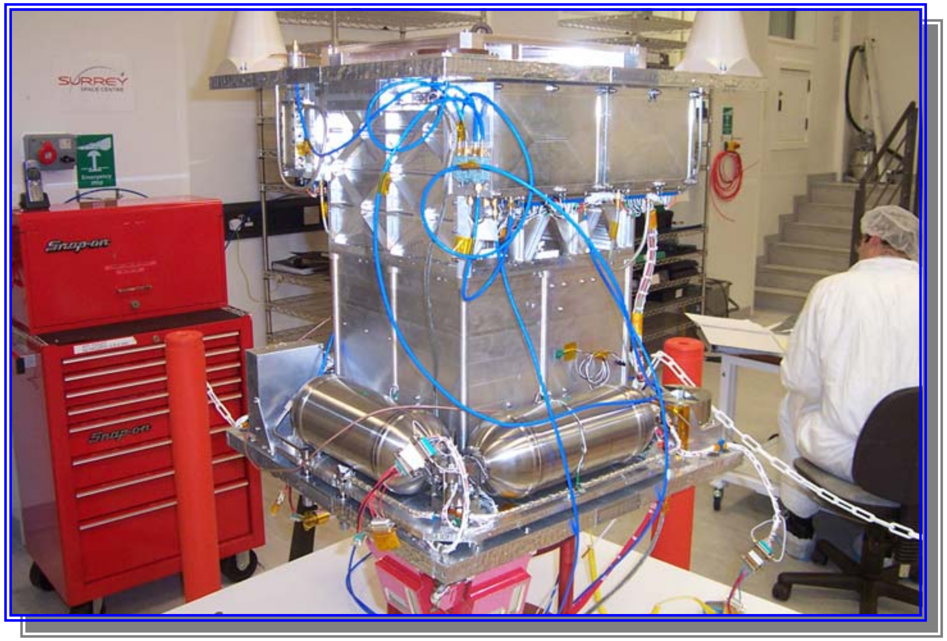
Real Time image compression;

BILSAT Additional Payloads (II)

Propulsion system



A propulsion system will be installed on the satellite to make semi major axis corrections. A single thruster fires through the Centre of Gravity to perform orbit change manoeuvres



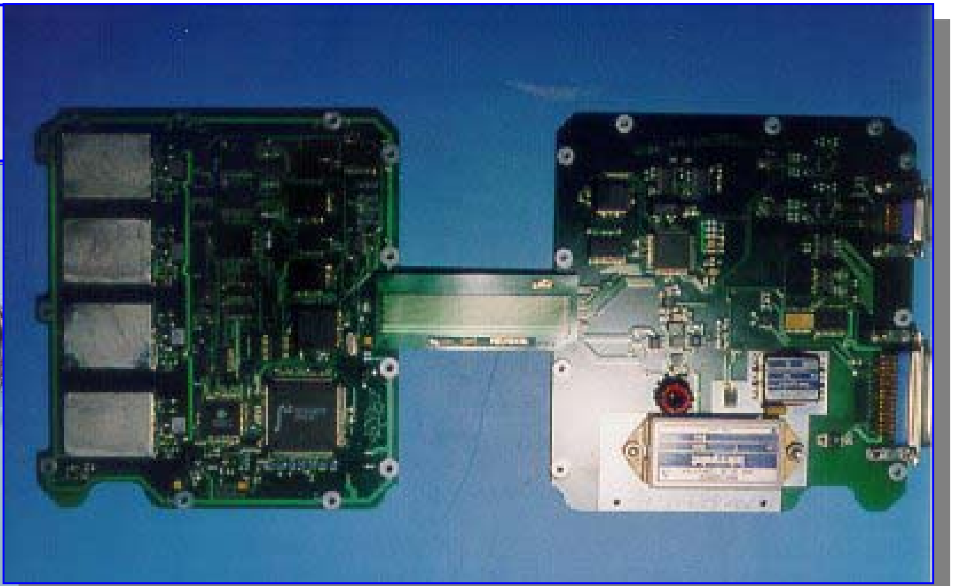
System Features

- -Propellant - butane
- -System dry mass < 6kg
- -Propellant mass = 2.3 kg
- -15 Watt resistojet thruster
- -Thrust ~ 50 mN
- -Delta V ~ 9 m/sec

BILSAT Additional Payloads (III)

GPS Receiver

A GPS receiver:
: To give position knowledge = +/- 50 m
: To perform attitude determination = +/- 1 degree



Control Moment Gyro (CMG)

A Control Moment Gyro to improve the agility of the satellite

- Rapid Pitch axis control (2 °/s)

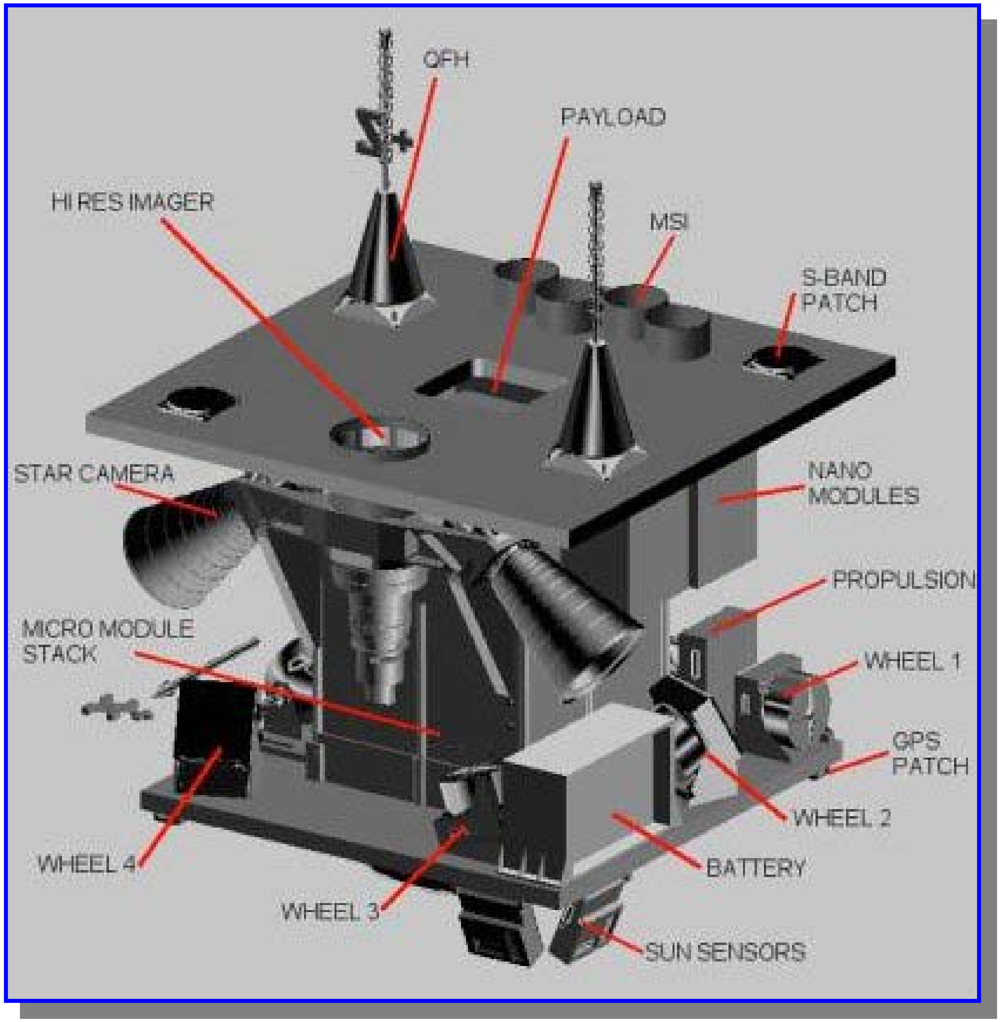
BILSAT-1 Satellite Architecture

- BILSAT-1:a small satellite based on enhanced micro satellite platform of SSTL

Core: standard SSTL self supporting stack of equipment boxes

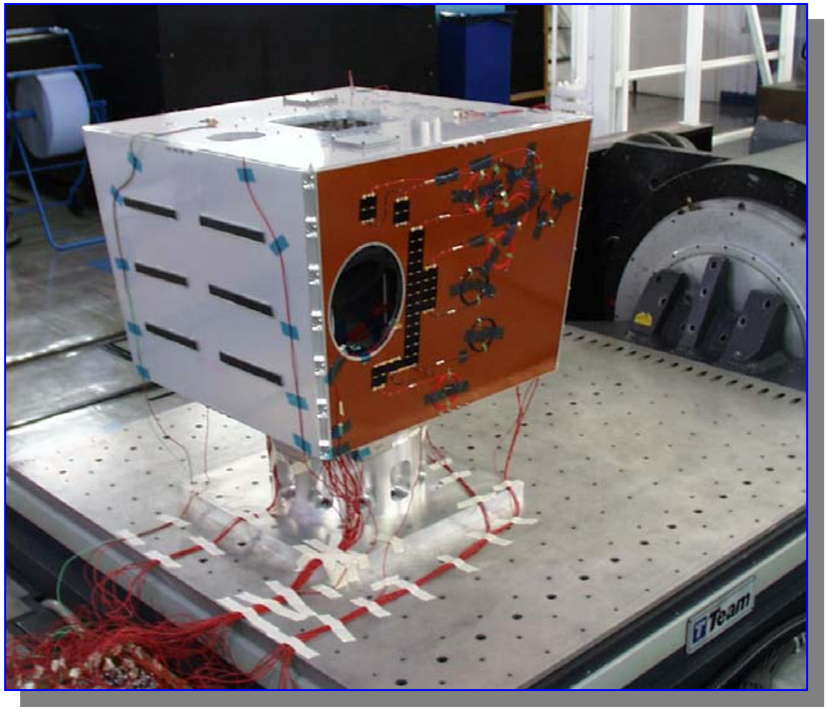
Below earth Facing Facet : enclosure that holds some of the customer built payloads

Nano modules: There are also nano modules which are non structural elements



BILSAT-1 Project Status

- Structure qualification tests successful

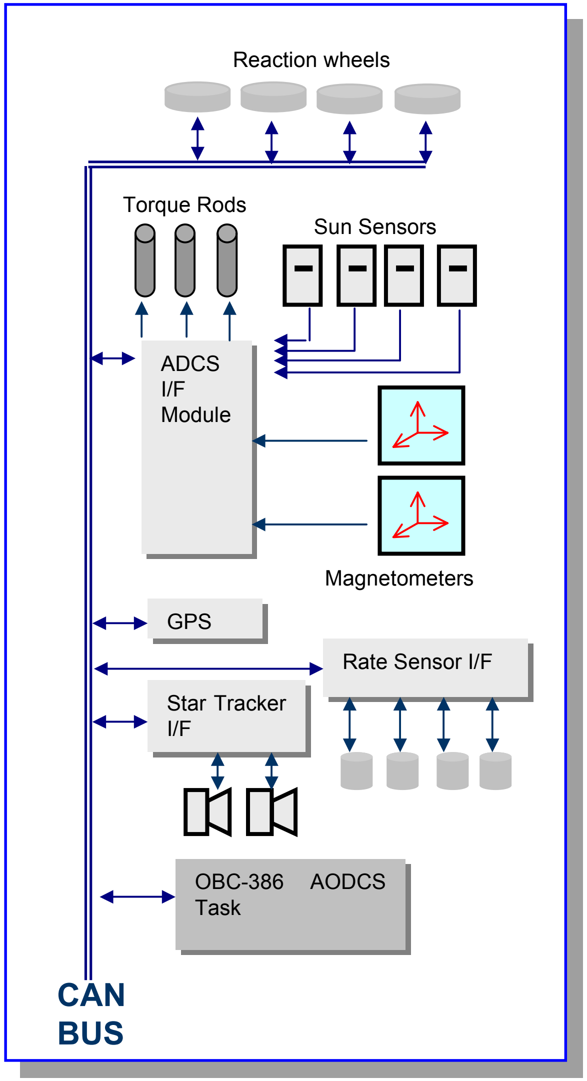


- Spacecraft in AIT
- EMC Testing this week
- TVT
- Vibrations
- Launch scheduled for July

BILSAT Attitude Determination and Control System (ADCS)

BILSAT ADCS Subsystem (I)

BILSAT can achieve
- attitude control +/- 0.02 deg
- attitude knowledge of 0.006 deg

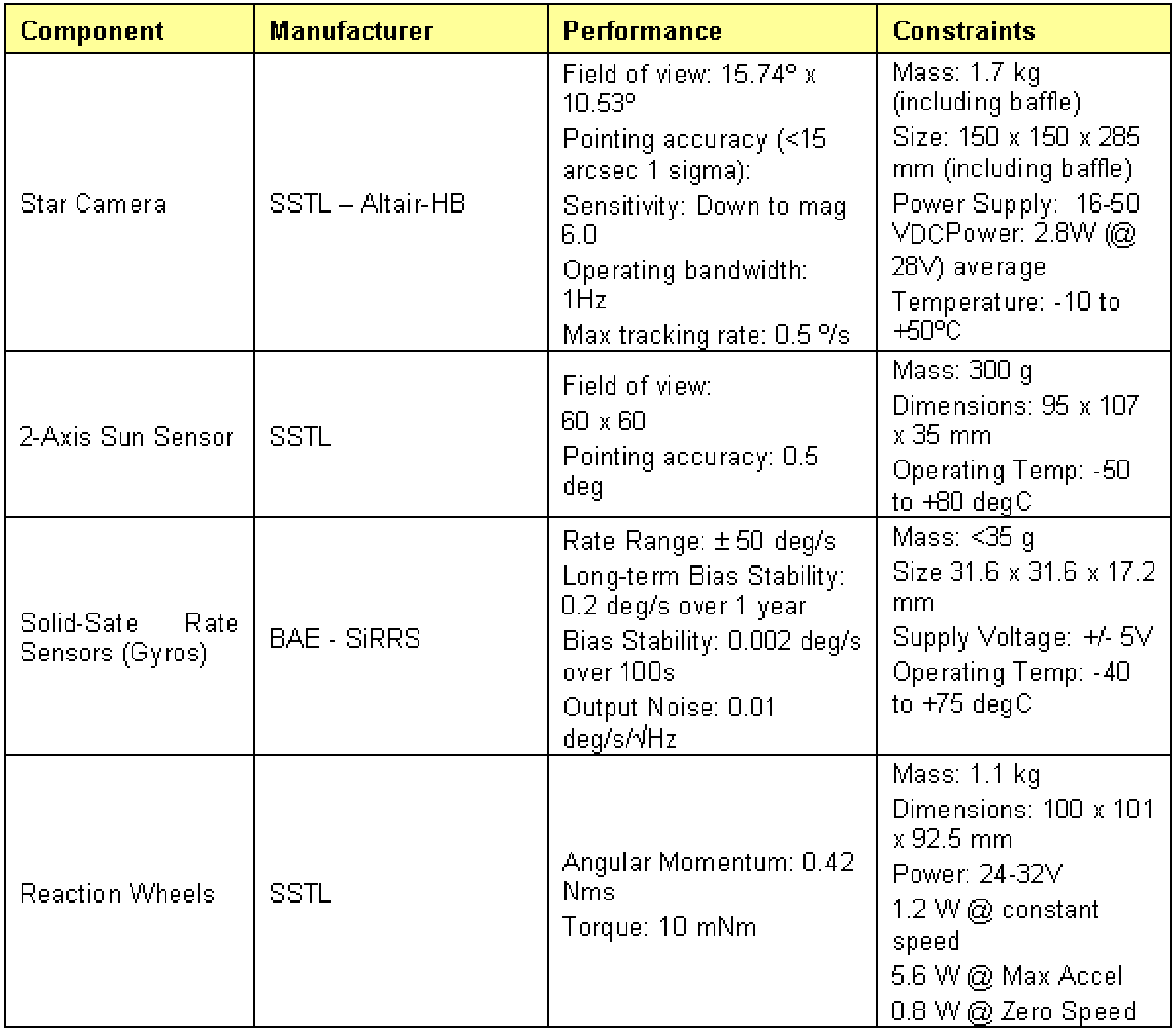


BILSAT sensors
- four sun sensors,
- four rate sensors,
- two magnetometers
- two star cameras

BILSAT actuators
- four reaction wheels,
- three torque rods,
- gravity gradient boom

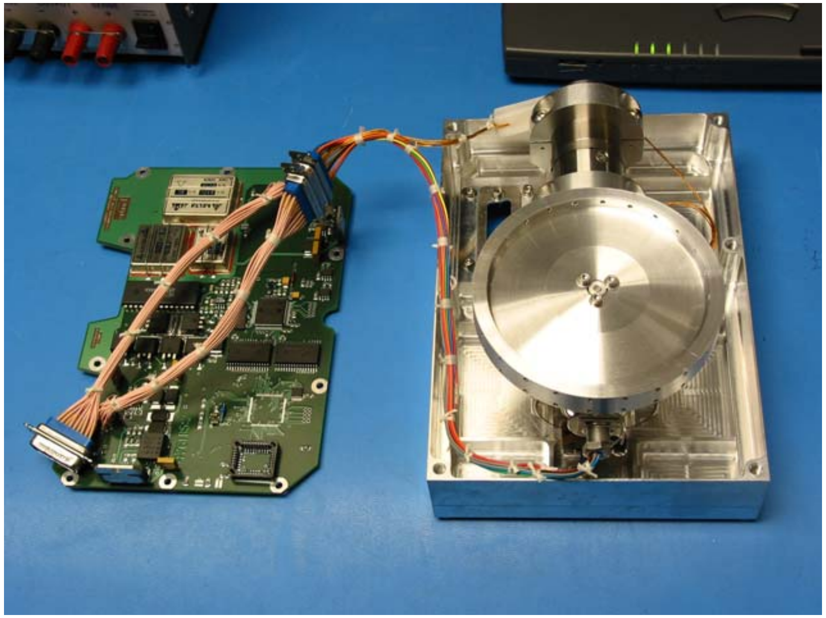
A GPS receiver is also used
to obtain orbital position information of +/-50 m

BILSAT ADCS Subsystem (II)



Component	**Manufacturer**	**Performance**	**Constraints**
Star Camera	SSTL – Altair-HB	Field of view: 15.74° x 10.53° Pointing accuracy (<15 arcsec 1 sigma): Sensitivity: Down to mag 6.0 Operating bandwidth: 1Hz Max tracking rate: 0.5 °/s	Mass: 1.7 kg (including baffle) Size: 150 x 150 x 285 mm (including baffle) Power Supply: 16-50 VDCPower: 2.8W (@ 28V) average Temperature: -10 to +50°C
2-Axis Sun Sensor	SSTL	Field of view: 60 x 60 Pointing accuracy: 0.5 deg	Mass: 300 g Dimensions: 95 x 107 x 35 mm Operating Temp: -50 to +80 degC
Solid-Sate Rate Sensors (Gyros)	BAE - SiRRS	Rate Range: ±50 deg/s Long-term Bias Stability: 0.2 deg/s over 1 year Bias Stability: 0.002 deg/s over 100s Output Noise: 0.01 deg/s/√Hz	Mass: <35 g Size 31.6 x 31.6 x 17.2 mm Supply Voltage: +/- 5V Operating Temp: -40 to +75 degC
Reaction Wheels	SSTL	Angular Momentum: 0.42 Nms Torque: 10 mNm	Mass: 1.1 kg Dimensions: 100 x 101 x 92.5 mm Power: 24-32V 1.2 W @ constant speed 5.6 W @ Max Accel 0.8 W @ Zero Speed

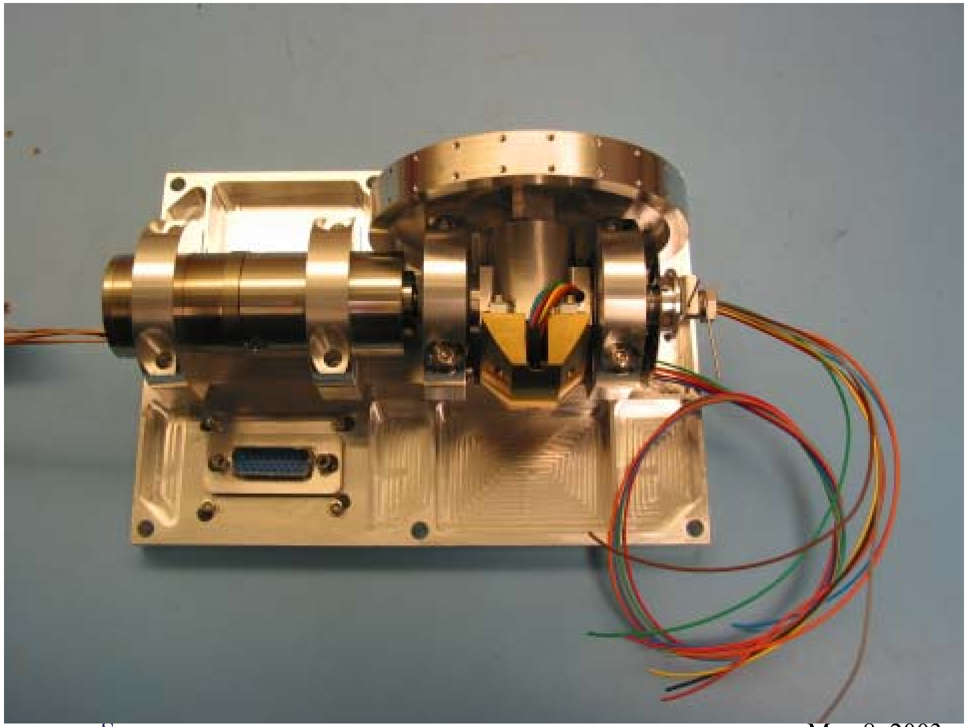
CMG Design



BILSAT CMG

- Attitude Actuator
  - High torque capability, High stability
  - Exceptional performance for small satellite
    - Fast slews (30deg in 15s for 130kg spacecraft)
    - E.g for tactical imaging, TDI, target tracking
  - Developed by University of Surrey/SSTL/ESA/BILTEN
  - First flight on BILSAT Q3 2003

Dimensions	135 x 155 x 190 mm
Mass	2.2kg
Power	12W peak
Torque	95mNm

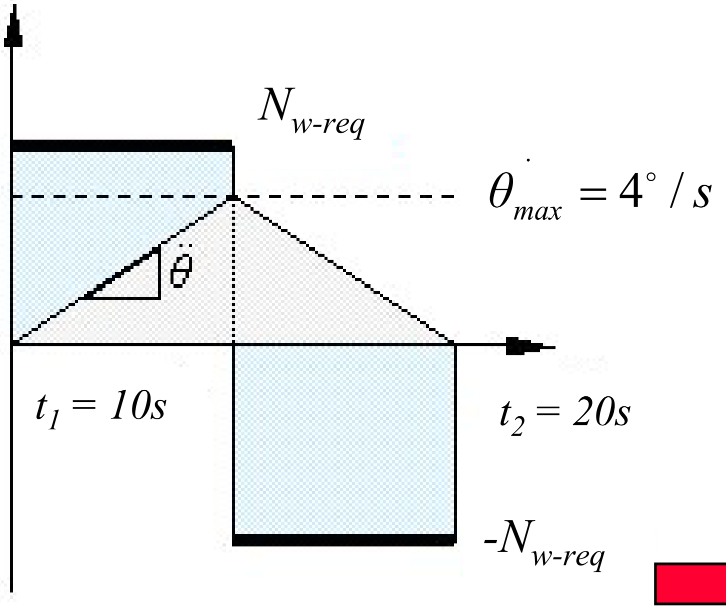


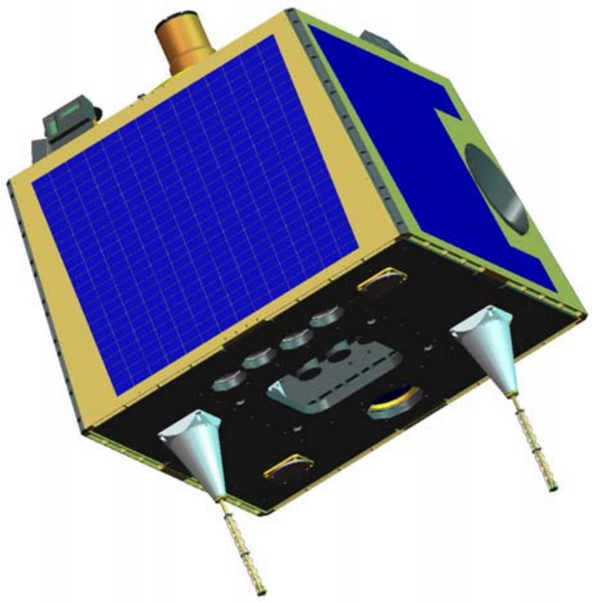
BILSAT CMG Requirements

- 2°/s average slew rate capability (pitch axis)
- Demonstrate the principle of a CMG
- Has to fit in the available volume on BILSAT-1
- Mass $\leq$ 1.5kg per CMG

Agility-Slew Rate Requirement

- Assumptions:
  - Average 2°/s slew requirement (40° in 20s)
  - Use BILSAT-1



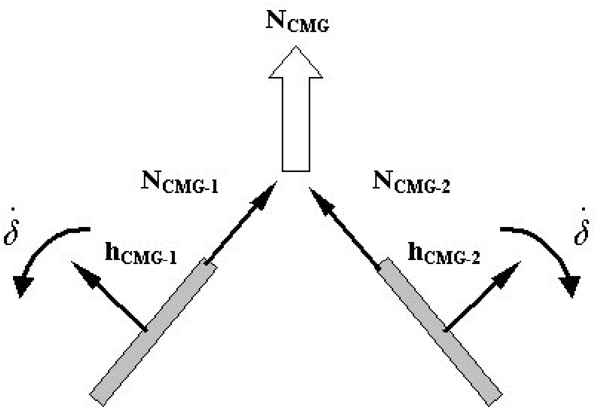


$\Rightarrow$ **$N_{w\text{-}req}$ = ~95 mNm**

- SSTL actuators: 3-20 mNm
- ACS based on RWs :
  - 10% of spacecraft mass
  - 40% of required torque

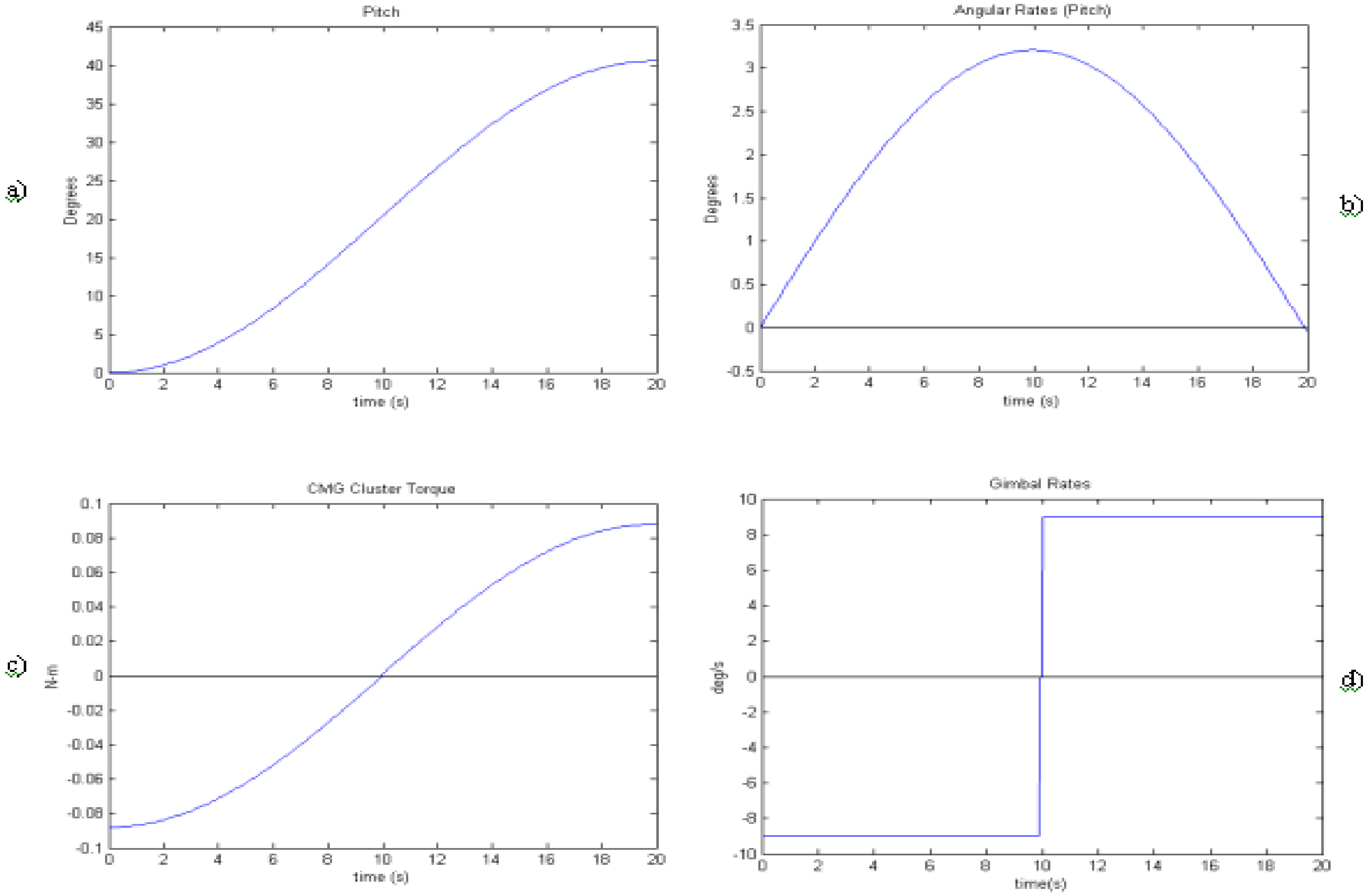
BILSAT CMG Configuration

- For a 2°/s average slew rate capability (pitch axis) for a 130 kg platform, a 95 mNm torque is required



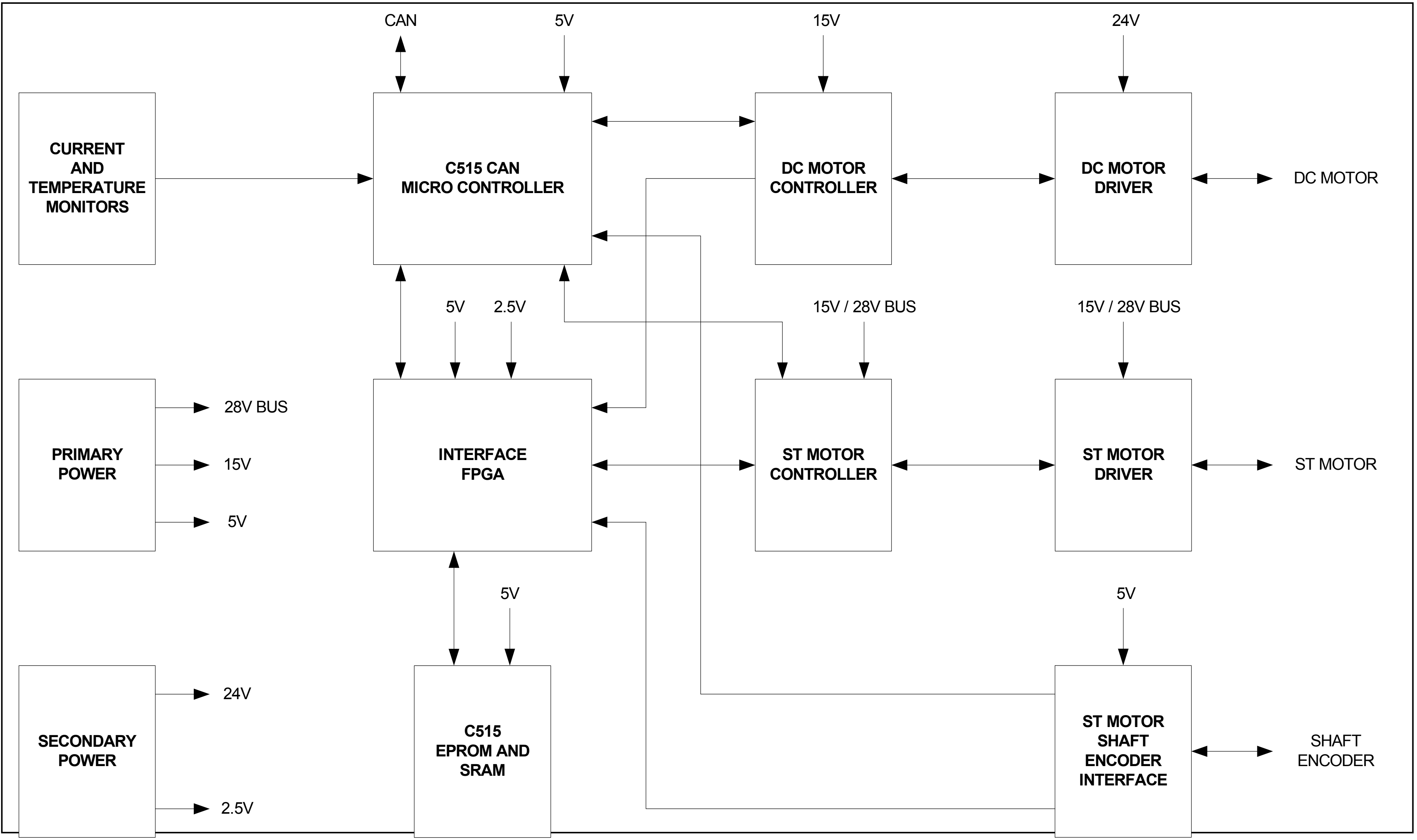
- Twin CMG payload in parallel configuration
- CMG h = 0.28 Nms, Flywheel speed operating at 16,900 rpm, gimbal rate of 9°/s
- Can vary flywheel speed and gimbal rate (> 9°/s)

CMG Simulations

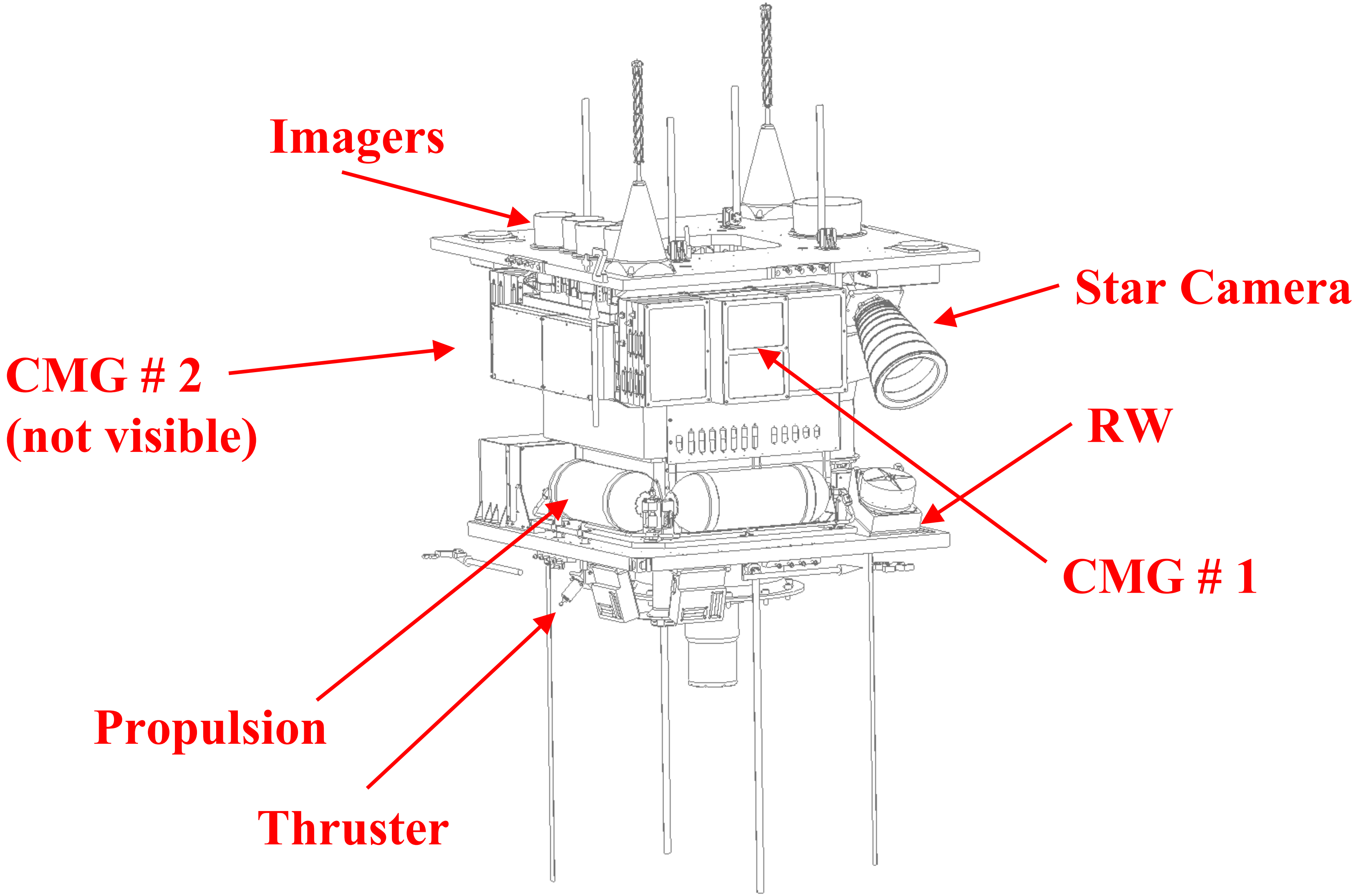


CMG Parameters: h_{cmg}= 0.28 Nms, (I_x, I_y, I_z) =10 kg-m^2

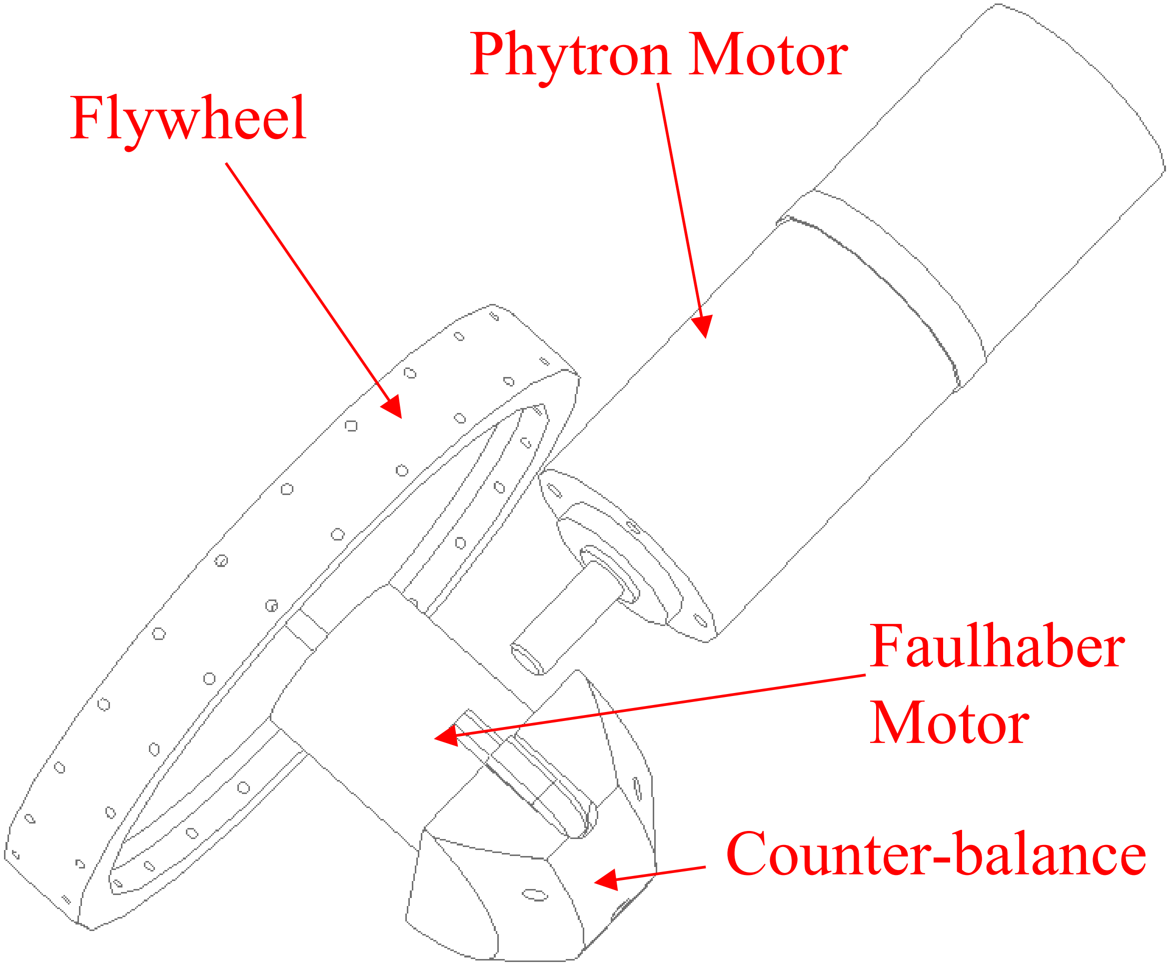
CMG Electronics



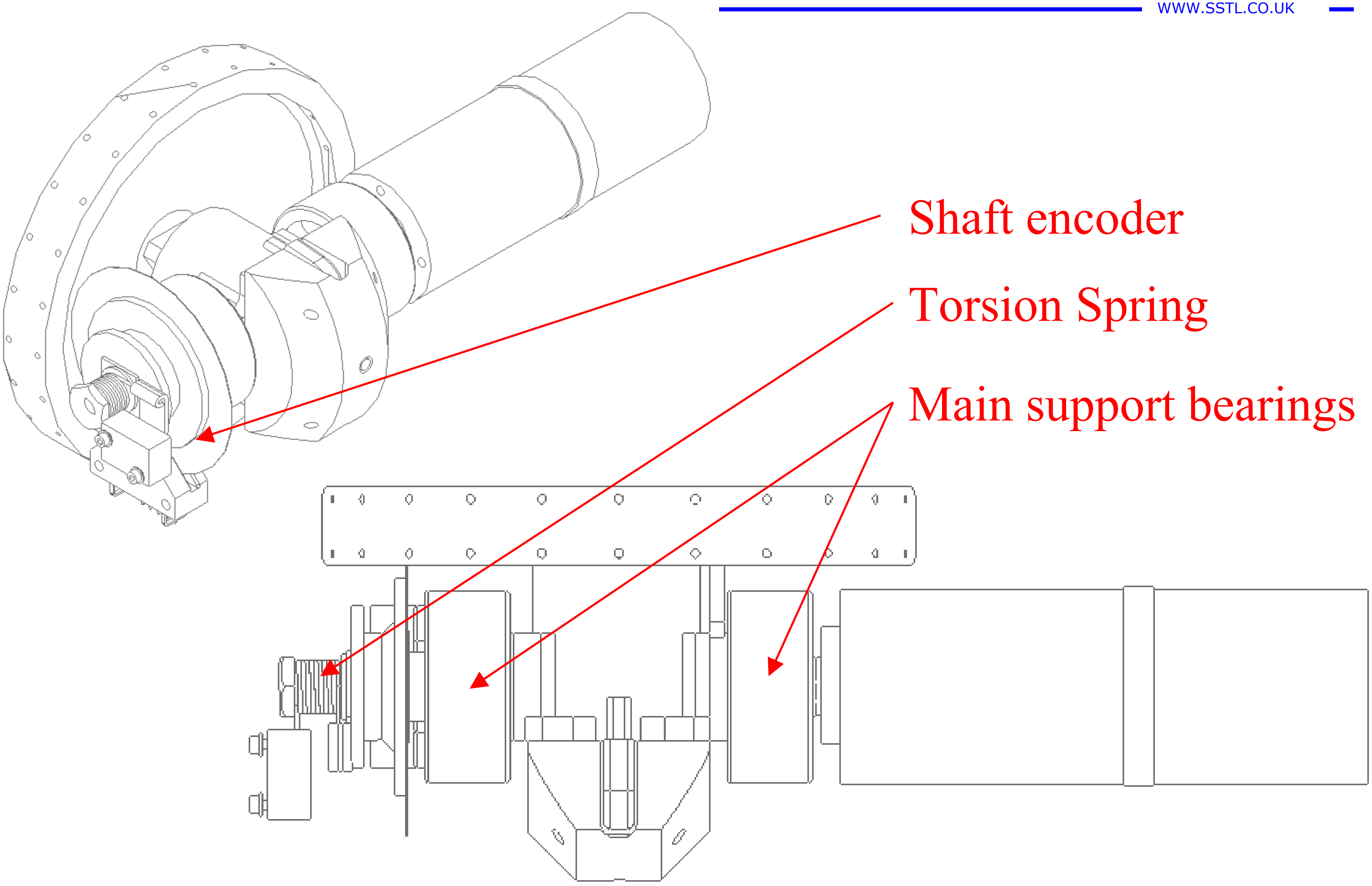
CMG Mechanics



CMG Mechanics



CMG Mechanics

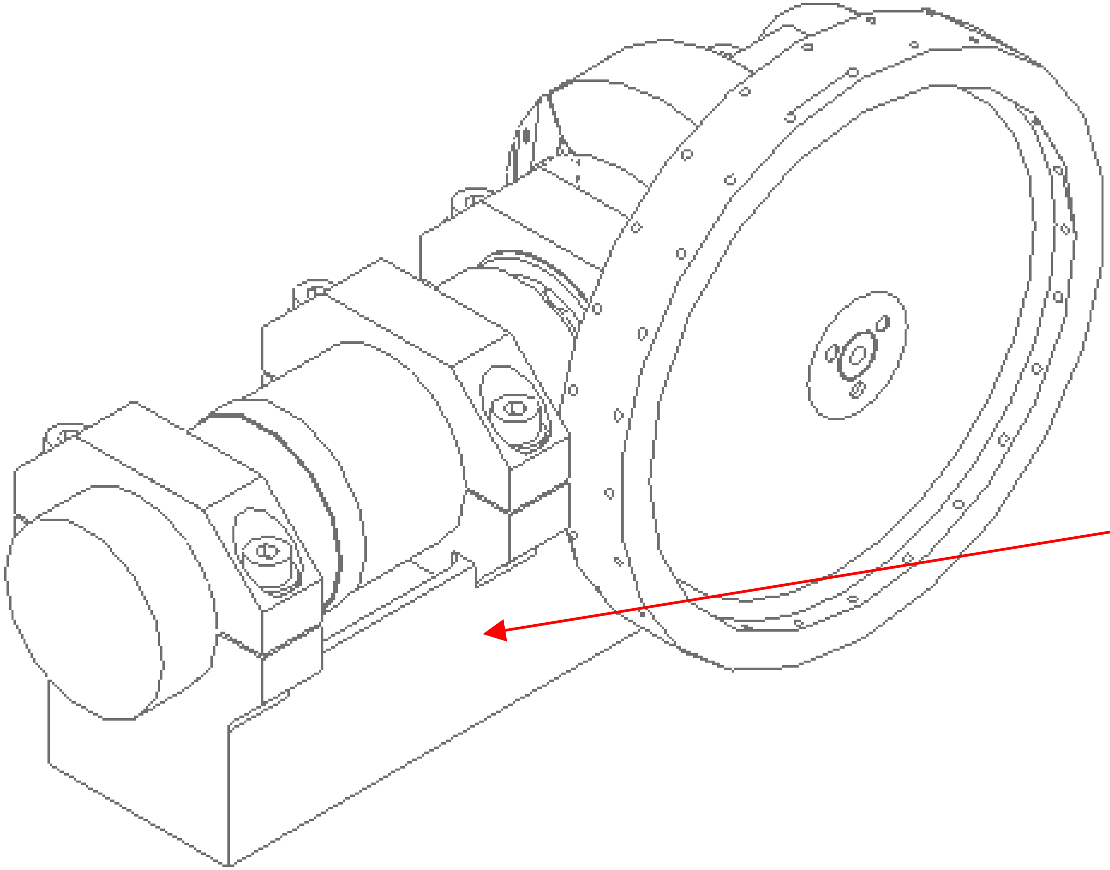


Shaft encoder

Torsion Spring

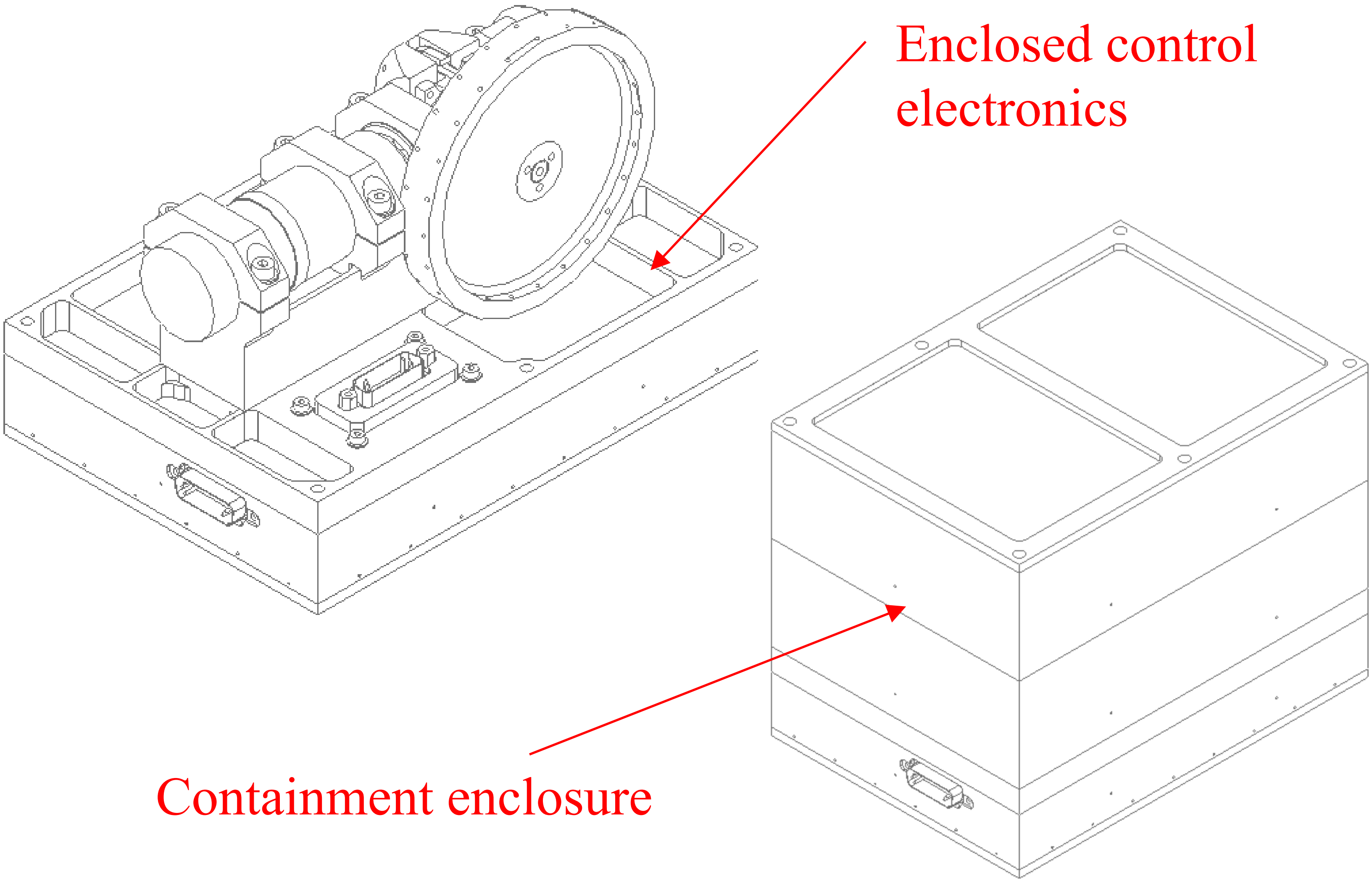
Main support bearings

CMG Mechanics



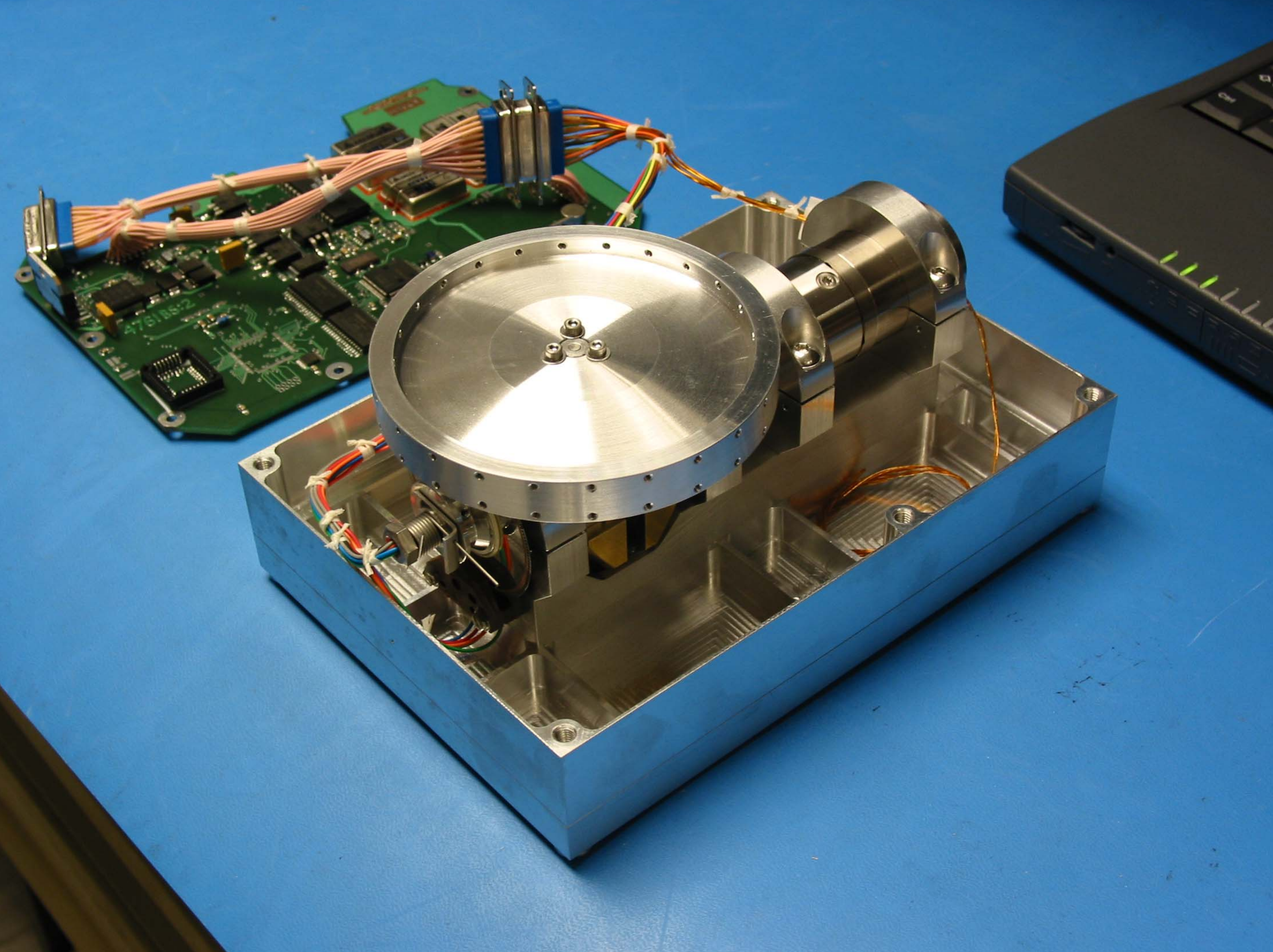
Support structure

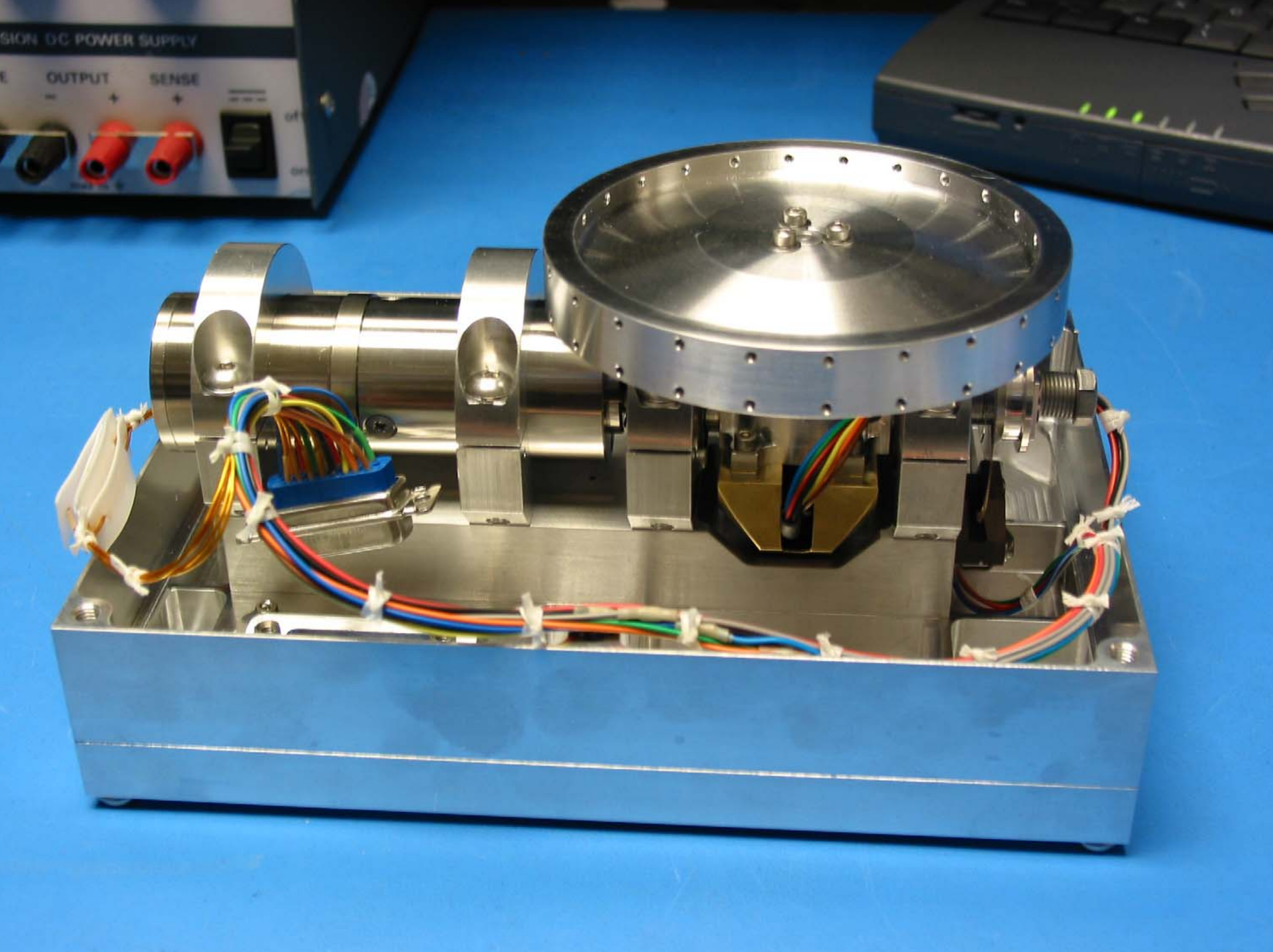
CMG Mechanics



Enclosed control electronics

Containment enclosure




SION DC POWER SUPPLY
OUTPUT
SENSE
−
+
+
off
on

CMG Mechanics - Mass

- Mass ~ 2.2 kg per CMG
  - 420g Phytron Motor
  - 100g Faulhaber Motor
  - 90g ‘Flywheel’ (aluminium)
  - 100g Counterbalance (brass)
  - 500g Electronics (in enclosure)
  - 400g Containment enclosure
  - 200g Support bearings
  - 200g Axle, interface structure, fasteners, cable, etc
    - (all figures approximate to show breakdown)

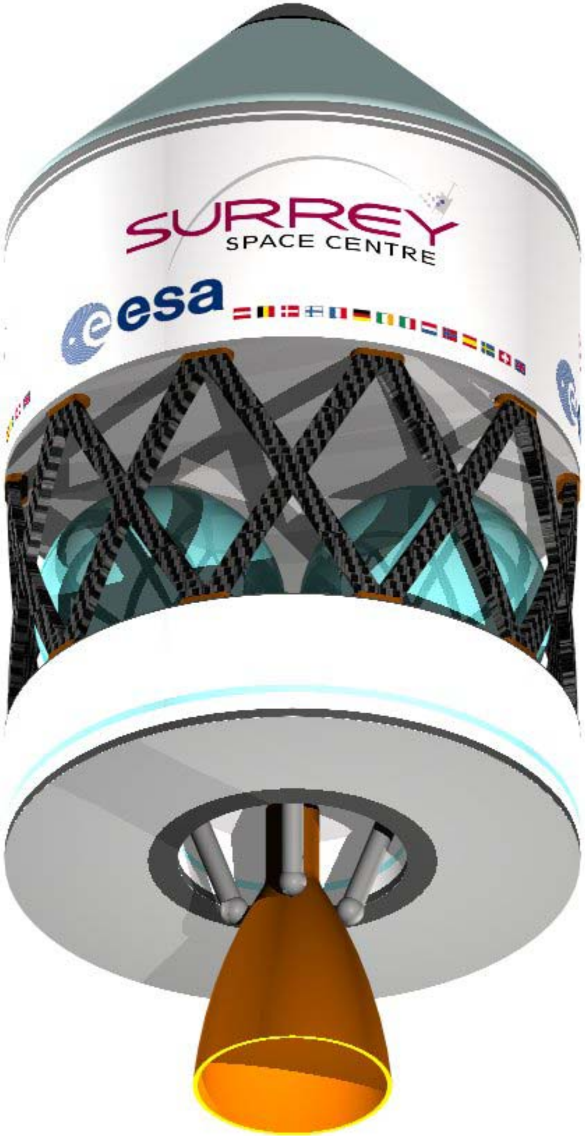
Other CMG Activities

- Working on BILSAT CMG payload exploitation
  - In-orbit data, compare CMGs to RWs, use CMGs as RW/MW/VSCMG
- Developing a Closed loop, hardware-in-the-loop, CMG cluster simulator
  - Constrained 3-axis simulator
  - 4-CMGs in pyramid configuration
- CMGs selected as an experimental payload on ESA's Proba II research satellite
- Developing CMGs for Minisatellites (ESA)
- Developing new CMG algorithms, Singularity Avoidance schemes, non-linear control strategies
- Modelling of CMG motor dynamics
- Collaboration with Prof. B. Wie (ASU) and Prof. P. Tsiotras (Georgia Tech.)
- Collaboration with METU (Aerospace) ?

9. Future Work

- Planetary Ascent Vehicles (PAV): Small Rockets…
- Mars/planetary sample return missions will require some means to transport samples of planetary soil back to earth
- Need to ferry these samples from the planet’s surface to an orbiting return spacecraft
- Need to develop a small rocket to take a 1 kg sample to a low Mars orbit (LMO)
- Surrey working on the conceptual (systems) design and Guidance, Navigation and Control System (GNC)
- GNC system baseline configuration: TVC, single cold gas engine, roll thruster, IMU

9.1 Planetary Ascent Vehicles (PAV)



9.2 Planetary Ascent Vehicles (PAV)

- Develop GNC system in MATLAB/Simulink
- Perform systems analysis of PAV:
  - 1 kg sample payload
  - 3 Astronauts as payload
- Demonstrate concept viability using software//visualisation tools
- Demonstrate Thrust Vector Control (TVC) GNC principles with closed-loop, hardware-in-the loop experiments
- Developing the software/hardware for the experiments

9.2 Micro-UAVs

- New research topic
- Use Surrey's innovative, low cost design approach
- Design a micro UAV (mass 2-3 kg, range 2-5 km, low power) for low cost civil/military reconnaissance
- Payload: Optical instrument for real/near real time imaging
- Activities:
  - Sizing of micro UAV
  - Design of RF link (laptop based)
  - Design of imager electronics
- Design drivers: Low cost (< $1000) , simplicity, ease of use
- Applications: Forest fire reconnaissance, refugee/border monitoring, military battle field reconnaissance

10 Conclusion

- CMGs can be an attractive, efficient, novel, alternative ACS systems for agile Small Satellites
- Proven that **CMGs** are viable for agile small satellites and can potentially make them more efficient, profitable and versatile platforms than before
- BILSAT CMGs will be the first commercial CMGs in the world to fly in space, perform actual mission tasks (stereo-imaging)
- Exciting research topics in controls (space, aeronautics)
- Collaborate with METU-Aerospace
- Surrey offers MSc, PhD in aerospace/satellite engineering

Questions ?