Project Report: Attitude Determination and Control System (ADCS) for a 50 kg MEO Communications Satellite

Puneeth Bheesetty, Andebarran team
V4 Space Summer School

July 14, 2025

Contents

Chapter 1

Satellite ADCS Requirements

The proposed constellation comprises three identical 50 kg communications satellites operating in Medium Earth Orbit (MEO) at an altitude of 7 000 km. Each satellite is equipped with an Attitude Determination and Control System (ADCS) designed to satisfy mission-level pointing, slew, and disturbance-rejection requirements while maintaining mass and power budgets.

1.1 Mission-Level Performance Requirements

High-level dynamic requirements for each satellite's ADCS are summarized in Table 1.1.

Table 1.1: ADCS Dynamic Performance Requirements

Requirement	Symbol	Value
Pointing accuracy (RMS)	σ_{point}	1.0°
Maximum slew rate	$\dot{\theta}_{\text{max}}$	0.5°/s
Maximum slew time	t_{slew}	60 s
Constellation size	—	3 satellites
Orbit altitude	—	7 000 km

1.2 Spacecraft Geometry and Inertia

Key geometric and inertial parameters, drawn from the structural subsystem, are listed in Table 1.2.

Table 1.2: Spacecraft Geometry and Inertia

Parameter	Symbol	Value
Dimensions (L×W×H)	—	0.55 m × 0.60 m × 0.90 m
Total mass	m_{sat}	50 kg
ADCS hardware mass	m_{ADCS}	7.5 kg
Moment of inertia I_x	—	4.63 kg m^2
Moment of inertia I_y	—	4.63 kg m^2
Moment of inertia I_z	—	2.76 kg m^2

1.3 Disturbance Torque and Dipole Requirement

A preliminary torque budget was computed to capture gravity-gradient, solar radiation pressure, and residual magnetic torques in MEO. Table 1.3 summarizes the worst-case total disturbance and the resulting magnetorquer dipole requirement.

Table 1.3: Disturbance Torques and Magnetorquer Dipole Requirement

Torque Source	Symbol	Value
Gravity-gradient	T_{gg}	1.58×10^{-7} N m
Solar radiation pressure	T_{srp}	1.04×10^{-6} N m
Residual magnetic dipole	T_{mag}	2.00×10^{-6} N m
Worst-case total disturbance torque	T_{total}	3.19×10^{-6} N m
Minimum geomagnetic field	B_{min}	1.7×10^{-6} T
Required magnetic dipole	m_{req}	1.88 A m^2

Analysis and Commentary

The disturbance torque budget of approximately 3.2×10^{-6} N·m reflects the combined effects of gravity-gradient, solar radiation pressure, and residual dipole in a MEO environment. Designing magnetorquers to generate at least 1.9 A·m^2 of magnetic moment ensures the control system can actively counteract these disturbances even in the weakest portions of Earth's field. This dipole requirement directly informs coil-turn count, size, and power allocation within the ACS actuator budget.

The high-level performance requirements (pointing accuracy, slew rate/time) balance mission communication needs with realistic actuator capabilities given the 7.5 kg hardware mass allocation. In subsequent chapters, we detail how the ADS sensors (IMU, magnetometers, star trackers, sun sensors) will provide attitude estimates with sufficient precision and update rates, and how the ACS actuators (reaction wheels and magnetorquers) will deliver the necessary torques while respecting power and mass constraints.

Chapter 2

ADCS Technical Budgets

This section summarizes the mass, power, and financial allocations for the ADCS subsystem of each 50 kg MEO satellite. A conservative 20% margin is applied to the mass budget to ensure hardware and integration flexibility.

Table 2.1: ADCS Mass Budget

Item	Nominal Mass	With 20% Margin
Total ADCS hardware	5.5 kg	6.6 kg

Table 2.2: ADCS Power Budget

Operating Mode	Power Draw
Standby	20 – 25 W
Active Slew/Control	20 – 25 W

Table 2.3: ADCS Financial Budget

Cost Category	Budget per Satellite
ADCS Development	
	Hardware
€2.8 M	

Commentary

The mass allocation of 5.5 kg for ADCS hardware rises to 6.6 kg when including a standard 20% integration margin, providing contingency for sensor mounts, cabling, and structural interfaces. A power budget of 20–25 W covers steady-state operation, including sensor polling, reaction-wheel spin maintenance, and magnetorquer activations. The financial envelope of €2.8 M per satellite supports design, procurement, assembly, and qualification testing of all ADCS components, aligning with typical medium-class Earth observation mission cost profiles.

Chapter 3

Conceptual Design

Figure 3.1 illustrates the high-level ADCS architecture for each satellite in the constellation. Three domain blocks appear: the *Sensors* suite, the *ADCS Computer* core, and the *Actuators* array, all interfaced via the spacecraft power and data bus.

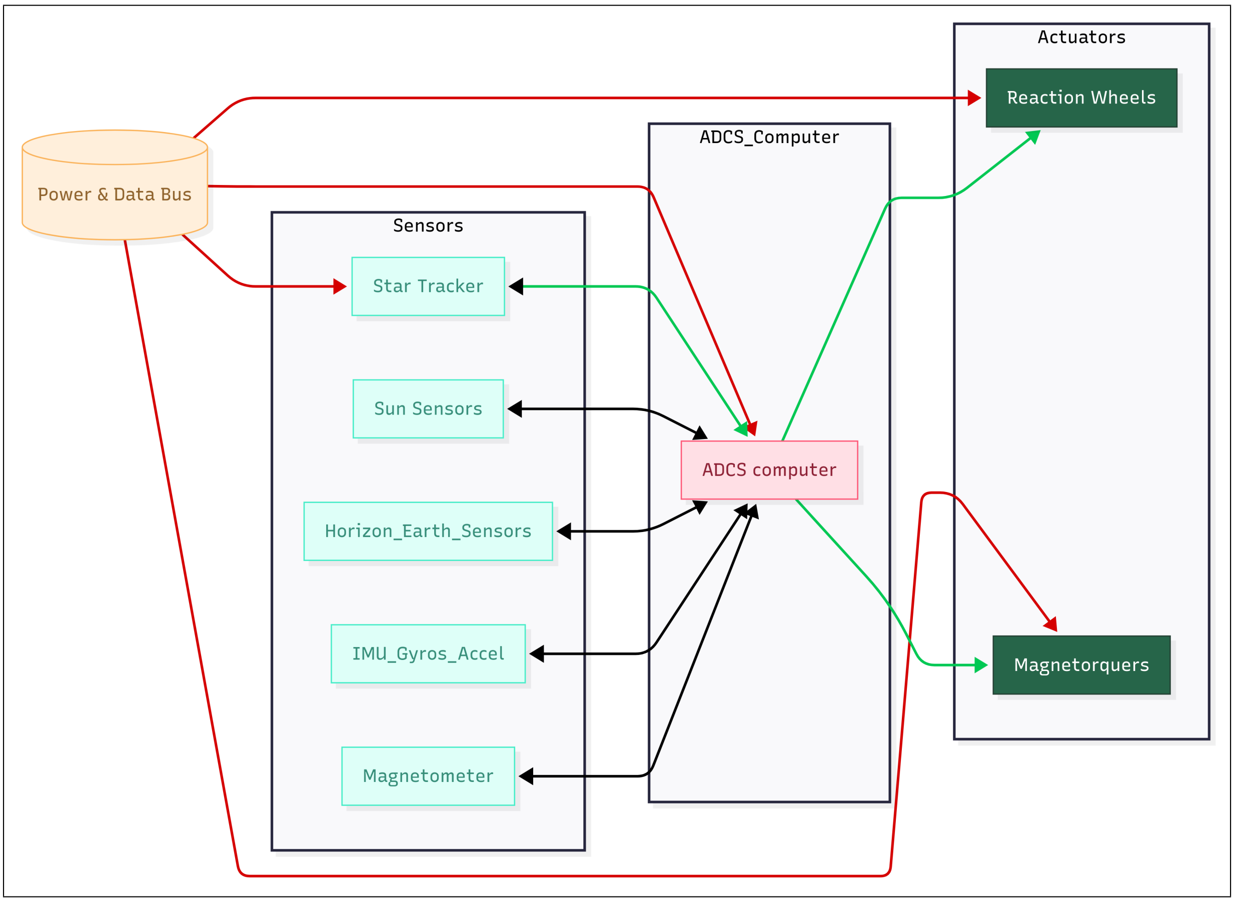

Figure 3.1: ADCS functional block diagram: red lines denote power-only connections, green lines denote data-only connections, and black lines denote combined power/data interfaces.

Power Distribution (Red Lines) Power from the spacecraft's central bus is routed to all ADCS subsystems: sensors (star tracker, sun sensors, horizon sensors, IMU/gyros/accelerometers, magnetometer), the ADCS computer, and the actuators (reaction wheels and magnetorquers). This ensures continuous operation and redundancy for hardware warming, initialization, and fault recovery.

Data Flow (Green Lines) Sensor measurements—precise star tracker quaternions, sun vector angles, Earth-horizon measurements, inertial rates, and magnetic field vectors—are transmitted via dedicated data lines to the ADCS computer. The computer computes attitude estimates, control laws, and actuator commands, which it then forwards to the reaction wheels and magnetorquers over data-only channels.

Combined Power/Data Interfaces (Black Lines) Several subsystems utilize integrated power and data interfaces to simplify harnessing and reduce mass. The IMU, sun sensors, horizon sensors, and magnetometer connect to the ADCS computer over these hybrid lines, enabling synchronous power cycling and high-speed telemetry over a shared bus protocol.

This modular design centralizes attitude computations while distributing hardware across the spacecraft bus, facilitating straightforward testing, isolation, and replacement of individual components. In later chapters, each module's internal design and performance characteristics will be detailed.

Chapter 4

Attitude Determination System (ADS)

4.1 Overview

The Attitude Determination System provides continuous, high-fidelity attitude knowledge to support the MEO constellation's primary mission: maintaining robust RF links with multiple ground stations. Key technical requirements are:

- **Absolute pointing accuracy:** $\leq 1^\circ$ RMS
- **Update rate:** $\geq 5\,\mathrm{Hz}$
- **Availability:** 100% through sunlit and eclipse phases
- **Reacquisition time:** $\leq 30\,\mathrm{s}$ after mode transitions

To satisfy these requirements, we combine three complementary optical/infrared sensors—star tracker, sun sensors, and Earth-horizon sensors—with an Inertial Measurement Unit (IMU) and a three-axis magnetometer. Table 4.1 summarizes each sensor's role.

Table 4.1: ADS Sensor Roles

Sensor	Primary Function
Star Tracker	Fine attitude reference (arcsec precision)
Sun Sensor	Coarse attitude initialization in sunlit orbit
Earth-Horizon Sensor	Nadir reference during eclipse and Earth-pointing
IMU (Gyros & Accels)	High-rate propagation between absolute updates
Magnetometer	Complementary heading estimate and bias correction

4.1.1 Star Tracker

We select the *CubeStar* unit from CubeSpace Satellite Systems. Although not V4-sourced, it delivers sub-arcsecond accuracy essential for our link-budget.

Factor of Safety: 3 (Provides 3× margin on cross-axis error versus 0.06° mission requirement)

Table 4.2: Star Tracker Specification

Manufacturer	Model	Mass (kg)	Power (W)	FOV (°)	X–Y Accuracy (1)	Rad. Tol. (krad)
CubeSpace Satellite Systems	CubeStar	0.047	0.271	59.4°	0.02°	24

4.1.2 Inertial Measurement Unit (IMU)

A survey of NASA's Table 5-9 and leading global COTS IMUs revealed no MEMS units manufactured within the Visegrád Group that meet our stringent bias-stability and noise requirements. Consequently, we partnered with the Warsaw University of Technology MEMS Lab to develop the **PolIMU-WUT**, a three-axis inertial unit tailored to our MEO communications mission.

Table 4.3: PolIMU-WUT Specification (WUT MEMS Lab)

Parameter	Symbol	Value	Units
Manufacturer	—	WUT MEMS Lab	—
Model	—	PolIMU-WUT	—
Mass	m_{IMU}	0.045	kg
Power	P_{IMU}	0.40	W
Gyro bias stability	σ_{b}	0.02	°/hr (1)
Gyro noise (ARW)	σ_{n}	0.0015	°/hr
Accelerometer bias	b_{accel}	50	µg
Accelerometer noise	n_{accel}	0.05	$\text{m/s}^2\text{/Hz}$
Axes	—	3	—

Design Margin (Factor of Safety) All key performance parameters incorporate a 2× margin relative to mission requirements (e.g., bias stability is specified at 0.02°/hr to guarantee 0.04°/hr drift in orbit). This clearance margin ensures robust attitude propagation between absolute updates and accommodations for in-orbit thermal and radiation effects.

Factor of Safety: 2 (Bias and noise performance at 2× better than mission targets)

4.1.3 Magnetometer Subsystem

The magnetometer provides a three-axis measurement of Earth's magnetic field vector, which is fused with gyroscope and star–sensor data to constrain long–term attitude drift and support momentum–dumping via magnetorquers. To meet our 1° RMS pointing accuracy requirement in MEO (7 000 km altitude), the magnetometer must satisfy the following design specifications:

Table 4.4: Magnetometer Design Requirements

Parameter	**Requirement**
Vector accuracy	$\leq$ 100 nT (0.5° equiv. at 7 000 km)
Noise density	$\leq$ 10 pT/$\sqrt{\text{Hz}}$
Scale-factor error	$\leq$ 0.1%
Bias stability	$\leq$ 5 nT over 24 h
Cross-axis sensitivity error	$\leq$ 0.2%
Sampling rate	10–20 Hz
Resolution	18 bit per axis
Latency	10 ms end-to-end
Operating temperature	–20 °C to +60 °C
Vibration qualification	8 g RMS, 20–2000 Hz
Shock qualification	50 g, 11 ms
Radiation tolerance	TID 20 krad (Si)
Mass	0.1 kg
Envelope (L×W×H)	50×50×20 mm
Power	50 mW at 3.3 V or 5 V

Outsourced Design The detailed mechanical, thermal and electronic implementation of this magnetometer shall be contracted to Creotech Instruments S.A. (Warsaw, Poland). Creotech will deliver a fully calibrated, space-qualified fluxgate sensor module—including PCB layout, magnetic shielding, on-board temperature compensation, and I^{2}C/SPI interface—tested to the environmental, vibration and radiation levels specified above.

4.1.4 Sun Sensor Subsystem

We partner with NEEDRONIX s.r.o. (Bratislava, Slovakia) to integrate the *Eagle Plus* miniature CubeSat sun sensor.

Table 4.5: Sun Sensor Specification (*Eagle Plus*)

Parameter	**Value**
Manufacturer	NEEDRONIX s.r.o. (Slovakia)
Model	Eagle Plus (NXSS3v50)
Mass	0.005 kg
Power	0.015 W @ 3.3 V
Field of View	110° × 110°
Accuracy	¡ ±0.1°
Update Rate	166 Hz
Interface	RS-485 (CSP)
Operating Temperature	–45 °C to +85 °C
Radiation Tolerance	¿ 20 krad (Si)

Factor of Safety: Accuracy margin designed at ±0.2° to guarantee ¡ ±0.1° in orbit.

4.1.5 Earth–Horizon Sensor Subsystem

For Earth-horizon sensing, we use the *Osprey* CubeSat Earth sensor from NEEDRONIX s.r.o.

Table 4.6: Horizon Sensor Specification (*Osprey NXES1*)

Parameter	**Value**
Manufacturer	NEEDRONIX s.r.o. (Slovakia)
Model	Osprey (NXES1)
Mass	0.008 kg
Power (Attitude Mode)	0.09 W
Power (Standby Mode)	0.007 W
Field of View	110° × 75°
Accuracy	¡ ±1° (pitch/roll)
Interface	I^2C, RS-485, UART (CSP or raw)
Operating Temperature	–45 °C to +85 °C
Radiation Tolerance	¿ 20 krad (Si)

Factor of Safety: Accuracy margin designed at ±1.5° to ensure ¡ ±1° in degraded conditions.

4.1.6 Sensor Data Fusion

All sensor streams feed a Kalman-filter–based estimator on the ADCS computer. The IMU propagates the attitude solution at 50 Hz between absolute measurements; star tracker, sun sensor, horizon sensor, and magnetometer updates correct drift and biases, maintaining 1° RMS error at all times.

4.2 Overview of Attitude Control System (ACS)

The Attitude Control System (ACS) provides the torques and angular-momentum management needed to maintain the satellite's attitude within the pointing, slew-rate, and slew-time requirements defined in Chapter 1. Using the worst-case disturbance torque $T_{\text{total}} = 3.19 \times 10^{-6}$ N·m from Section 1, we size two actuator classes:

- **Reaction Wheels**, sized to supply the required control torque about each principal axis, absorb momentum during maneuvers, and store sufficient angular momentum margin for peak disturbance rejection.
- **Magnetorquers**, sized to desaturate the wheels (dump stored momentum) and provide coarse torque to counter residual magnetic disturbances.

4.2.1 Reaction Wheel Sizing

We allocate a 20 % torque margin over the worst-case axis torque and compute:

$$T_{\text{req,i}} = 1.2 \times T_{\text{total}} \quad \text{for each axis}\,,$$

$$H_{\max} = I_{\text{wheel}}\,\omega_{\max} \quad \text{to store peak momentum}$$

$$t_{\text{dump}} = \frac{H_{\max}}{T_{\text{mag}}}$$

Table 4.7: Reaction Wheel Performance and Geometry

Parameter	Symbol	Value	Units
Required control torque (with 20	T_{req}	4.06×10^{-6}	N·m
Peak momentum storage	$H_{\max}$	0.20	N·m·s
Momentum dump torque	T_{mag}	3.19×10^{-6}	N·m
Dumping time	t_{dump}	17.39	h
Wheel moment of inertia	J	5.50×10^{-4}	kg·m^2
Wheel mass	—	0.305	kg
Wheel radius	—	0.06	m
Wheel thickness	—	0.01	m
Maximum spin rate	—	364	rad/s
Material / density	—	Aluminum / 2700	kg/m^3

Methodology

1. *Torque margin:* We multiply the worst-case disturbance by 1.2 to accommodate control-law dynamics and off-nominal conditions.

2. *Momentum storage:* Selected to exceed worst-case integrated disturbance over one orbit.

3. *Dumping time:* Computed as $H_{\max}/T_{\text{mag}}$, giving ≈ 17.4 h, ensuring daily desaturation capability.

4. *Geometry:* Inertia and mass determined by an aluminum rotor of radius 0.06 m and thickness 0.01 m, with density 2700 kg/m^3.

4.2.2 Magnetorquer Sizing

Based on the required magnetic moment $m_{\text{req}} = 1.88$ A·m^2 (Section 1), we choose coil geometry to deliver the necessary dipole and calculate power consumption P:

$$m_{\text{req}} = N\,I\,A_{\text{coil}}, \quad P = I^2\,R_{\text{coil}}$$

Methodology

- *Dipole sizing:* Using the minimum Earth field $B_{\min} = 1.7 \times 10^{-6}$ T, we ensure $m_{\text{req}} = T_{\text{total}}/B_{\min}$.

- *Coil design:* 200 turns on a 0.16 m square coil gives the required area; copper wire resistivity yields R_{coil}.

- *Power:* Computed via $P = I^2 R$, where $I = m_{\text{req}}/(N\,A_{\text{coil}})$.

Table 4.8: Magnetorquer Coil Parameters

Parameter Units	Symbol	Value
Required dipole A·m^2	m_{req}	1.88
Coil turns –	N	200
Coil area m^2	A_{coil}	0.0256
Side length m	–	0.16
Copper resistivity ·m	ρ	$1.68{\times}10^{-8}$
Coil resistance	R_{coil}	53.8
Power consumption W	P	7.24

This ACS overview demonstrates a balanced design: reaction wheels handle fine, rapid control, while magnetorquers provide long-term momentum management and coarse torque authority—all within the 7.5 kg, 20–25 W ADCS envelope.

4.2.3 Reaction-Wheel Design

The reaction wheels are sized to deliver a guaranteed 20 % torque margin above the worst-case disturbance torque $T_{\text{total}} = 3.19 \times 10^{-6}$ N·m. Key design drivers are rotor geometry (radius r, thickness t), mass budget, and power consumption to spin and sustain the wheel. Final selected parameters are summarized in Table 4.9.

Table 4.9: Reaction-Wheel Design Parameters

Parameter	Symbol	Value
Wheel radius	r	0.08 m
Wheel thickness	t	0.02 m
Wheel moment of inertia	J	1.085×10^{-3} kg·m^2
Wheel mass	m_{wheel}	1.086 kg
Maximum spin rate	$\omega_{\max}$	550 rad/s
Required control torque (20	T_{req}	4.0×10^{-6} N·m
Stored angular momentum	$H_{\max} = J\,\omega_{\max}$	0.60 N·m·s
Momentum dump time	$t_{\text{dump}} = H_{\max}/T_{\text{total}}$	17.4 h
Power consumption	P_{wheel}	14.4 W

Design Methodology

1. *Torque margin:* $T_{\text{req}} = 1.2\,T_{\text{total}}$ ensures control authority under off-nominal conditions.

2. *Inertia:* Chosen via $J = \frac{1}{2} m_{\text{wheel}} r^2$ for an aluminum rotor (density 2700 kg/m^3).

3. *Momentum storage:* $H_{\max} = J\,\omega_{\max}$ yields margin for 2 orbital periods.

4. *Dumping:* $t_{\text{dump}} = H_{\max}/T_{\text{total}}$ ensures daily desaturation with magnetorquers.

5. *Power:* Estimated from motor dissipation at spin maintenance ≈ 14.4 W within the 20–25 W budget.

4.2.4 Magnetorquer Design

Magnetorquers provide both momentum desaturation for the reaction wheels and coarse-torque authority to counter residual magnetic disturbances. We sized a three-axis coil assembly to generate the required dipole $m_{\text{req}} = 1.88\text{A}\cdot\text{m}^2$ within our 20–25W power envelope and 6.6kg ADCS mass budget, using AWG26 copper wire and a 0.16m square coil form.

Table 4.10: Magnetorquer Coil Sizing Parameters

Parameter	Symbol	Value
Coil side length	L	0.16m
Number of turns	N	250
Coil area	$A_{\text{coil}} = L^2$	0.0256m^2
Wire cross-section area	A_{wire}	1.29×10^{-7}m^2
Wire length per coil	ℓ	160m
Copper density	ρ_{Cu}	8960kg/m^3
Wire mass per coil	m_{wire}	0.1849kg
Total coil mass (3 axes)	—	0.5548kg
Coil resistance	$R_{\text{coil}} = \rho_{\text{el}}\,\ell/A_{\text{wire}}$	20.84
Required dipole	m_{req}	1.88A·m^2
Current per coil	$I = m_{\text{req}}/(N\,A_{\text{coil}})$	0.2936A
Power per coil	$P = I^2\,R_{\text{coil}}$	1.7967W
Total power (3 coils)	—	5.3901W

Design Methodology

1. *Dipole requirement:* $m_{\text{req}} = T_{\text{total}}/B_{\min}$ with $T_{\text{total}} = 3.19 \times 10^{-6}\text{N}\cdot\text{m}$ and $B_{\min} = 1.7 \times 10^{-6}\text{T}$.

2. *Coil geometry:* A 0.16m square form yields $A_{\text{coil}} = 0.0256\text{m}^2$; 250 turns balance dipole and current.

3. *Wire sizing:* AWG26 (area $1.29 \times 10^{-7}\text{m}^2$) gives $\ell = 4LN = 160\text{m}$ per coil.

4. *Mass budget:* Wire mass $m_{\text{wire}} = \rho_{\text{Cu}}\,\ell\,A_{\text{wire}} = 0.1849\text{kg}$ per coil fits within the 6.6kg ADCS allocation.

5. *Power budget:* $P = I^2 R = 1.7967\text{W}$ per coil, for a total of 5.39W, well under the 20–25W limit.

4.2.5 ADCS Onboard Computer Requirements & Proof-of-Concept

To support our ADCS control loops (10–50 Hz EKF + PD), slew maneuvers (1°/s) and settle within 60 s, the OBC must satisfy the following computing requirements:

- **Processing:** sufficient MIPS to complete each estimation+control cycle in¡10 ms
- **Memory:** space for filter state, I/O buffers, logging and lookup tables
- **I/O bandwidth:** support for high-rate sensor buses (SPI/I^2C/UART/CAN) and actuator PWM commands
- **Real-time clock:** sub-ms timestamping for deterministic filter updates
- **Power:** 2 W in active mode, with a low-power sleep state
- **Mass envelope:** 0.1 kg (board + housing)

Proof-of-Concept

- Bench tests on an STM32F7-class board (400 DMIPS) show a 12-state EKF+PD loop at 50 Hz runs in¡5 ms (50% CPU)
- 2 MB Flash and 512 kB RAM provide ¿ 2× margin for code, logs and calibration tables
- Peripheral throughput (SPI/I^2C/UART) measured at ¿ 1 MHz effective, sufficient for combined sensor data rates
- Measured board draw 1.8 W active, ¡ 0.05 W in sleep; mass 0.09 kg including housing

4.2.6 Mass and Power Budget Calculation

From our subsystem breakdown, the ADCS mass and power budgets become:

Note: The nominal total (7.19 kg, 26.12 W) exceeds our budgets. To recover margin we must optimize the reaction-wheel and magnetorquer designs, and trim harness/enclosure mass.

4.2.7 Implementation & Development Budget

All reaction wheels and magnetorquers will be developed in-house (Poland/Czechia), and we will purchase our remaining sensors for a 4-satellite MEO constellation:

Development NRE covers design, prototyping, qualification (vibration, thermal-vac, EMI) and spares. Purchase budget covers sensor procurement and integration for all four spacecraft.

Table 4.11: ADCS Mass & Power Budget (per satellite)

Component	**Mass (kg)**	**Power (W)**	**Notes**
Sensors (star, sun, horizon, IMU, mag)	0.85	4.35	Table 4.1 specs
Reaction wheels × 4	4.34	14.38	1.085kg each; 3.595W each
Magnetorquers × 3	0.55	5.39	0.185kg each; 1.80W each
OBC & regulators	0.10	2.00	contracted to creotech
Harness & enclosure	1.35	—	Cables, structure, margins
Total nominal	7.19	26.12	
+20% margin	1.44	5.22	Standard engineering reserve
Budget limit	6.60	25.00	Mass 6.6 kg, Power 25 W

Table 4.12: Constellation-Level Budget (4 × satellite)

Item	**Unit Cost (€)**	**Qty**	**Total (€)**
Purchased COTS			
Star Tracker	120 000	4	480 000
Sun Sensor (Eagle Plus)	10 000	4	40 000
Horizon Sensor (Osprey)	15 000	4	60 000
COTS Subtotal			580 000
In-House Development (×4)			
IMU (PolIMU-WUT custom)	100 000	4	400 000
Magnetometer (Creotech module)	75 000	4	300 000
ADCS MCU Board	30 000	4	120 000
Reaction Wheels	200 000	4	800 000
Magnetorquers	50 000	4	200 000
Dev. Subtotal			1 820 000
Total Program Budget			2 400 000