Elixir training school

Attitude and orbit control subsystem (AOCS)

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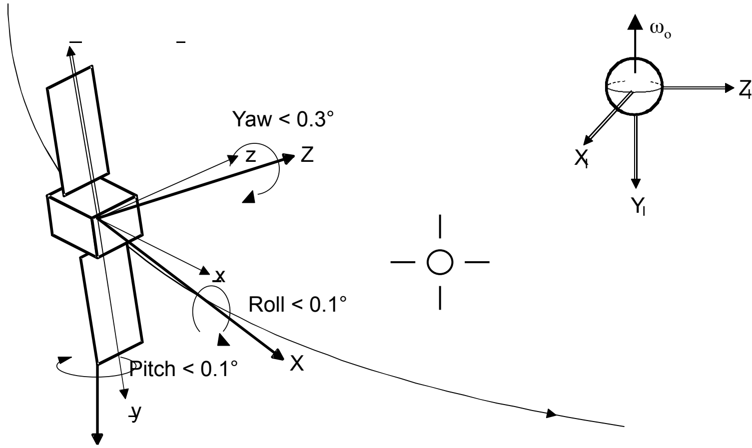
20/05/2011

Contents

Introduction to AOCS

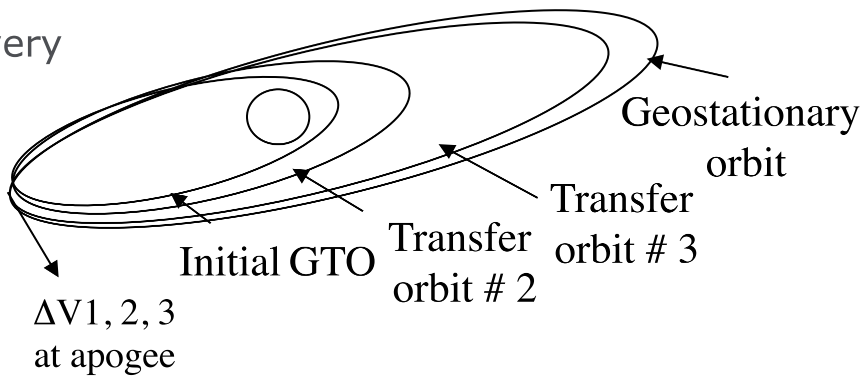
Attitude and Orbit Control System Functions

1. The AOCS performs the following functions:
   a. Attitude (and position) estimation based on sensors measurements and processing
   b. Attitude control using actuators (torques)
   c. Orbit corrections with actuators (forces)



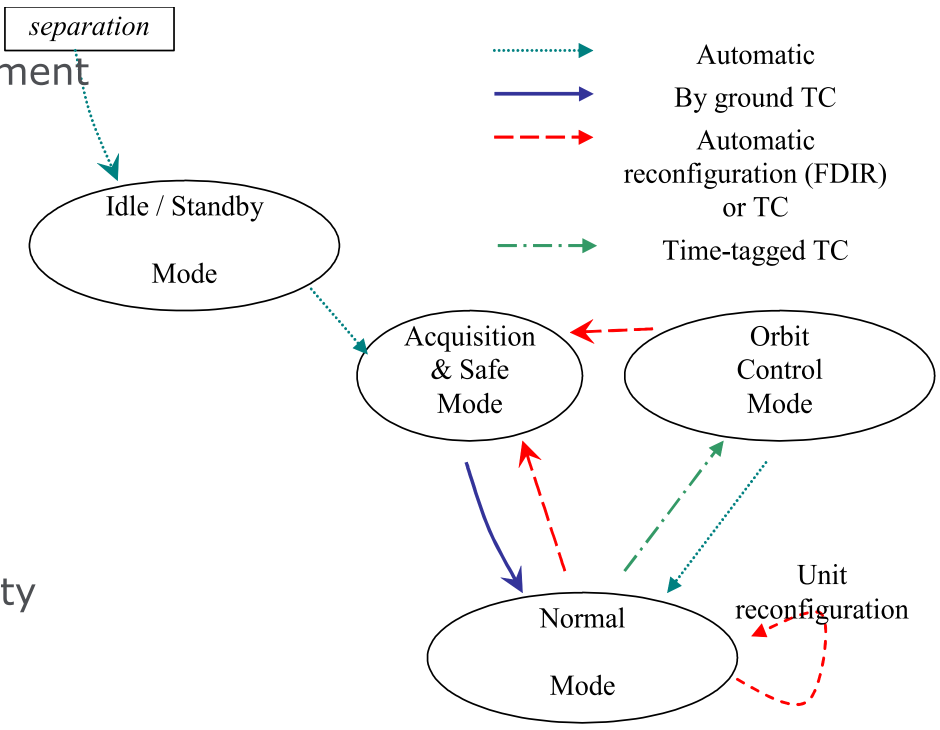
2. With a high level of autonomy:
   a. Initialisation without ground intervention
   b. Automatic closed loop control:
      command = feedback (attitude, rate)
   c. Autonomous management of modes
   d. Failure Detection, Isolation and Recovery

3. Throughout the various mission phases:
   a. Launch & Early Orbit Phases
   b. Operational phase
   c. FDIR and Reacquisition



Typical mission timeline and AOCS modes

1. Launcher separation
   a. AOCS units automatic initialisation
2. Acquisition Mode
   a. Damping of tip-off angular rates
   b. Sun acquisition/solar array deployment
   c. Earth acquisition
3. Normal Mode
   a. Pointing performance
   b. Mission availability
4. Orbit Control Mode
   a. Delta-V's to reach final orbit
   b. Periodic orbit maintenance
5. Safe mode
   a. Stable state ensuring satellite safety (power, thermal, communications)
   b. Minimisation of orbit degradation



Sharing on-board / on-ground operations

Sharing between on-board and ground operations: a trade-off

a. Autonomy level (reactivity, complexity)
b. On board storage and processing capabilities, downlink/ uplink capacity
c. Cost (on-board vs on ground functions validation)

AOCS requirements and interfaces

Typical AOCS requirements (1/2)

1. Telecom missions:
    a. typ. ~0.12° for absolute pointing (half cone, at antenna level)
    b. minimisation of mission outage (back up modes before safe mode)
    c. Large solar arrays (flexible modes 0.01 Hz), transfer GTO to GEO
    d. Long lifetime (typ. 15 years) and harsh environment (radiations)

2. Earth Observation missions:
    a. typ. from 0.1° to 0.01° for absolute pointing
    b. Angular rate stability for image acquisition: typ. 0.001 °/s, agility
    c. on-ground post-processing (image rectification and localization)
    d. LEO: eclipse and intermittent link with Control Centre

Typical AOCS requirements (2/2)

3. Science missions:
    a. from 0.1° to <1 milliarcsec for absolute pointing
    b. Cutting edge missions with very specific requirements
    c. instrument as AOCS sensor, relative attitude/position requirements for formation flying
    d. Variety of orbits: LEO, GEO, Lagrange point L2

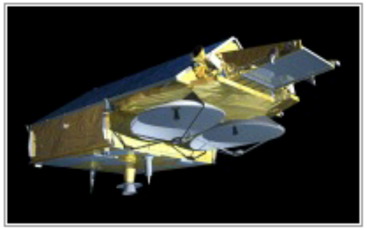
4. Navigation missions:
    a. typ. ~0.2° for absolute pointing
    b. Yaw steering due to non sun synchronous orbit
    c. MEO: high level of radiations

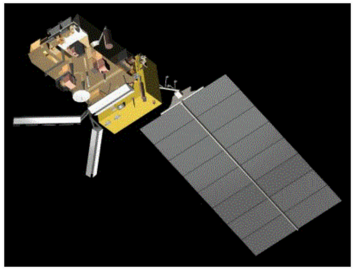
Minimization of disturbing torques and forces

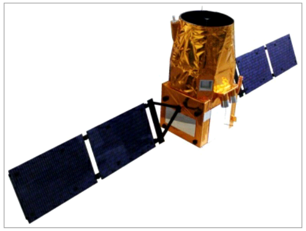
1. Disturbing torques strongly impact on the AOCS design
    a. Minimised by Platform design trade-offs

2. Orbit and Platform configuration dependant:
    a. Aerodynamic torque/force: LEO $k.e^{-altitude}$
        – typ. mNm at 600km (Solar Array) or align with velocity
    b. Gravity gradient torque: LEO (GEO) $1/R^3$
        – typ. mNm at 600 km or get principal axis towards Earth
    c. Magnetic torque: LEO (GEO) $1/R^3$
        – typ. 10 mNm with small residual magnetic momentum
    d. Solar pressure torque/force: GEO (LEO) constant
        – typ. 10 mNm in GEO with 2 symmetrical Solar Arrays then 50 Nms wheel can provide gyroscopic stiffness

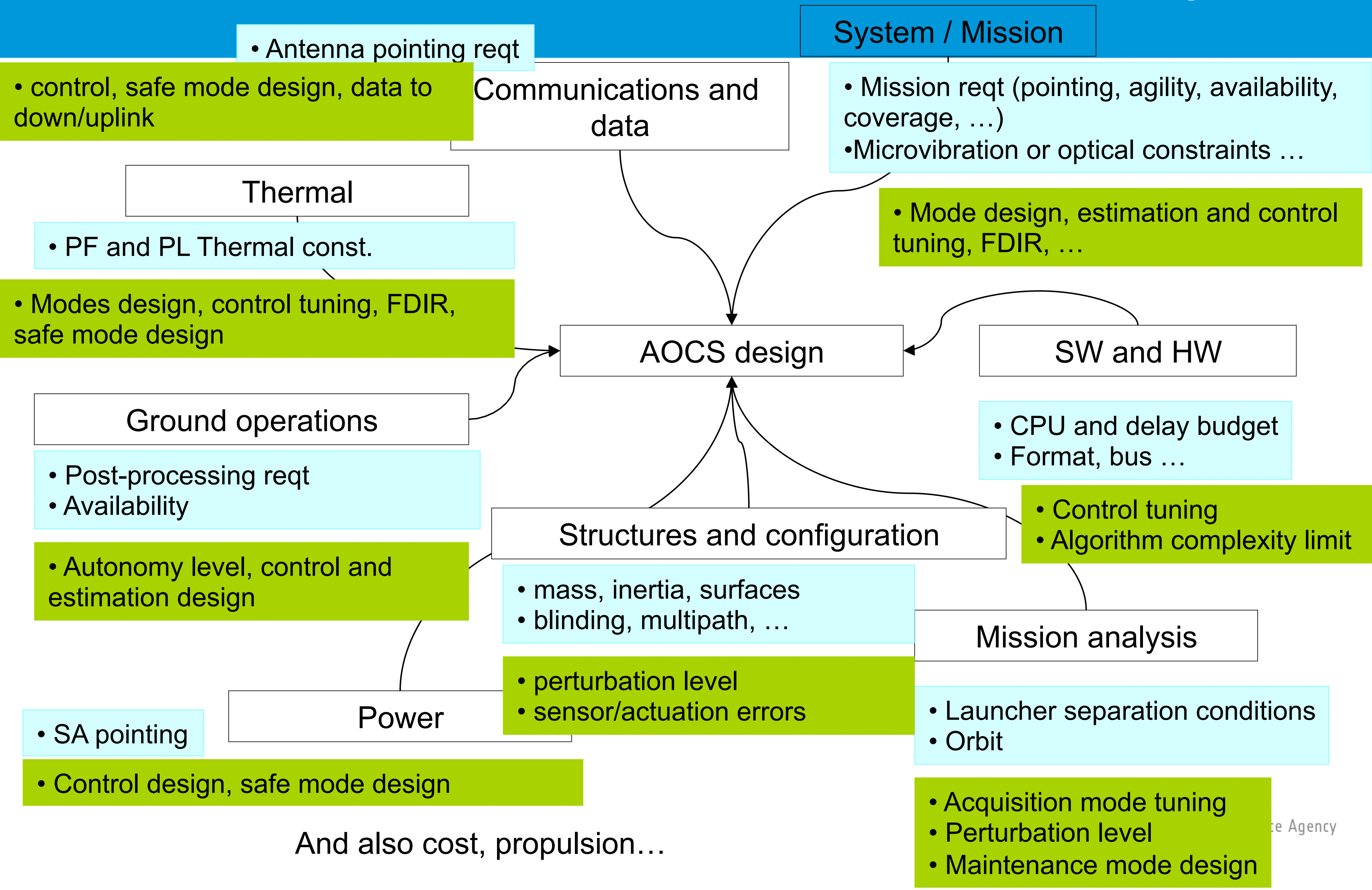
3. Generated by the Satellite:
    a. Micro-vibrations (wheels, cryocoolers, instruments)
    b. Propellant sloshing (tanks)
    c. Orbit control thrusters: typ. 1Nm





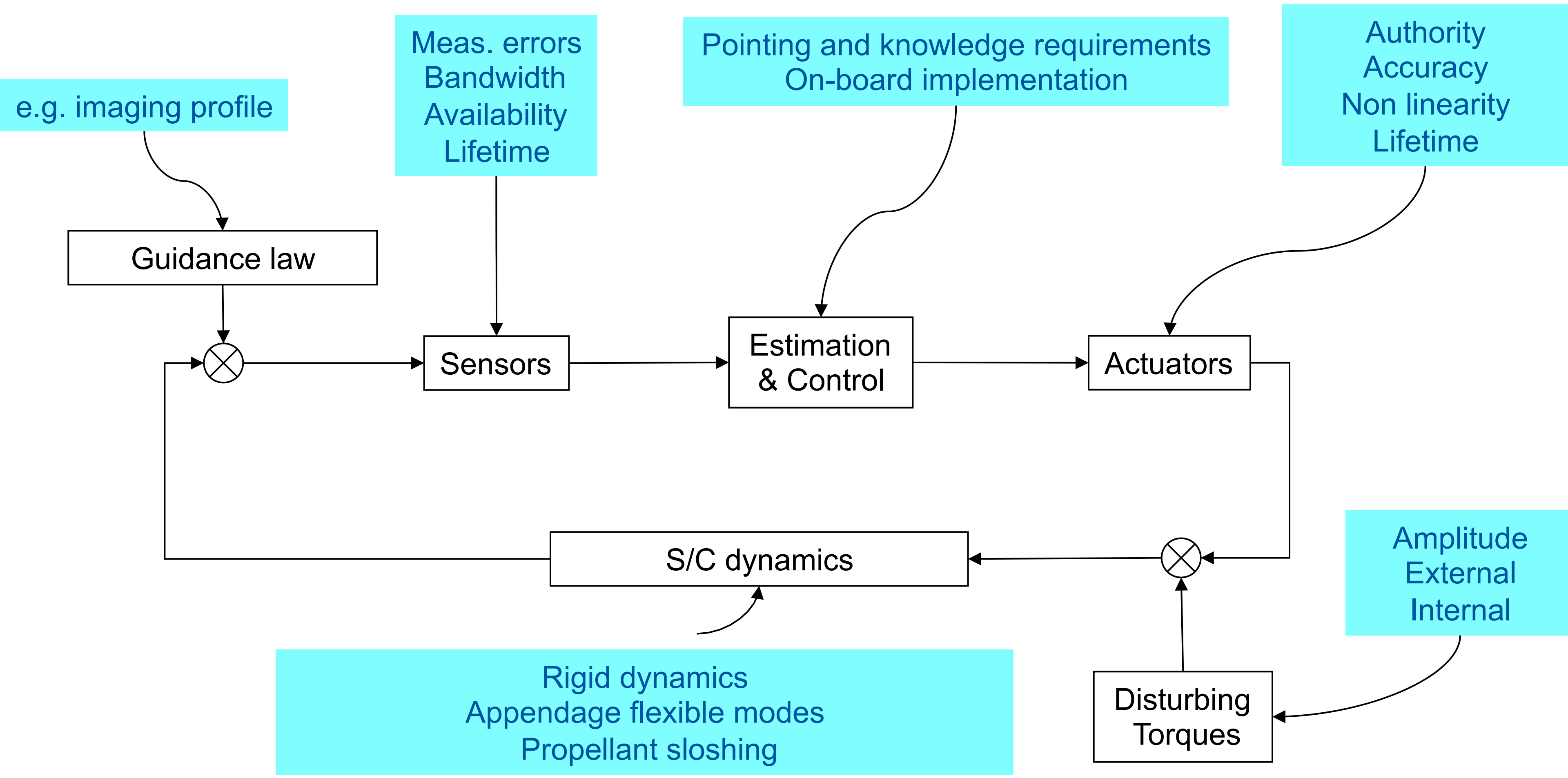


Interfaces with other systems



AOCS implementation

AOCS block diagram

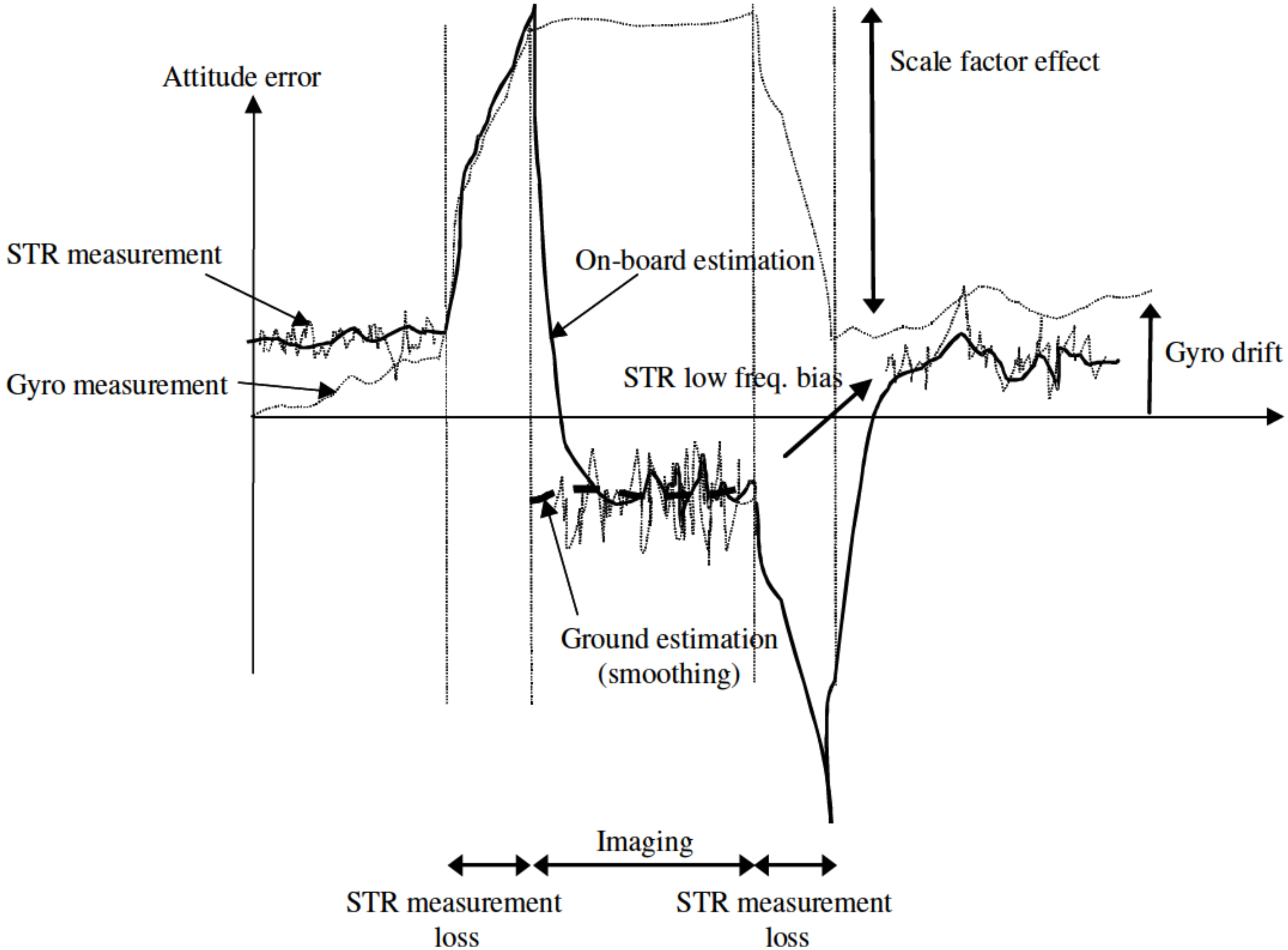


Estimation function (1/2)

1. Aim
    a. determine the current dynamic behaviour (states) of the S/C from sensor measurements and models
        – e.g. noise filtering, bias calibration, hybridising (data fusion) of sensors, …

2. Estimation design
    a. Which sensors (precision level, maturity, cost, size, mass, …)
    b. Analysis of the sensor error sources, initialisation, potential partial unavailability, dynamics range for sensing, field of view, lay-out…
    c. Analysis of estimation SW aspects (CPU, estimation cycle, delay)
    d. Estimation design (which type of filter: Kalman filter…)

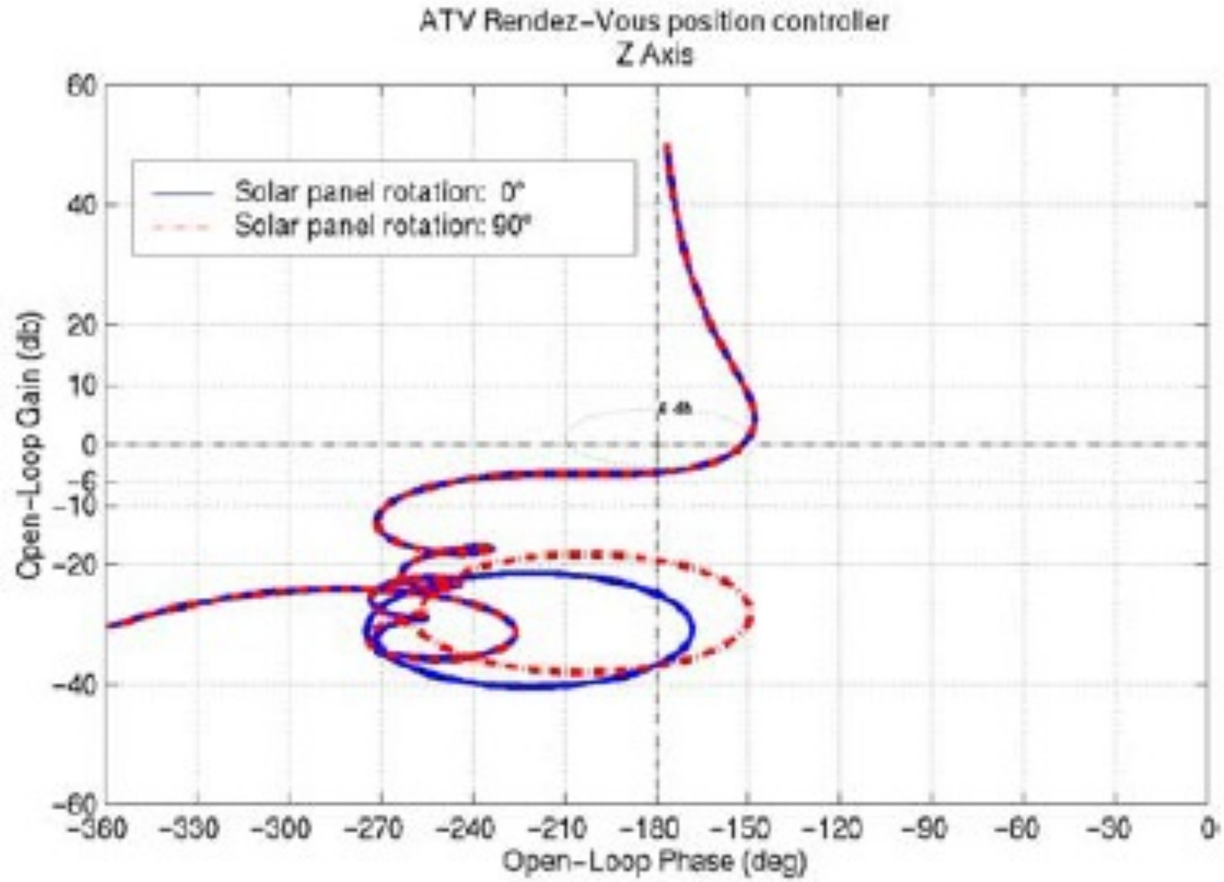
Estimation function (2/2)



Control function (1/2)

1. Aim: ensure that the spacecraft dynamics behaviour follows the desired state (guidance)
    a. e.g.: ATV lateral position
    b. the spacecraft is scarcely a rigid body:
    flexible solar arrays and antennas, propellant sloshing, solar array drive mechanism, …
2. Main control characteristics to be tuned:
    a. Performance versus Stability
        - Rapidity (to follow a guidance command)
        - Precision (transient state and permanent state)
        - Perturbation rejection
        - Robustness (over spacecraft dynamics uncertainties, variations over life cycle – e.g. depletion of tanks)
    b. Propellant consumption (propulsion system)
    c. Actuator saturation (non-linear system)

Control function (2/2)



FDIR and reliability

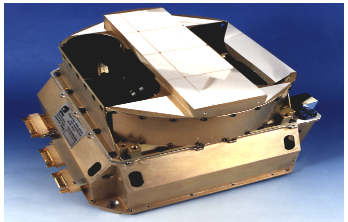
1. FDIR = Failure Detection Isolation and Recovery
2. Different levels of complexity:
   a. Compromise between mission continuation and spacecraft safety
      – Ensure smooth automatic reconfiguration in case of H/W anomaly
      – Ultimately go to Sun pointing Safe Mode (mission outage but S/C safety)
   b. Implement or not independent sensors to monitor critical operations, in addition to the sensors and actuators in the loop
3. Redundancy
   a. Branch A and branch B or single string
   b. Cross strapping between units to combine A and B units
   c. At unit level, or only electronics
   d. example: 4 Reaction Wheels in a skewed configuration
      – 3 out of 4: 3 RWs being sufficient for 3-axis torque generation
4. False alarm risks
   a. tuning of the monitoring threshold and time constant to avoid false alarm
5. Reliability
   a. Compute probability of success over the required lifetime, based on H/W units MTBF (Mean Time Between Failure)

Sensors and actuators overview

Sensors technology - Optical sensors

1. Star tracker
    a. Provides precise 3-axis inertial attitude 10”
    from Lost in Space (star pattern recognition)
    b. Orbital position required for Earth pointing
    c. New generation: APS (CMOS) instead of CCD
2. Earth sensor
    a. Provides 2-axis attitude w.r.t. Earth
    b. Third axis = sun sensor or gyroscope stiffness
    c. 0.03 deg GEO (radiance sensitivity)
    d. Scanning or static
3. Sun sensor
    a. Provides 2-axis attitude w.r.t. Sun
    b. Either coarse analogue (acquisition) or fine digital
4. Navigation camera
    a. Celestial body imaging and navigation algorithms

Autonomous CCD-Star Tracker

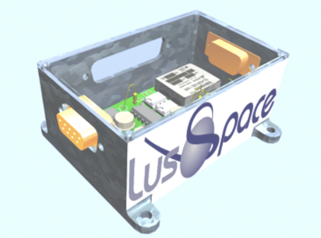


Scanning infra-red Earth sensor

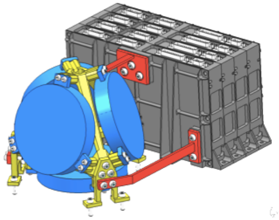
2-axis Digital Sun sensor

Sensors technology - Magnetic and Inertial sensors

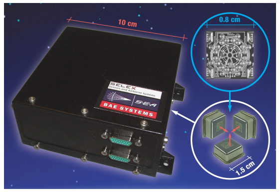
1. Magnetometer
   a. Provides (coarse) magnetic field measurement
   b. Light and cheap sensor for acquisition in LEO
2. Integrating gyros
   a. Provides integrated angular rate
   b. High bandwidth and accuracy (but drift error)
   c. Hybridising with optical sensor (Kalman filter)
3. Accelerometer
   a. Stand-alone or within IMU
   b. No space qualified European sensor
4. Coarse rate sensors
   a. Provides angular rate <10 deg/h accuracy
   b. Light and cheap sensor for rate damping, acquisition, short term attitude propagation



3-axis magnetometer AMR



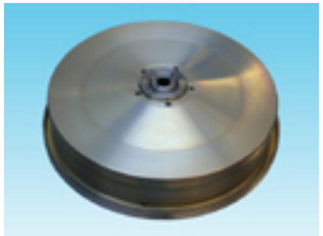
4-axis Fiber Optic Gyroscope



3-axis MEMS rate sensor

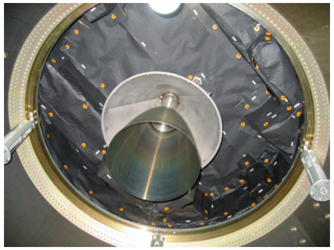
Actuators technology

1. Reaction Wheels
   a. Momentum capacity 10 to 40 Nms
   b. Torque up to 0.1Nm (momentum exchange)
   c. Off-loading needs, micro-vibration issues
2. Control Momentum Gyroscopes
   a. Gyroscopic Torque: 5 to 45 Nm
   b. Satellite Agility
3. Propulsion
   a. High to low external torque capacity
   b. Used for orbit control and initial acquisition
   c. Efficiency Isp(s): $\Delta m.g\ Isp = F.\Delta t = M_{sat}.\Delta V$
   d. Cold gas, hydrazine, bi-liquid
   e. Electric propulsion (high Isp, low thrust)
4. Magnetic torquer
   a. Interaction with Earth magnetic field
      T= M x B
   b. LEO: acquisition/safe mode and RW off-loading
      w/o orbit perturbation (no force)

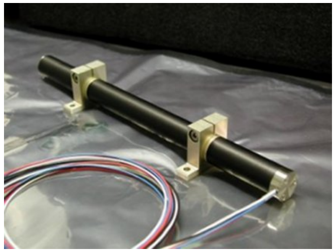


12 Nms Reaction wheel

CMG



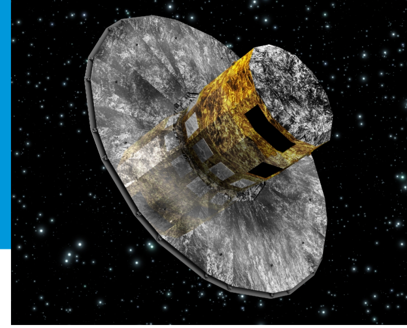
400N main engine

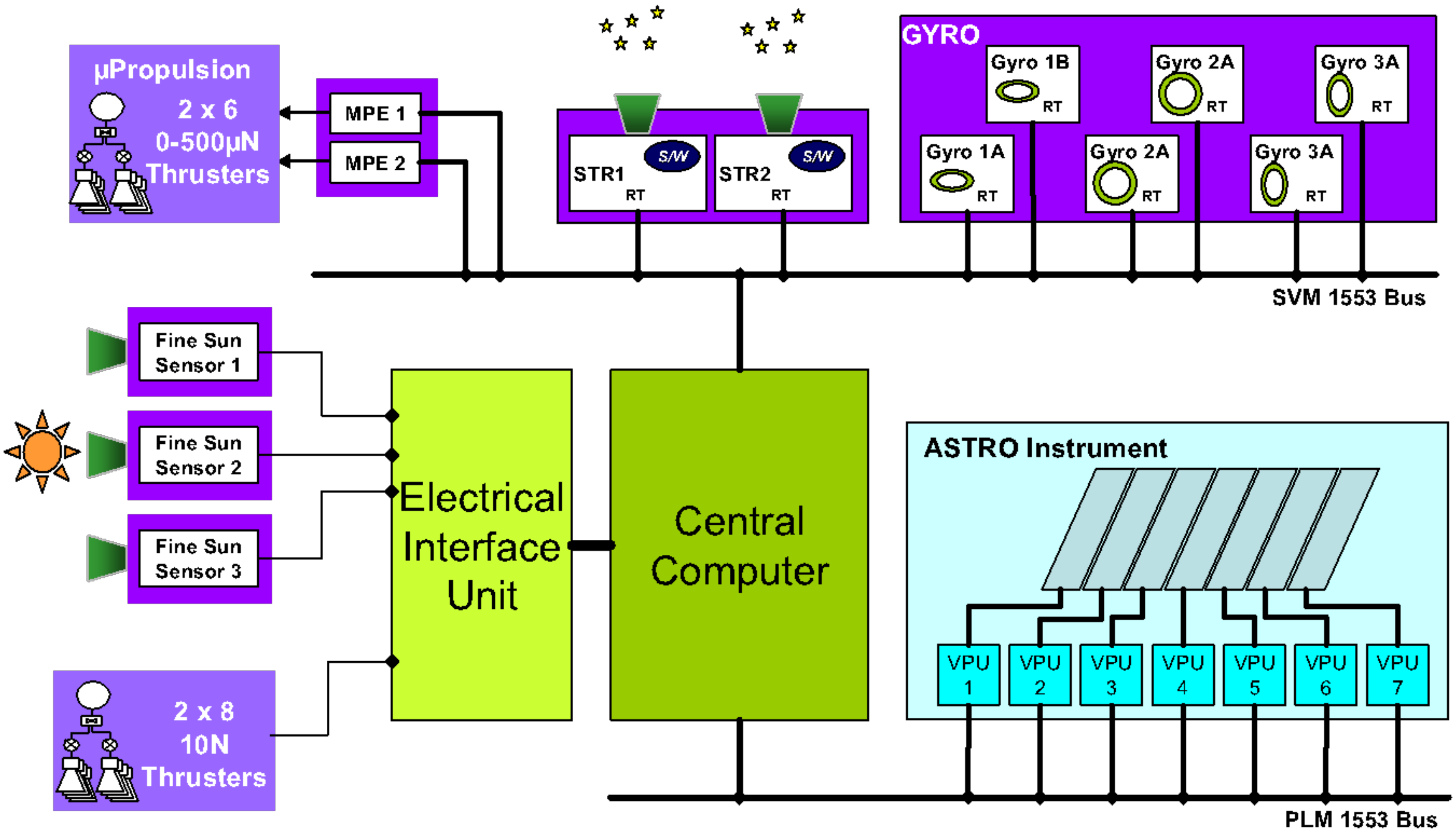


Magnetic torquer

Examples

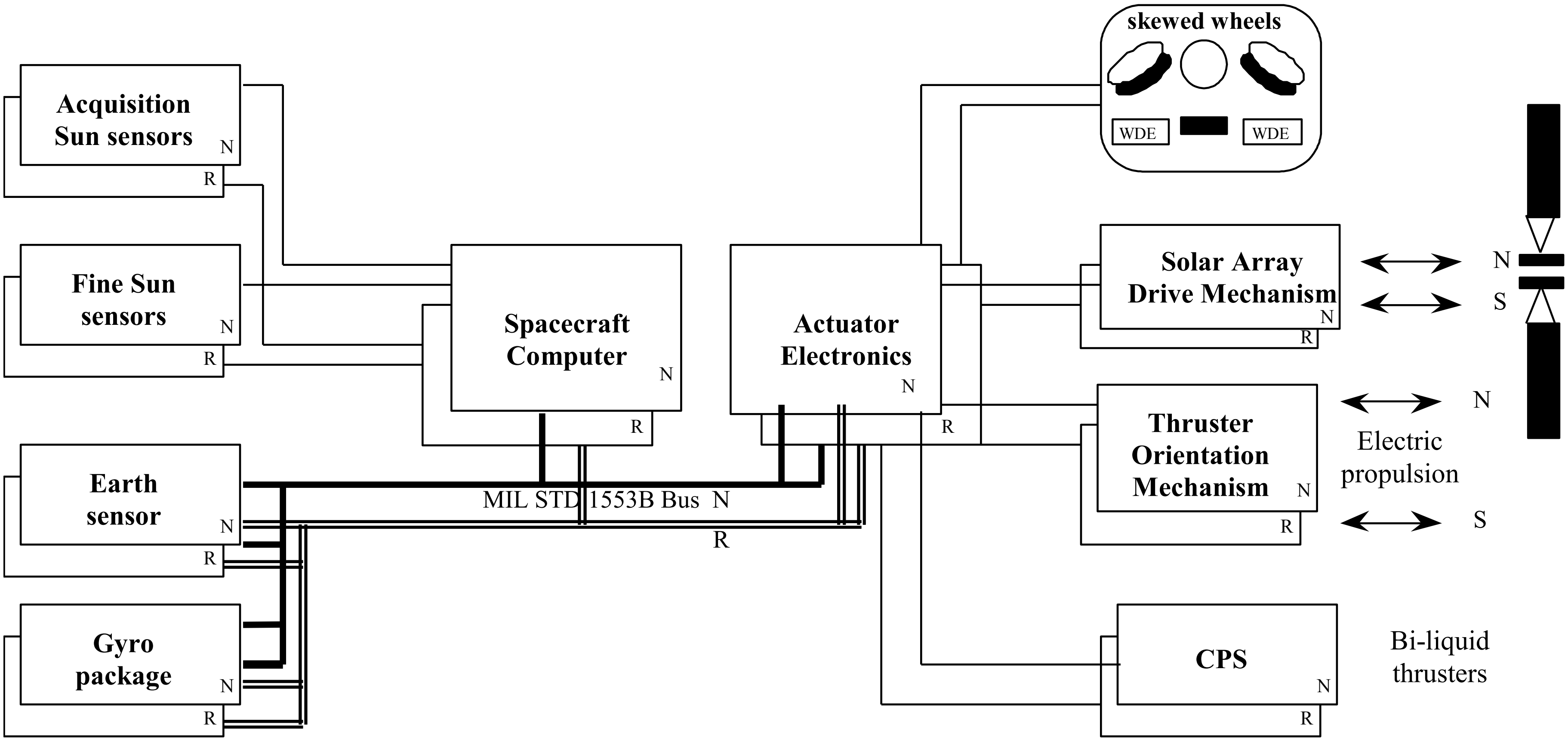
GAIA AOCS



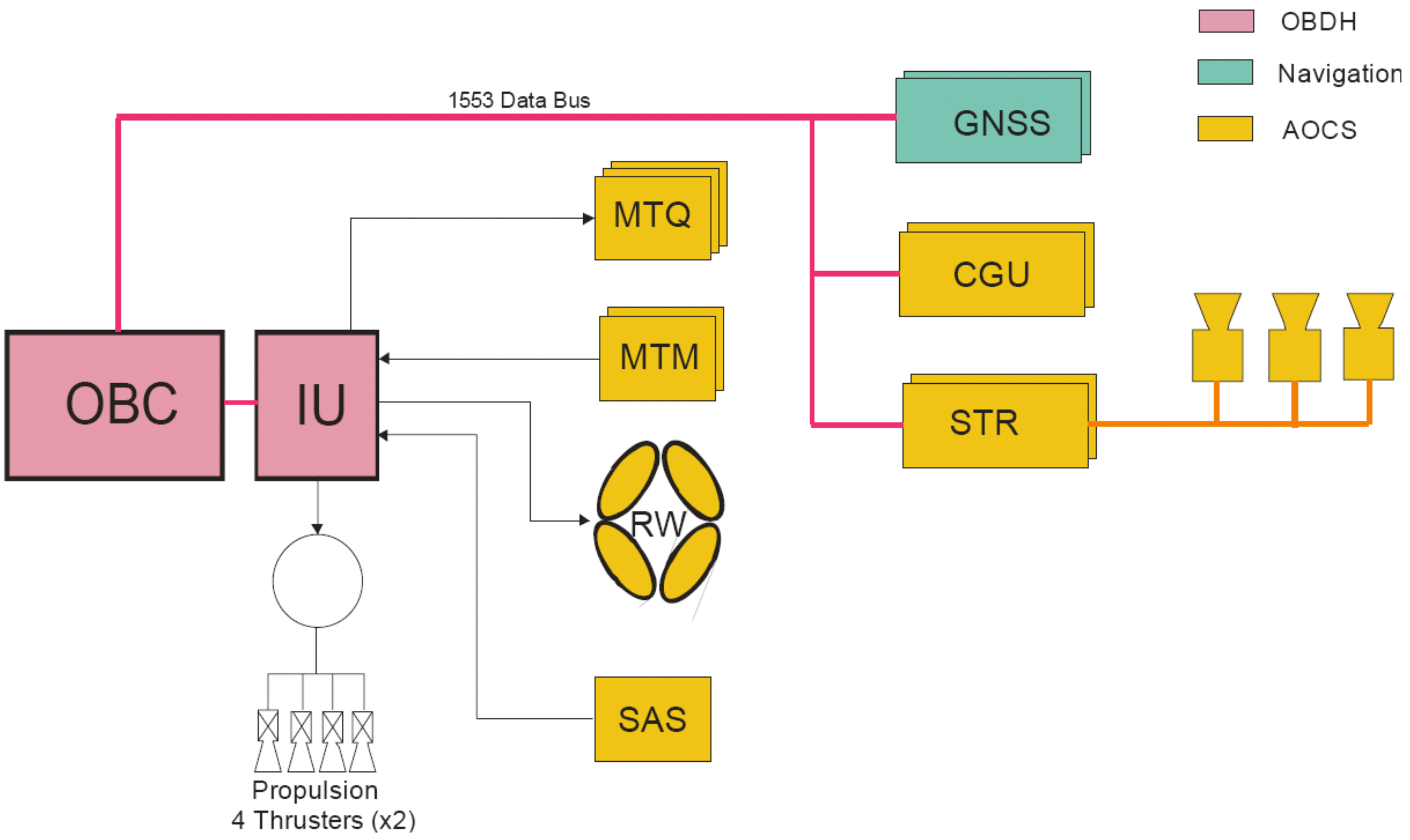


µPropulsion
2 x 6
0-500µN
Thrusters
MPE 1
MPE 2
STR1
S/W
RT
STR2
S/W
RT
GYRO
Gyro 1B
RT
Gyro 2A
RT
Gyro 3A
RT
Gyro 1A
RT
Gyro 2A
RT
Gyro 3A
RT
SVM 1553 Bus
Fine Sun Sensor 1
Fine Sun Sensor 2
Fine Sun Sensor 3
Electrical Interface Unit
Central Computer
ASTRO Instrument
VPU 1
VPU 2
VPU 3
VPU 4
VPU 5
VPU 6
VPU 7
2 x 8
10N
Thrusters
PLM 1553 Bus

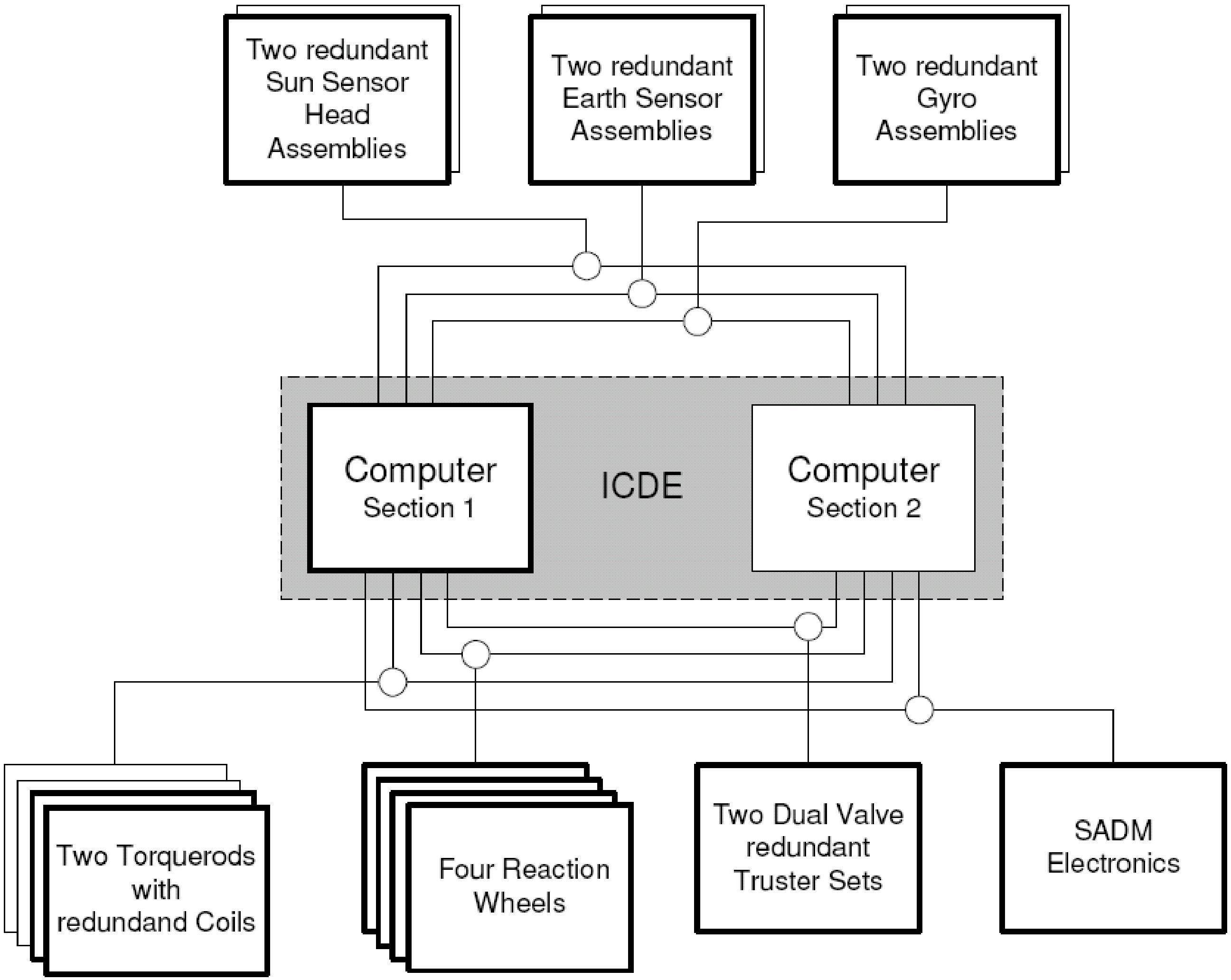
Telecommunication Mission AOCS



Earth Observation AOCS



Navigation Mission AOCS



Questions and answers