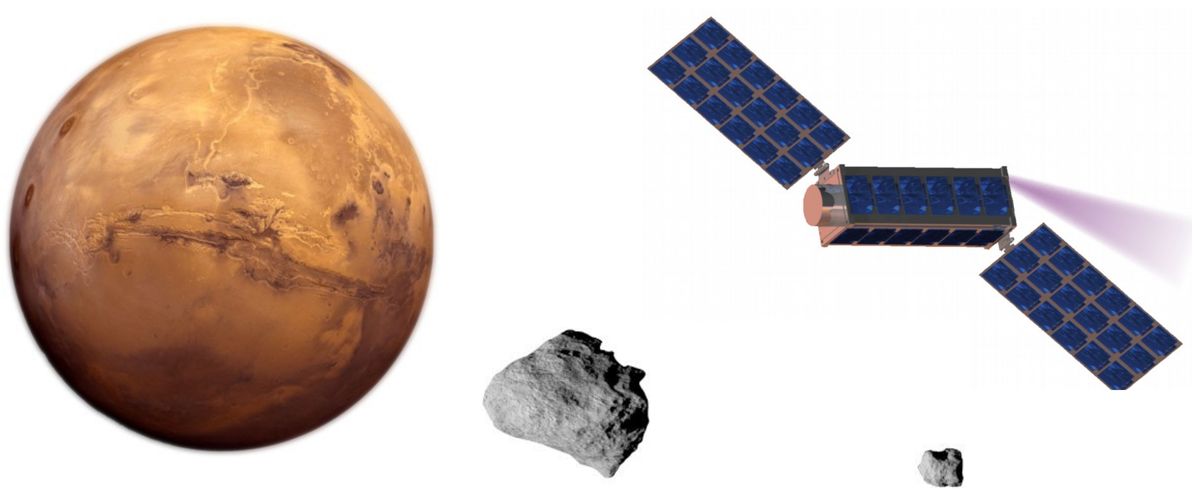
Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

Functional analysis of an Attitude and Orbit Control System for CubeSats with propulsion for deep-space missions



Gary Quinsac, PhD student at PSL | Supervisor: Benoît Mosser | Co-supervisor: Boris Segret

09/06/2016

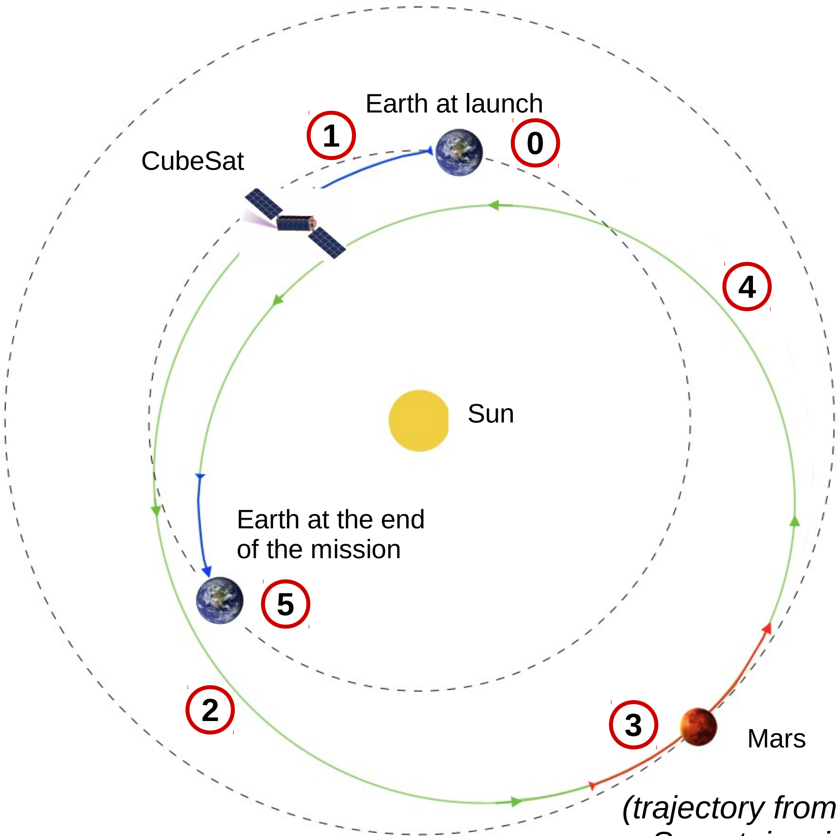
Outline

- Mission contexts
- Birdy technology
- External constraints - Torques
- Sensors and actuators
- CubeSat propulsion systems
  - Basics and classification
  - Performances
- L-µPPT system
- AOCS modes and block diagram

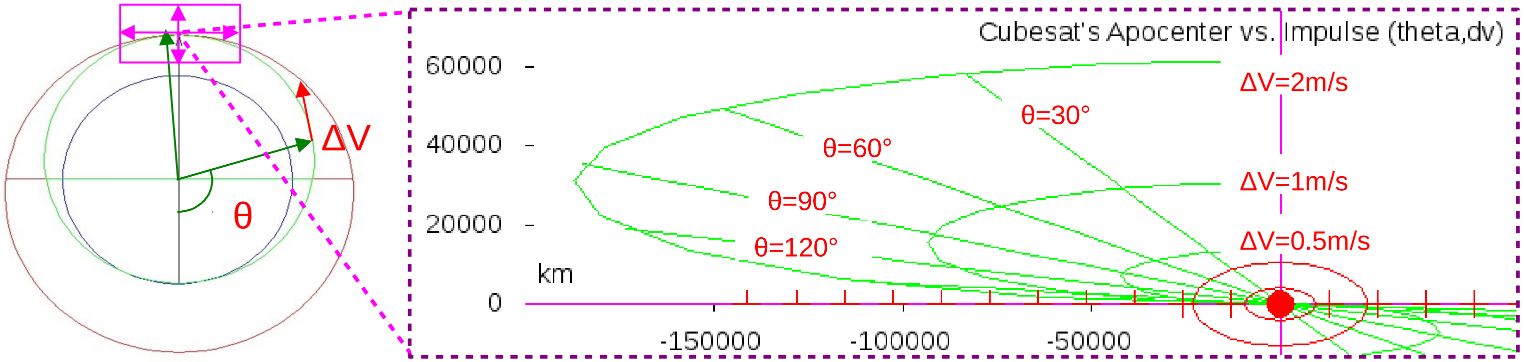
1st context: deep-space cruise

Earth-Mars-Earth free return trajectory

0. Reference orbit computation
1. Deployment after IOI
2. Earth-to-Mars science and navigation (~1 m/s)
3. Mars fly-by: first datalink
4. Marth-to-Earth science and navigation (~1 m/s)
5. End of mission: final datalink



(trajectory from Boris Segret, inspired by Dennis Tito for 2018)

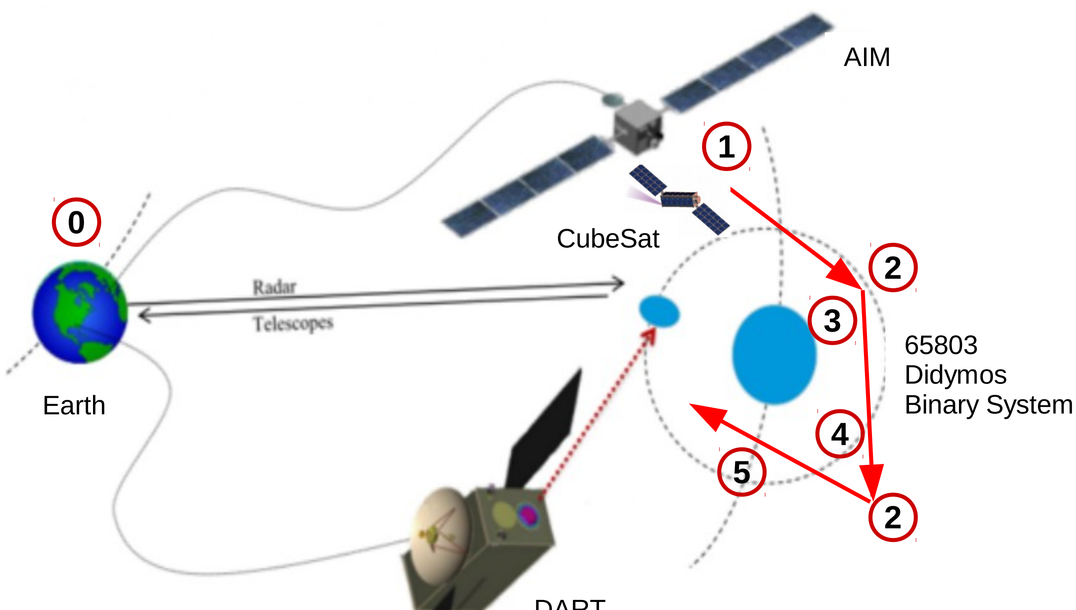


(Boris Segret)

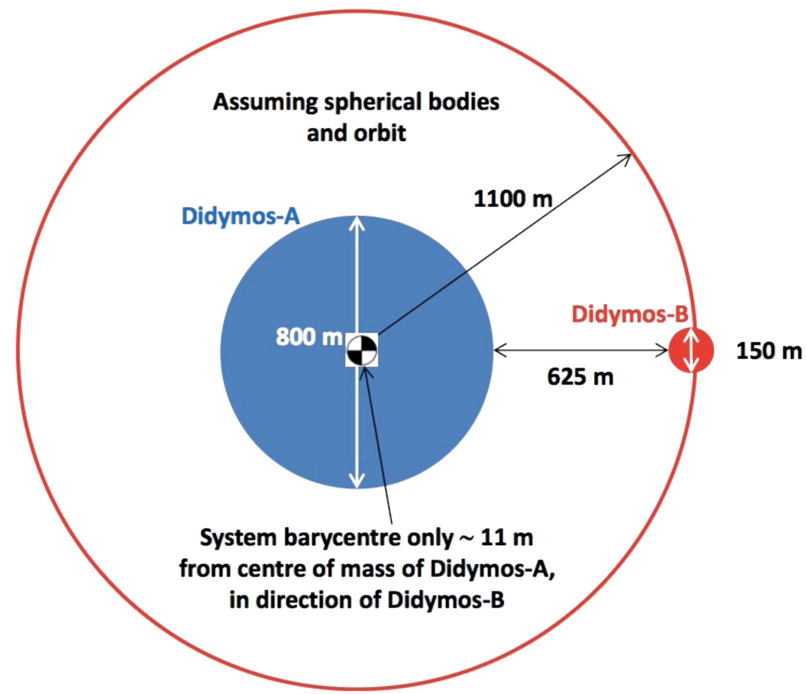
2nd context: "flying-legs"

Radio science

0. Propagators with model in the loop
1. Released in situ by mothercraft
2. Navigation mode – TCM: set new ΔV~1 m/s (1 day)
3. Science mode (1 day ~80 km)
4. Navigation mode – orbit determination
5. TT&C to Mothercraft

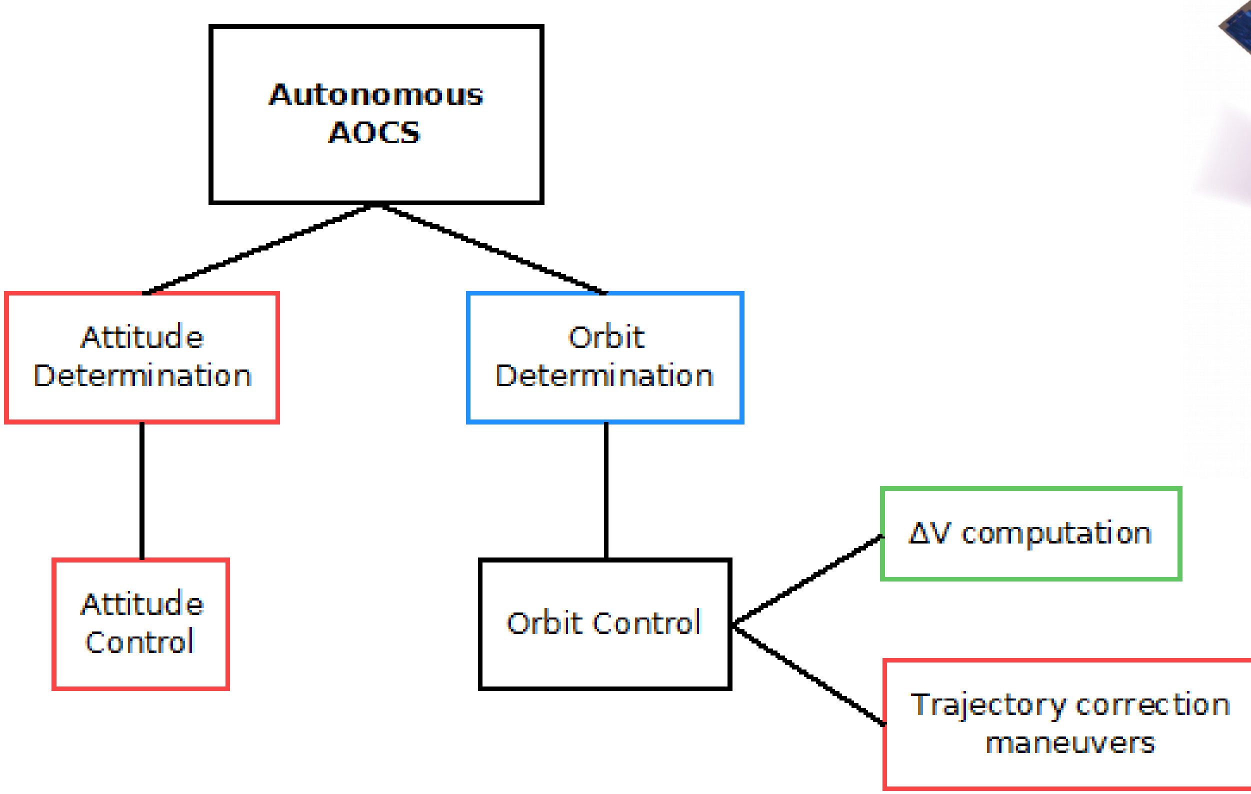


Models © ESA (Galvez/Carnelli)

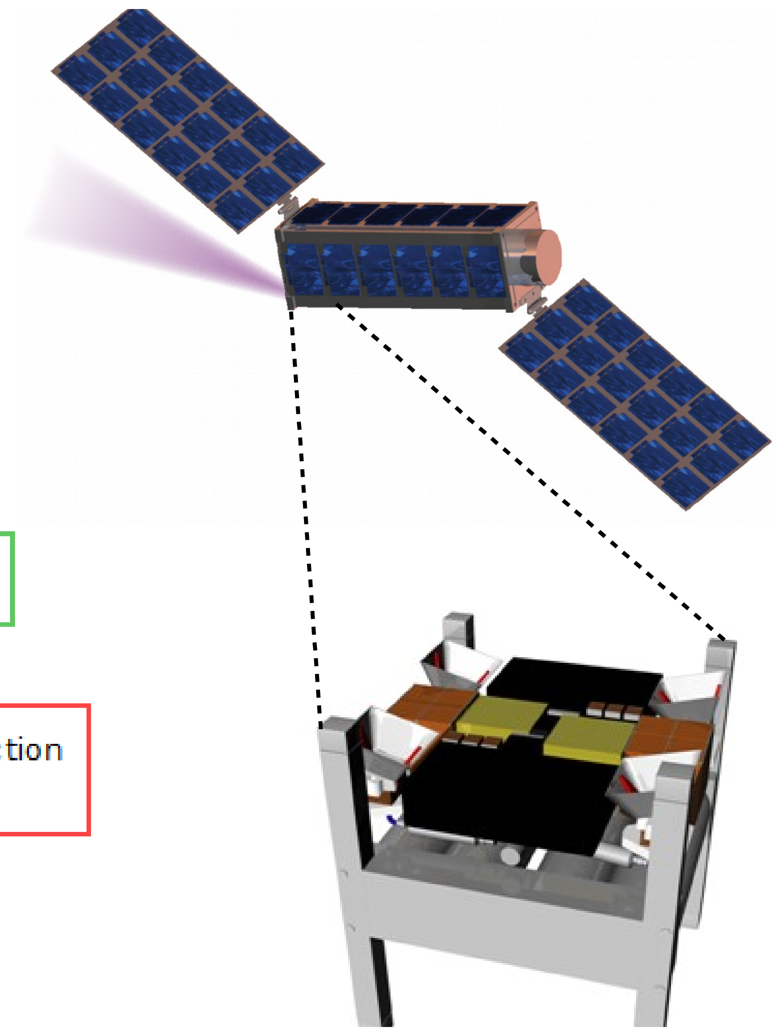


Caroll et al. 2015

AOCS functional integration in Birdy technology



- Scope of this work
- Segret et al. (2016)
- Still to be adressed



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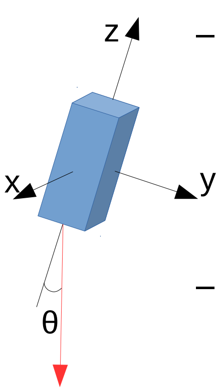
External constraints: torques

Solar radiation pressure (SRP)

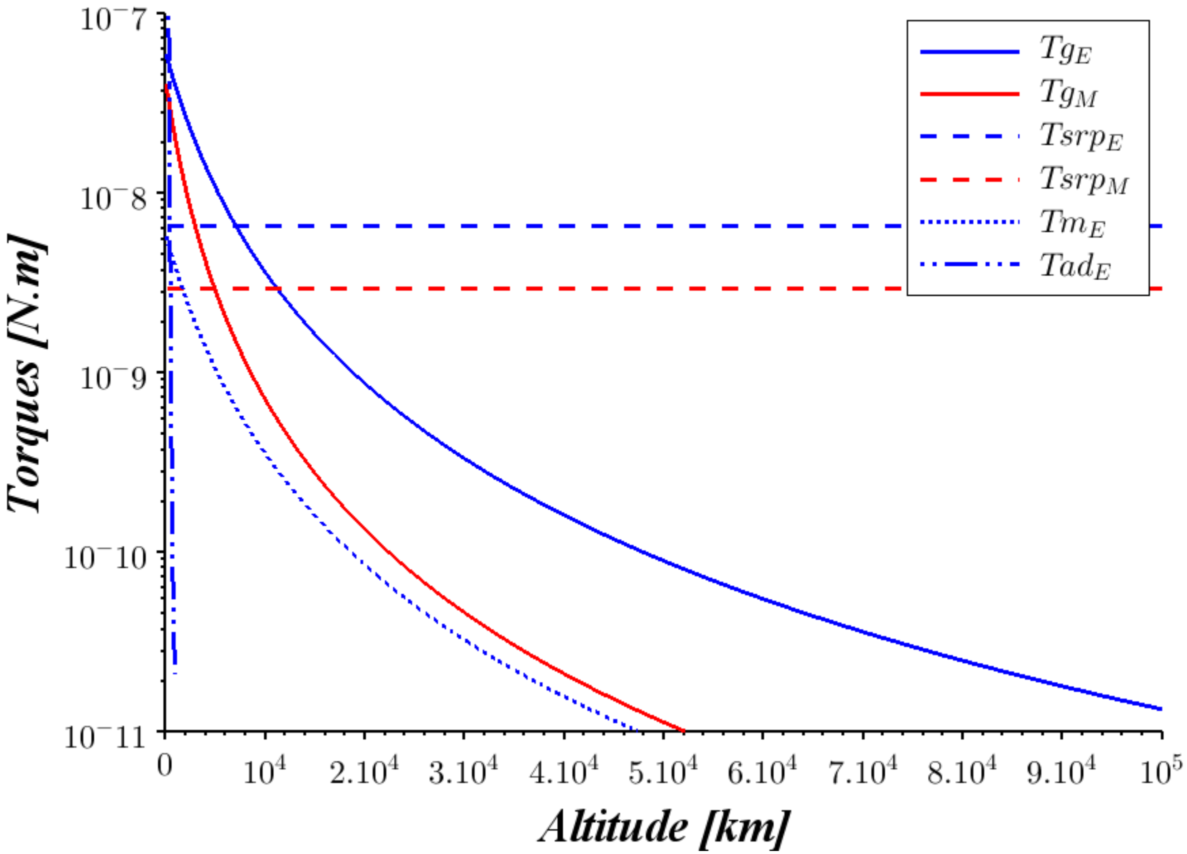
- Orbit perturbations *
- Attitude perturbations:
  - $T_{srp} = \frac{F_s}{c} A_s (1+\rho) \cos(i) (c_{ps} - c_g)$

Gravity gradient torque (GG)

- Orbit perturbations *
- Attitude perturbations:
  - $T_g = \frac{3\mu}{2R^3} |I_z - I_y| \sin(2\theta)$



  - Minimum distances to Earth and Mars surfaces = 1000 km



Torques estimations	$T_{g, Earth}$	$T_{g, Mars}$	$T_{g, Sun}$	T_{srp}
T_{max} [N.m]	$\sim 10^{-8}$	$\sim 10^{-8}$	$\sim 10^{-15}$	$\sim 10^{-9}$

* The ground segment computes it in advance

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Sensors and actuators

Sensors	Accuracy	Comments
Magnetometers	~ 1 deg	unusable
Earth sensors	~ 1 deg	unusable
Sun sensors	~ 1 deg	Safe mode and rough acquisition
Star tracker	~ 1" – 50"	Fine acquisition and navigation
3-axis accelerometers	Drift: 0,001 – 1 deg/h	Rough and fine acquisitions

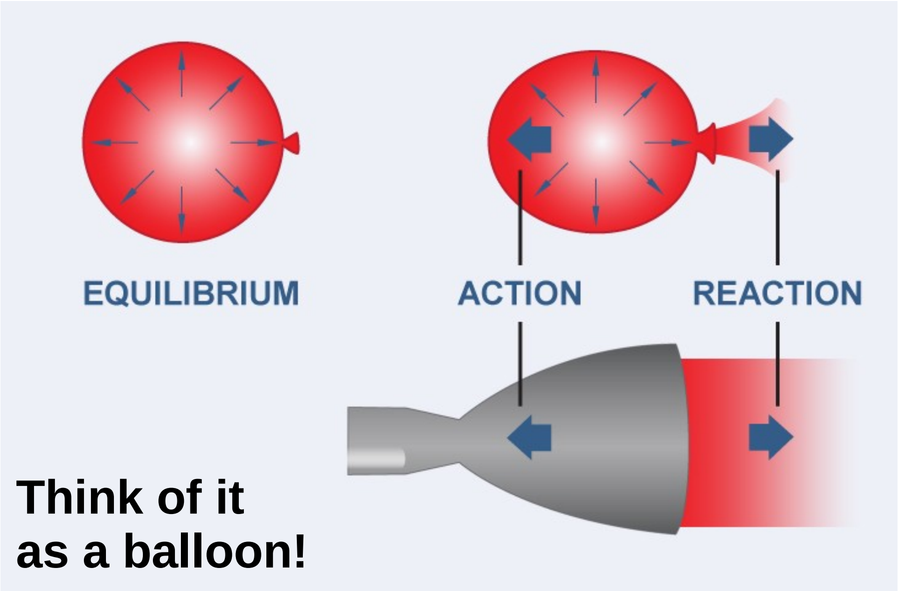
© SolarmemsTechnologies, Nano-SSOC-A60 analog sun sensor

© Maryland Aerospace Inc., MAI-SS Space Sextant

© VACCO, JPL MarCO Micro CubeSat Propulsion System

Actuators	Accuracy	Comments
Magnetic torquers	~ 1 deg	unusable
Reaction wheels	< 0,1 deg	Saturation => Momentum dumping
Propulsion	Depends a lot on the propulsion	Attitude and Orbit, Propellant limited

Propulsion systems' basics



Main features:

- Velocity increment capability (ΔV), (<=> control budget)
- Thrust levels (F), related to the maneuver time and precision
- Storability

- Basic equation for force of thrust [N]

$$F = \dot{m} \cdot v_e$$

- Total Impulse [N.s]

$$I_{tot} = \int_0^{\tau} F \cdot dt = v_e \cdot \int_0^{m_p} dm = v_e \cdot m_P$$

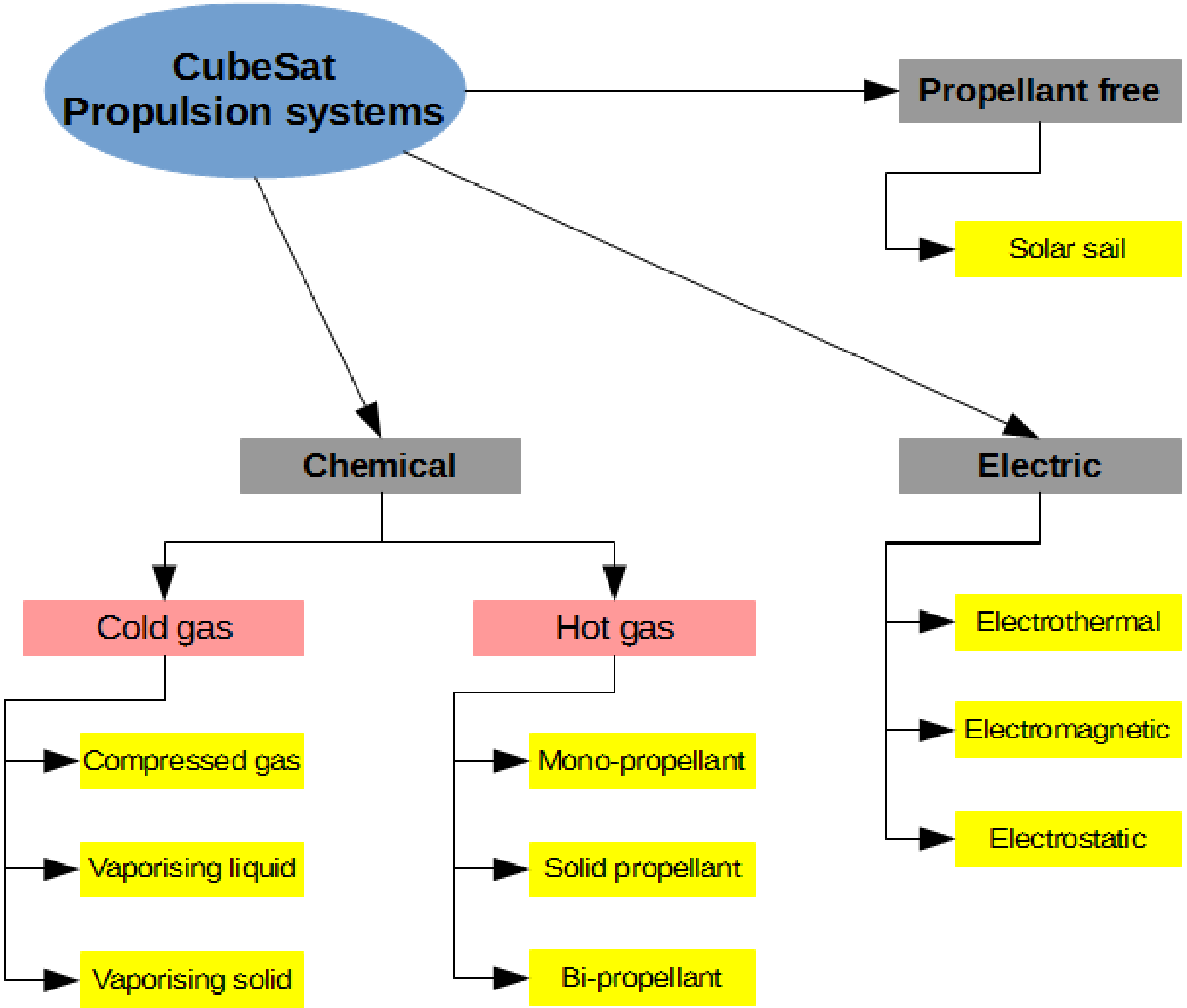
- Specific Impulse and System Specific Impulse [s]

$$I_{sp} = \frac{F}{(\dot{m} \cdot g_0)} = \frac{I_{tot}}{(m_P \cdot g_0)} \qquad I_{ssp} = \frac{I_{tot}}{(m_{PS} \cdot g_0)}$$

- Total velocity increment [m.s-1]

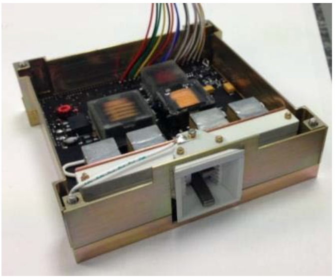
$$\Delta v = -I_{SP} \cdot g_0 \cdot \ln\left(\frac{m_f}{m_{SC}}\right)$$

CubeSat propulsion systems

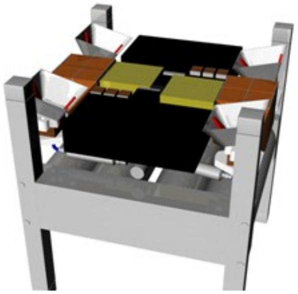


- **Cold gas**: simple and reliable, good thrust to power ratio, very low I_{sp}
- **Hot gas**: quite simple and reliable, good thrust to power ratio, average I_{sp}
- **Electric**: more complicated, low thrust to power ratio, high I_{sp}
- **Propellant free**: very early stages

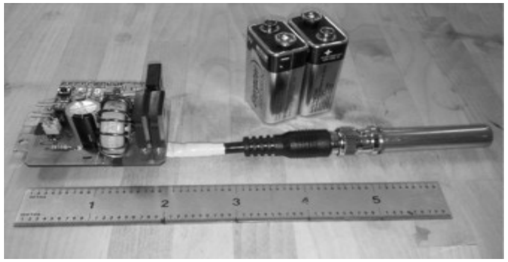
CubeSat propulsion systems comparison



PPTCUP, Ciaralli et al. (2015)

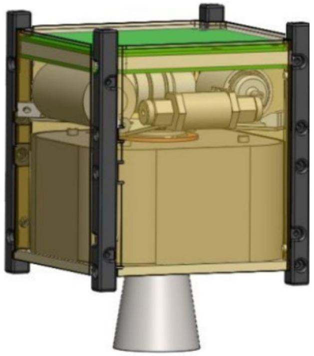


© L-μPPT project (2015)



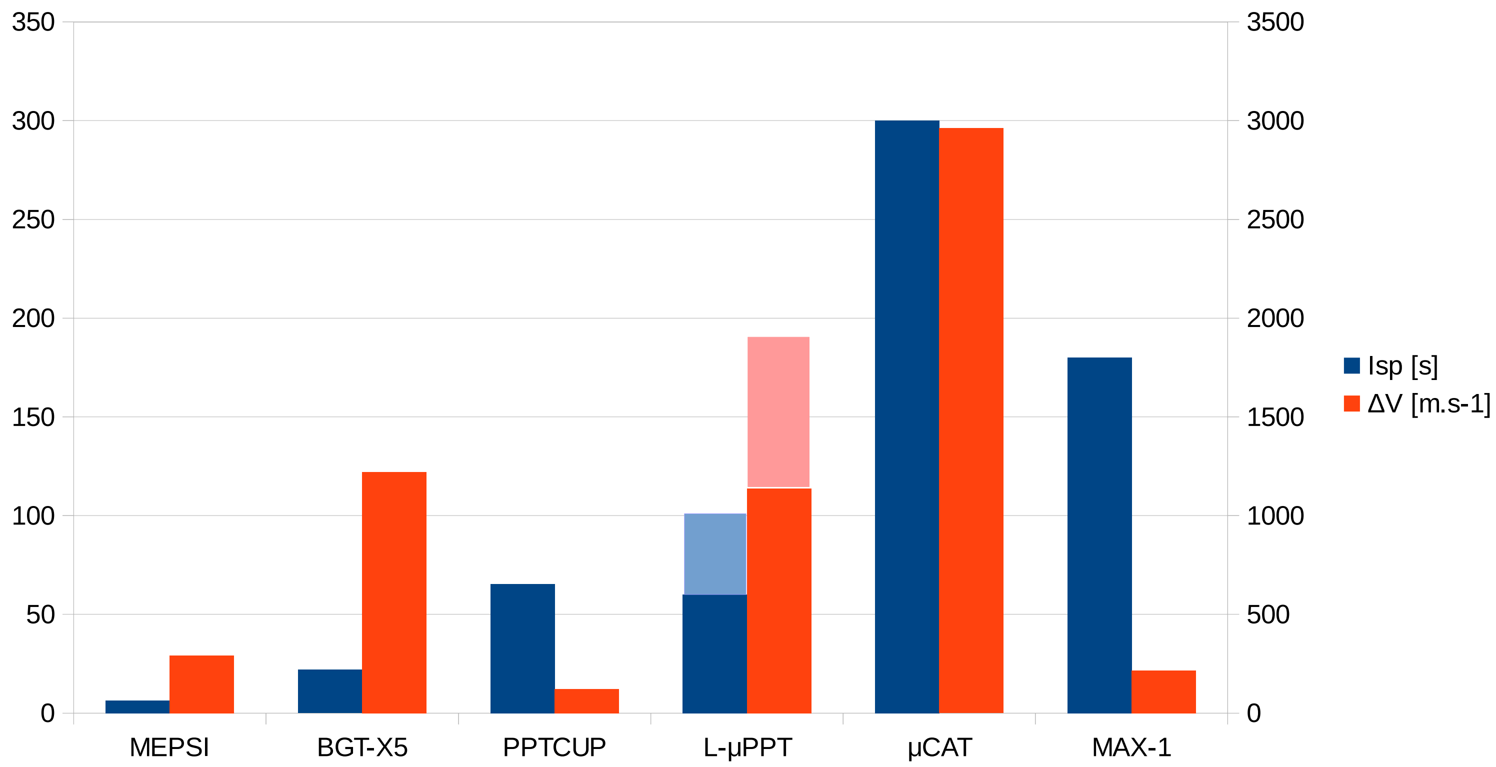
μCAT, The George Washington University, Keidar et al. (2015)

MAX-1, Accion systems Inc. (2015)

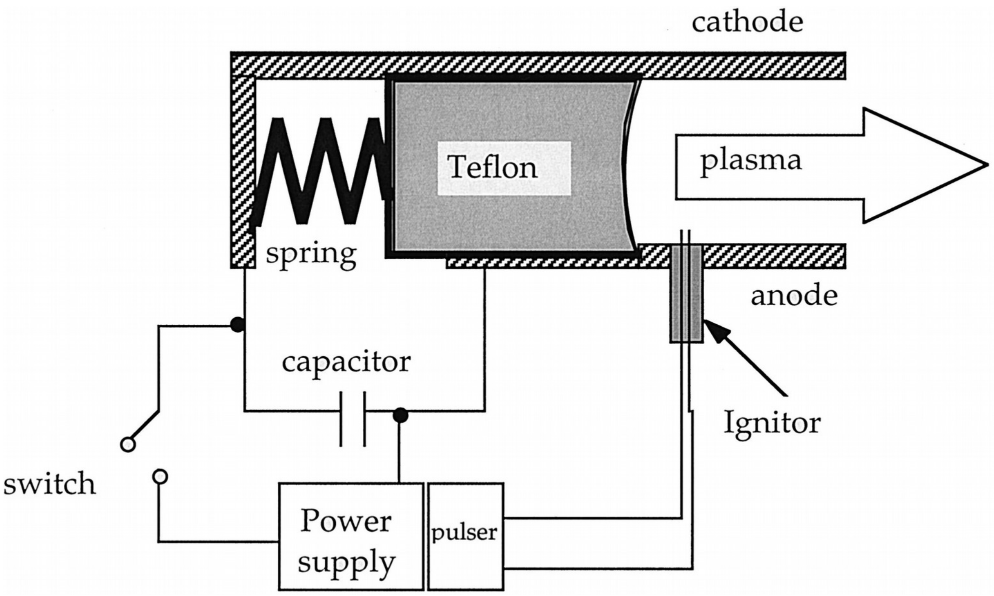


BGT-X5, Busek, Tsay, Frongillo, Lafko,& Zwahlen (2014)

MEPSI, VACCO, Stevenson, T. et al. (2015)



L-µPPT Vs. classic PPTs



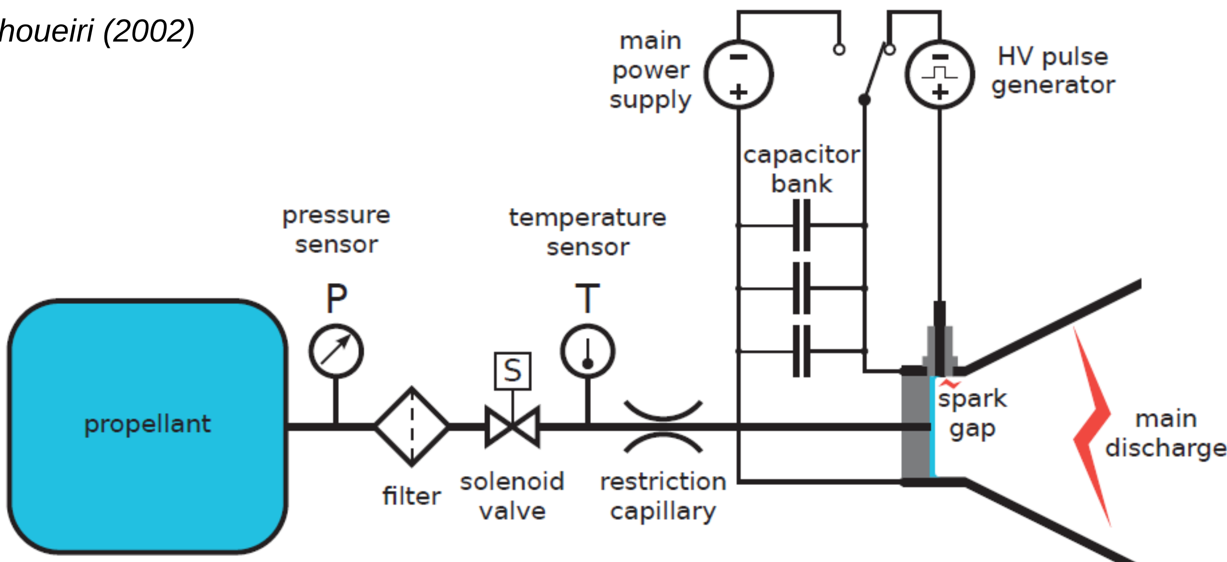
Robert G. Jahn, Edgar Y. Choueiri (2002)

PPT:

- Propellant fed by a spring
- Propellant ablation through a high voltage discharge
- Ablated propellant accelerated by a self-generated magnetic field

L-µPPT:

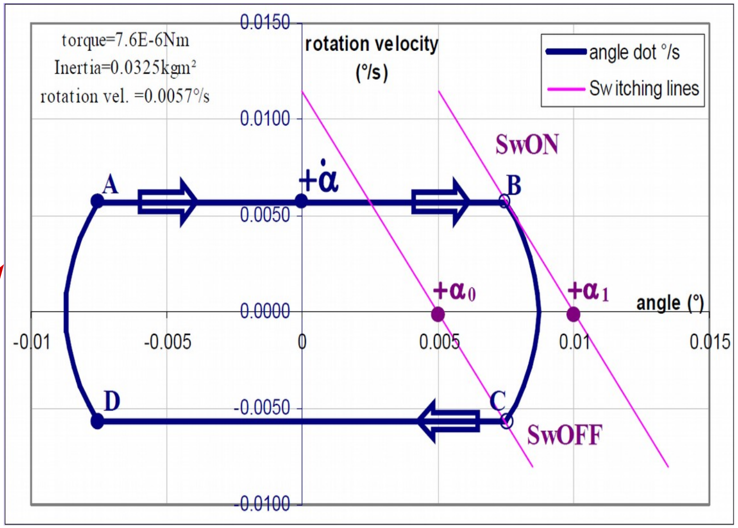
- Propellant mass not limited by geometry
- Steady propellant feed geometry
- Propellant balancing capability in multi-thrusters configuration



L-µPPT, S. Barral et al. (2015)

L-μPPT

- TRL 3
- 4-thruster configuration ($T_{L\text{-}\mu PPT} > 10^{-7}$ N.m)
- Space qualified liquid propellant
- Schmitt triggers
  - Dead-band constant
  - Trade-off between accuracy and consumption
- Detumbling in 9 hours with initial 50°/s spin on each axis
- Attitude control induces linear ΔV



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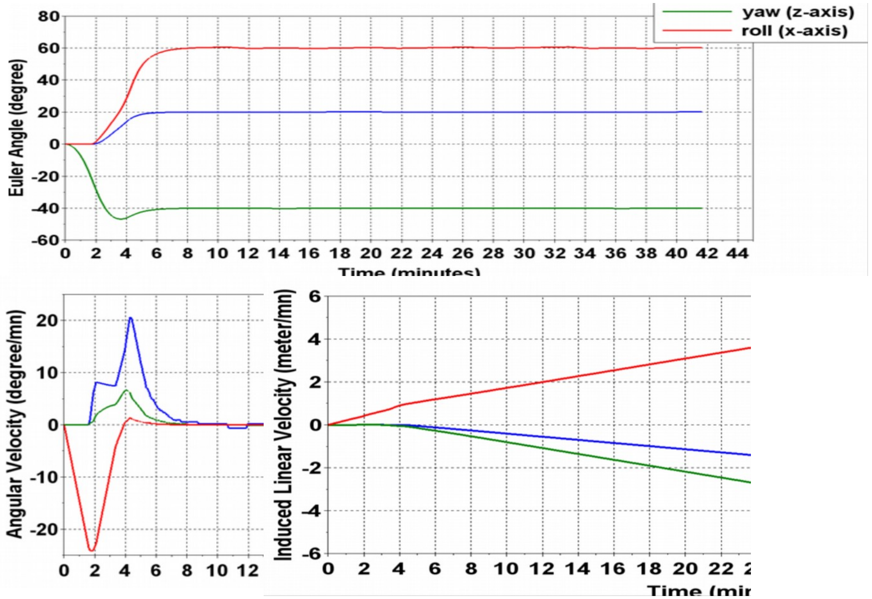

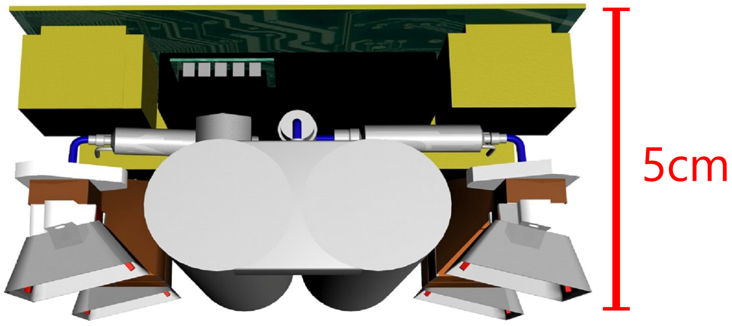

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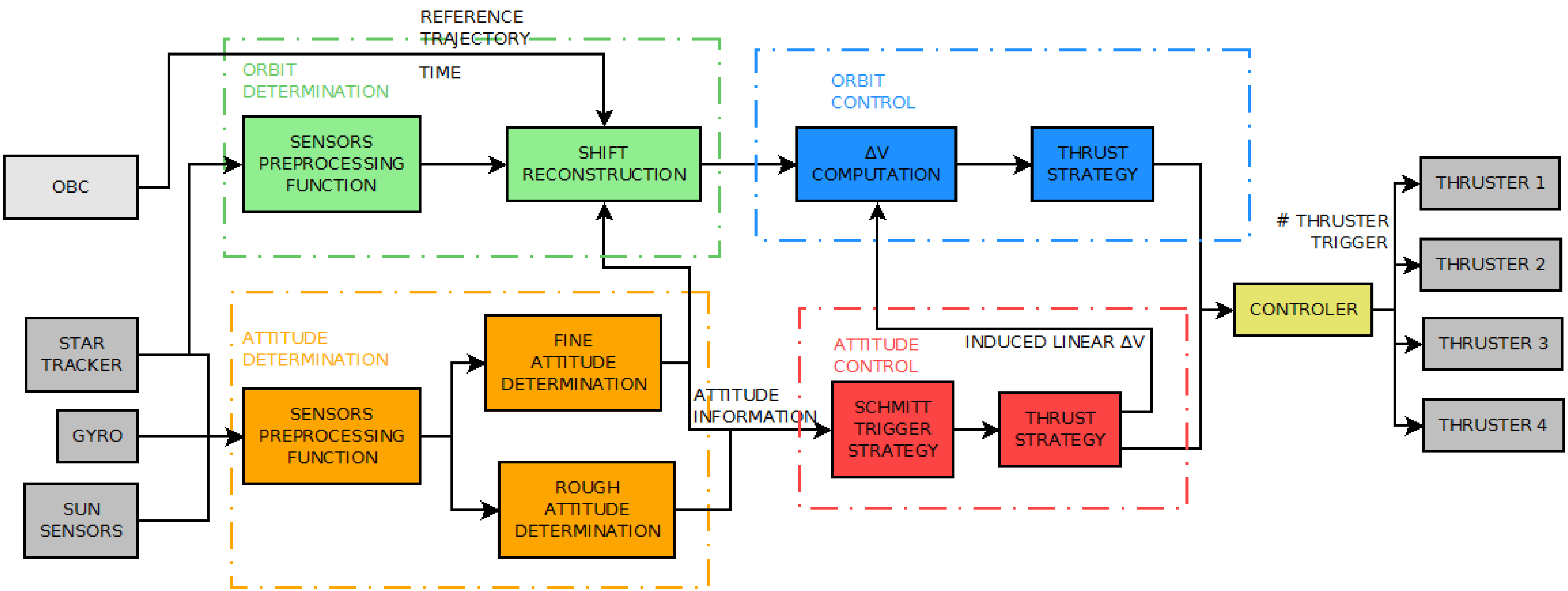
Tests from NCKU, DAA

Modes

Mission modes	Description
Orbit insertion	Provided by host mission: • on transfer orbit • in-situ
Acquisition (detumbling)	Initial angular velocities up to 50°/s
Navigation	• ΔV of ~ few m/s for cruise, ~ 50 m/s for flying legs • Pointing accuracy of several arcsec
Science	Depends on the science case: pointing / spinning
TT&C	Low accuracy pointing (>10°) at other satellites
Safe mode	Low accuracy pointing at the Sun

AOCS Modes	Description	Sensors and actuator
Orbit insertion		Turned off
Spin reduction mode	Especially for **detumbling**	• Gyroscopes • L-µPPT
Rough acquisition mode	Low attitude requirement-modes,	• Sun sensors and gyroscopes • L-µPPT
Fine acquisition mode	Especially for **navigation**	• Star tracker and gyroscopes • L-µPPT
TCM mode	ΔV computation and orbit correction (**navigation**)	• L-µPPT
Slew mode / Spin mode	Pointing change or continuous spin	• Gyroscopes and Sun sensors or star tracker • L-µPPT
Safe mode		• Sun sensors • L-µPPT

AOCS block diagram



Conclusion

- Development of an AOCS for autonomous navigation in interplanetary missions at the Observatory of Paris and NCKU
- L-μPPT system is expected to be the only actuator:
  - Fine attitude control (50 μN of thrust with 4 thrusters)
  - Trajectory correction maneuvers and in-situ operation (120 m/s to 190 m/s of ΔV)
  - Already 2 identified challenges: Schmitt trigger and induced linear ΔV
- Functional analysis approach general enough to fit to several types of interplanetary missions
- Objective: “off the shelf” high-level functions
- Considerations such as radiation protection and plume contamination have to be addressed