EPIC Workshop 2017

Liquid PPT for attitude and orbit control of space vehicles

PPT: PULSED PLASMA THRUSTER

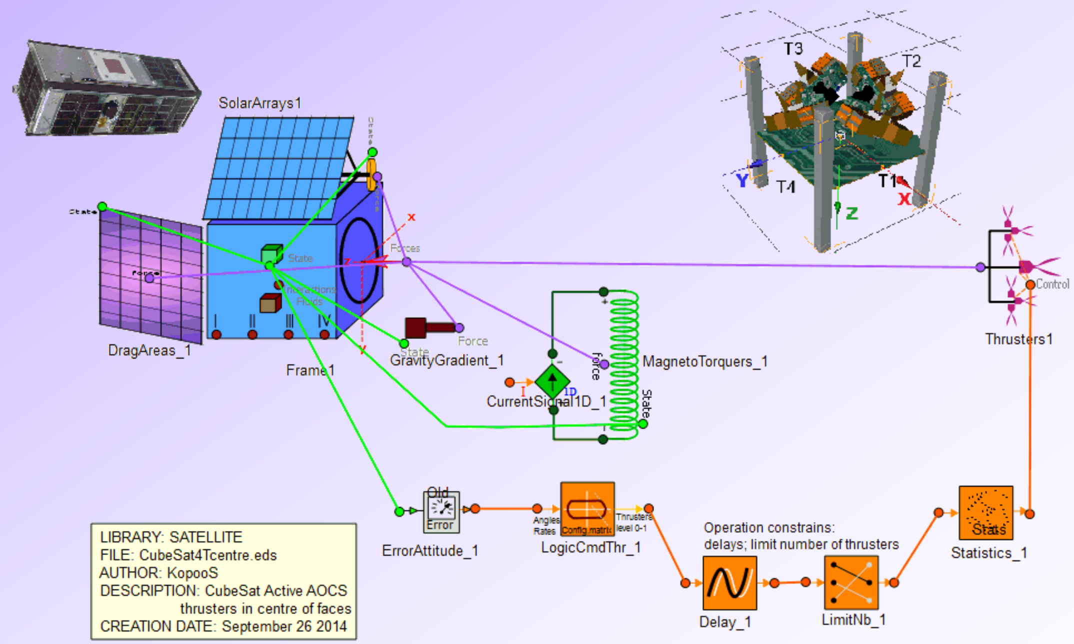
24th-25th October 2017, Madrid, Spain

➢*Advance in space technology for a breakthrough in the operational concept of spacecraft will be presented with a new opportunity of using electric propulsion for attitude control in replacement of the sophisticated, heavy and costly reaction wheels.*

➢*Tentative of such applications of electric propulsion have been disregarded up to now due to the fact that the electric propulsion were not efficiently able to fulfil the specific constraints needed for an attitude control.*

➢*The presentation will be focused on a concept of PPT, thruster specifically oriented for this application, using as propellant a kind of liquid Teflon (already used in space for mechanisms).*

➢*In medium term, complete disruptive unified liquid propulsion systems of attitude control for spacecrafts, and a full AOCS (attitude and orbit control system) for CubeSats may be foreseen.*



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Summary

- Introduction
  - Generalities on Propulsion Systems: Case of 1, several thrusters
- Liquid Pulsed Plasma Thruster history
  - General principle of operation
- Attitude and Orbit Control for CubeSat
- Active Attitude Control assessment with EcosimPro®
- Conclusions

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Generalities on Propulsion Systems: Case of 1 thruster

- **Having only one thruster in a spacecraft induces other needs:**
  - **Because the COM is never aligned with the thrust axis ➔Torques are accumulated and thrust axis may deviates dangerously**
  - **➔ Need of something, for example: Thruster or Mass Orientation Mechanism,** (or only in **LEO**: Magnetotorquers (MTQs) sized for the amplitude of misalignment and perturbations: MTQs for cubesat, cost roughly **14 µNm/kg** for 3 axis MTQs and power)
  - **➔Or need of high spin rate around the thrust axis… But this is difficult with solar arrays deployed in case of electric propulsion, and ➔ need something for attitude control**
  - **➔Or need of active propulsion system for attitude control during thrust or not**
  - **➔ Or use of Reaction wheels (RWs)**
    - But **alone RW are useless** for controlling the attitude for long runs of the thruster because they become fast saturated and nothing can off-load them
    - ➔ Need of something for off loadings (only in LEO for example MTQs sized for off loading)
    - ➔Or need of active propulsion system for attitude control off loadings
- **The robust answer: propulsion system with several thrusters**
  - **This covers all orbit transfers: in LEO, to GEO, to Moon, etc…**

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Generalities on Propulsion Systems with several Thrs

- **The concept of unified propulsion system has proved its advantages for operations: no other needs**
  - **Design: only a unique propellant tanks system for all thrusters**
  - **Share the propellant and the needed margins to cover worst cases between Orbital manoeuvres and attitude control ➔ Very efficient to cover any worst cases**
  - **Almost no loss of unused mass in the system contrary to non unified concept**
- **Some systems cannot implement such unified concept**
  - **Example: solid teflon PPT, electric conductive or ionic fluid thrusters (….) , mercury thrusters, caesium FEEP, and many many concepts never used, etc**
  - **What happen in such case?**
    - The ISP of the thruster alone is not the one taken into account at system level: **the first thruster out of propellant drive the end of life➔** loss of **unused mass** in the system
    - For attitude control with 4 thrusters, a worst case is to use only 2 such thrusters
      Hence to cover this worst case, **one shall double the propellant mass**
      ➔the effective ISP in the system is 50% of the thruster Isp… Even worse when using more than 4 thrusters (effective ISP ↘ **25%** of the thruster Isp when thrusters are redundant)
- **The concept LPPT is able to be used into an unified propulsion system : That is why this concept is so attractive**

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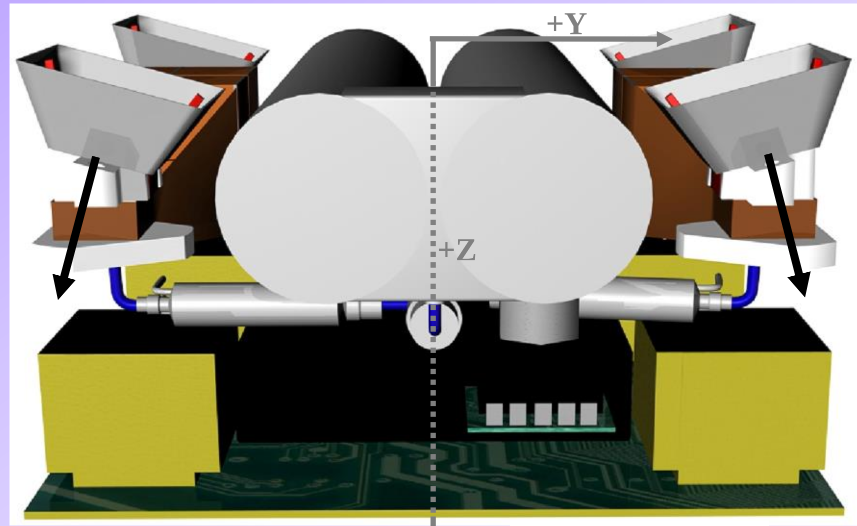
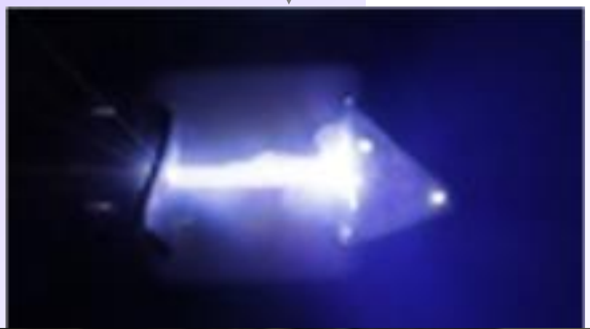
Liquid Pulsed Plasma Thruster history

HISTORY

- Financial support: FP7 “L-μPPT” project (2011–2014)
- Project to Design and demonstrate the feasibility of a liquid-propellant PPT for nanospacecrafts
- ➔Novel open capillary design with non-volatile propellant
- European Consortium (Spain, Poland, Sweden, France , Swiss)
- LPPT tested is a 1 MW thruster (1 J in 1 µs) every seconds
- Successful project with 50 000 pulses achieved with Isp **1000** to **1400** s (**measured**) and Impulse bit **15-25** µNs (**measured**)



System 4T **(preliminary)**



Proposed in COMPET 3 2016 B

- Full disruptive concept for active attitude control of large S/C with demonstration on small Cubesats
- European Consortium (Spain, Poland, Hungary, France, Swiss)
- Financial support requested: about 1.5 M€ (including Swiss)

Today status: stand-by, but all members interested for continuation of the project

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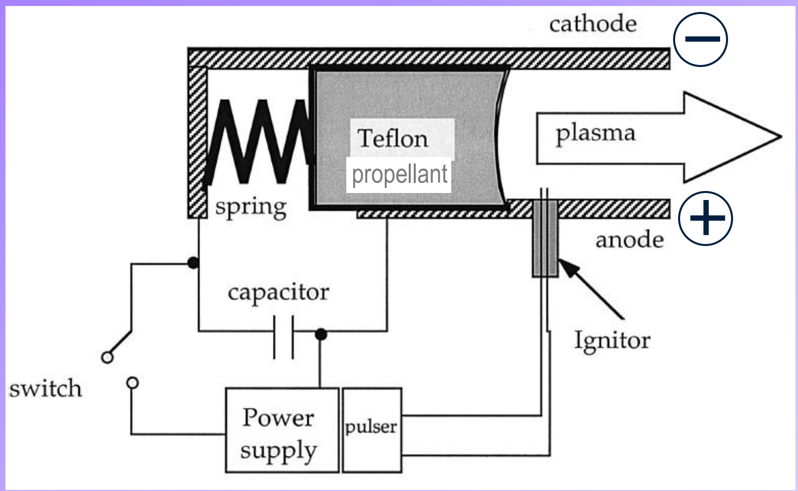
General principle of operation

Solid teflon PPT Principle

1. Propellant fed by the spring
2. A spark gap ablates all the propellant to be accelerated and ignites the main discharge
3. The main discharges ionizes and accelerates the ablated propellant
4. But low efficiency (10%)

Solid PPT *(Nasa)*



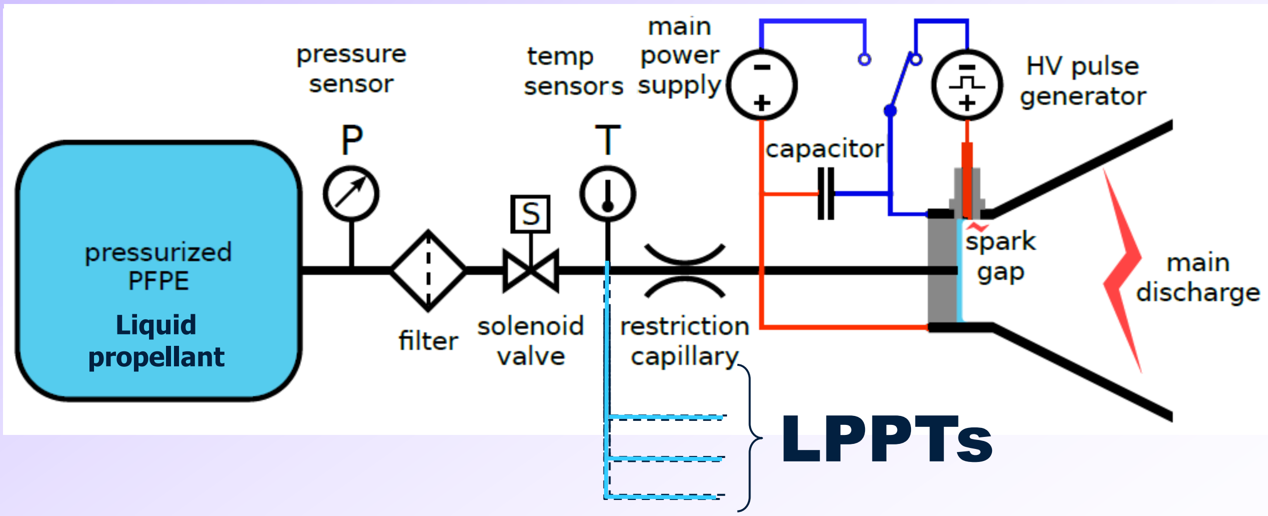
PPT: PULSED PLASMA THRUSTER

Liquid PPT: Smaller area exposed (narrow channel) ➔ strongly reduced late-time ablation contrary to solid Teflon PPT ➔ Higher efficiency potential

Liquid propellant PPTs **systems**

- Propellant mass not limited by geometry:
  - total impulse much less constrained than solid PPTs
- Steady propellant feed geometry:
  - no long term drift in terms of impulse bit
- Propellant balancing capability in multi-thrusters configuration:
  - Twice better utilization of total propellant mass

Liquid PPT



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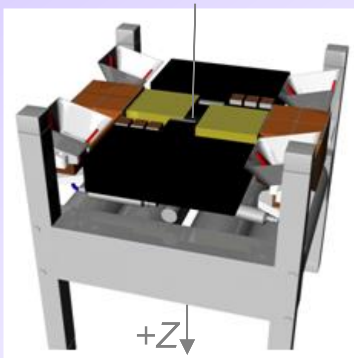
Attitude and Orbit Control for CubeSat

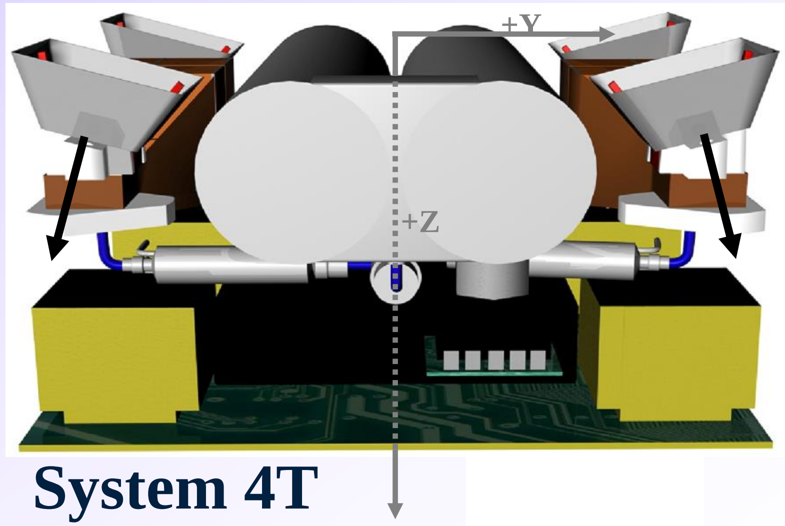
Design principles

- Priority to **Propulsion System** for **Orbit control**
  - **thrust vector along the axis Z**
  - **during thrust: Need of additional attitude control consistent with thrust levels and durations**
  - Reaction Wheels are **useless** when nothing can **off-load the 3 axis** (in GTO, Moon, interplanetary)
- ➔ Orbit control & Full 3 axis Attitude capability (4 dof) ➔ Minimum 4 thrusters
  - **Even if ref. Viktor & Chen theorem states a need of "dof+1" actuators**
- *Priority to orbit control* ➔ 4 thrusts mainly along the axis Z and in the corners: the 2 axis X, Y are fully controllable
- *Full Attitude capability*➔ also control around Z axis

  ➔ thrust vectors must be tilted by some angle α wrt the axis Z

Hence **not need of additional devices for thrust orientation in space (costs ↘)**





System 4T
(preliminary)

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Attitude Control: Dead Zone with Hysteresis

Principles

- Permanent compensation of the external torques
- Active attitude control with thrusters switched on and off
- ➔ Use of Schmitt triggers: dead-band and switching functions

Limit cycle: without perturbations, for each axis

- **Dead-band constant**

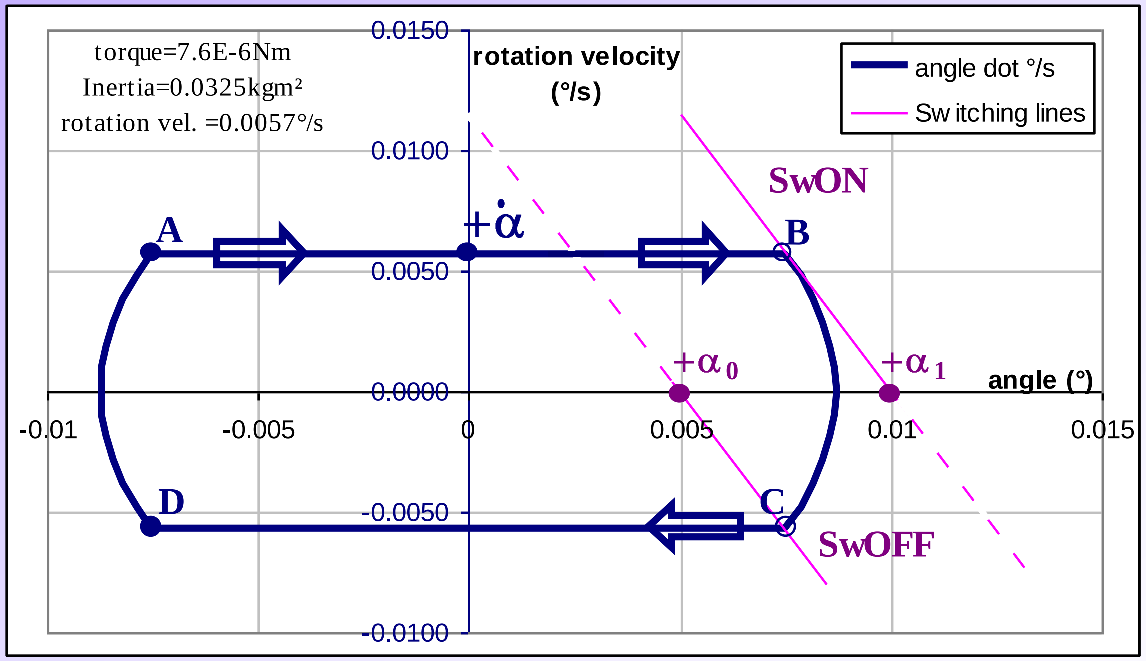
  Cost of Dead-band control accuracy in " torque impulse/year (T_{iy}) "

$$K_{DB} = \frac{T_{iy}}{I} \cdot \left(\frac{\alpha_1}{\dot{\alpha}^2} \right)$$

- **K_{DB}** is about **700 000**

  units $Ns^3(kg.m.year.deg)^{-1}$

  T_{iy} in Nms/year



This Dead-band cost must be added to the consumption for the simple compensation of the external torques…

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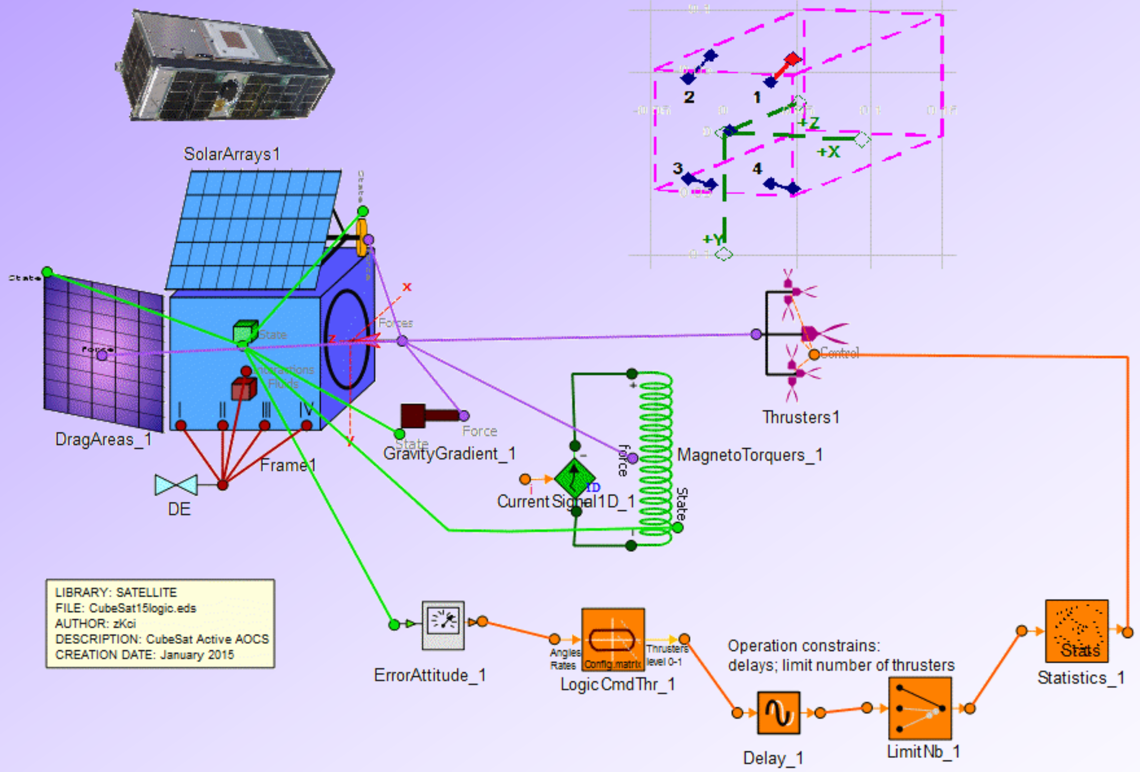
Active Attitude Control assessment with EcosimPro®

- Full attitude control of three axis with simplified logic (ESA ESPSS library under **EcosimPro®**)
- S/C mass 4 kg, 0.03 m² of drag area , reflective area 0.03 m² and drag coefficient Cd 2.2; Orbit 480 x 520 km
- Model: 4 thrusters, 4 solar arrays, 6 drag areas, Gravity gradient, 1 magnetotorquer (for dipole perturbation only)
  - Magnetic disturbance torque coming from a dipole of 0.0004 Am²
  - Solar Arrays on the 4 lateral sides
- Operations:
  - CubeSat COM set to a deviation of 6 mm on each axis (r=10mm) (ref.CDS “sphere of 2 cm”)
  - Simple logic for 3 axis dead-band control relying on configuration matrix pseudo-inverse
  - Delay 0.5 s between command and 1 s pulse
  - Number of thrusters used : limited to 1 among 4



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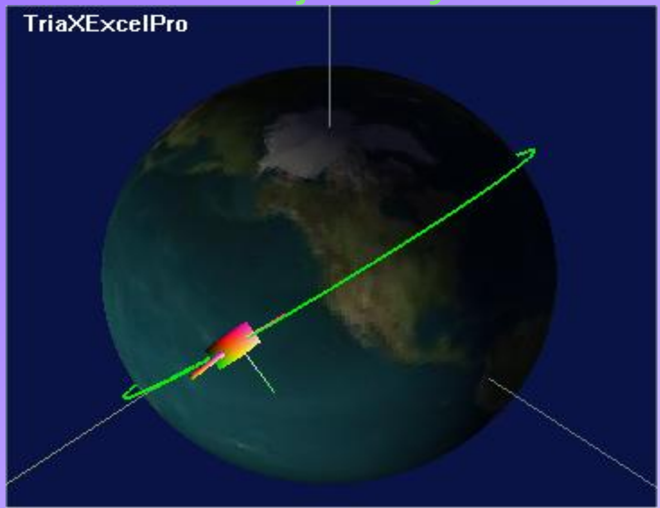
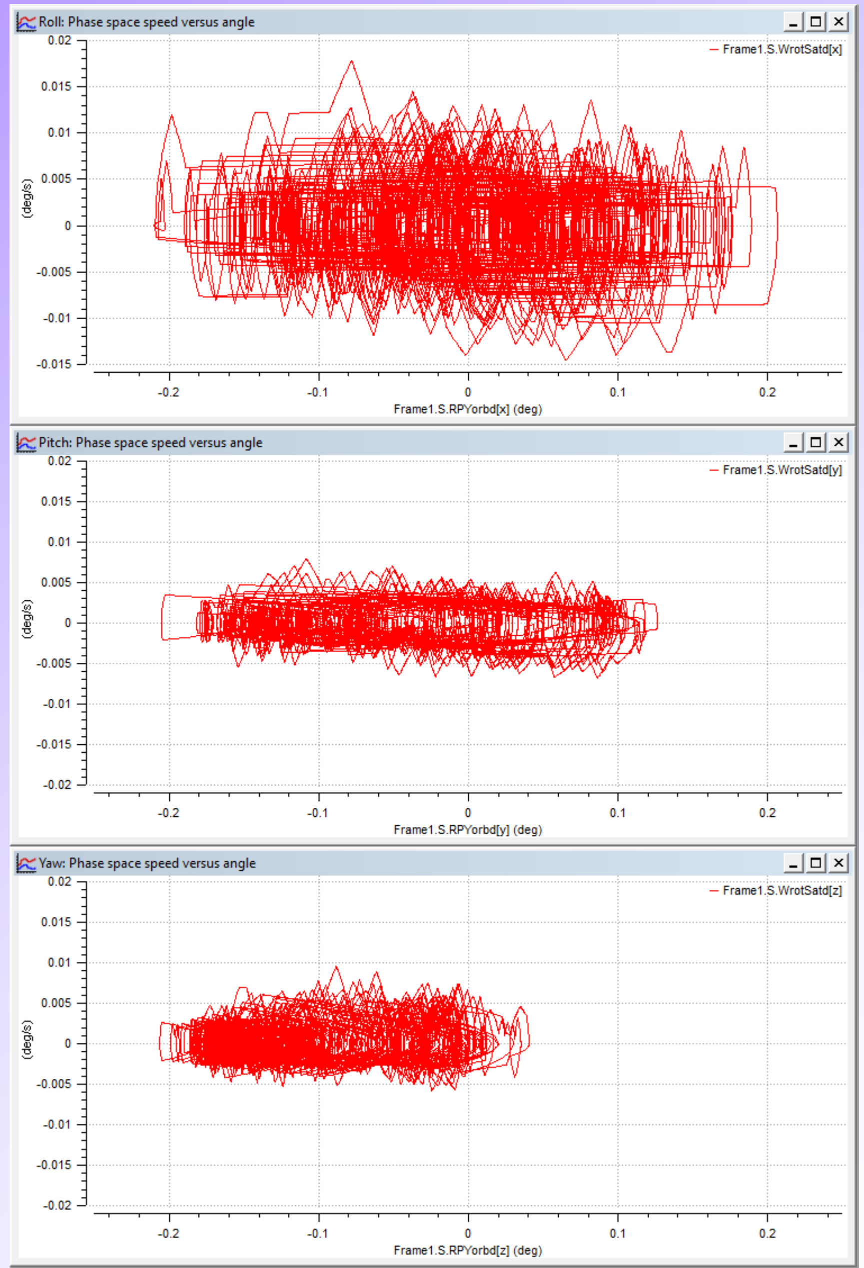
Active Attitude Control assessment with EcosimPro®

- Results for 10 000 s of control
  - Accuracy well controlled
  - Here +-0.2° all axes: 1 pulse every 5 to 10 s
  - ∆V used =25 m/s per year (for all axis, including perturb. in LEO)

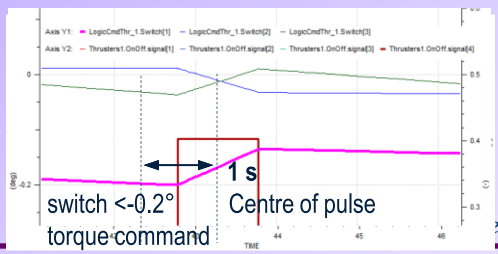
trajectory



Pointing vector trajectory



- Constrains
  - Only 1 thruster among 4, every period (1 s) or less.
  - Delay of one period between torque command and effective thrust impulse (µs)
  - ➔



delay of half period when pulse extends over 1 period as here

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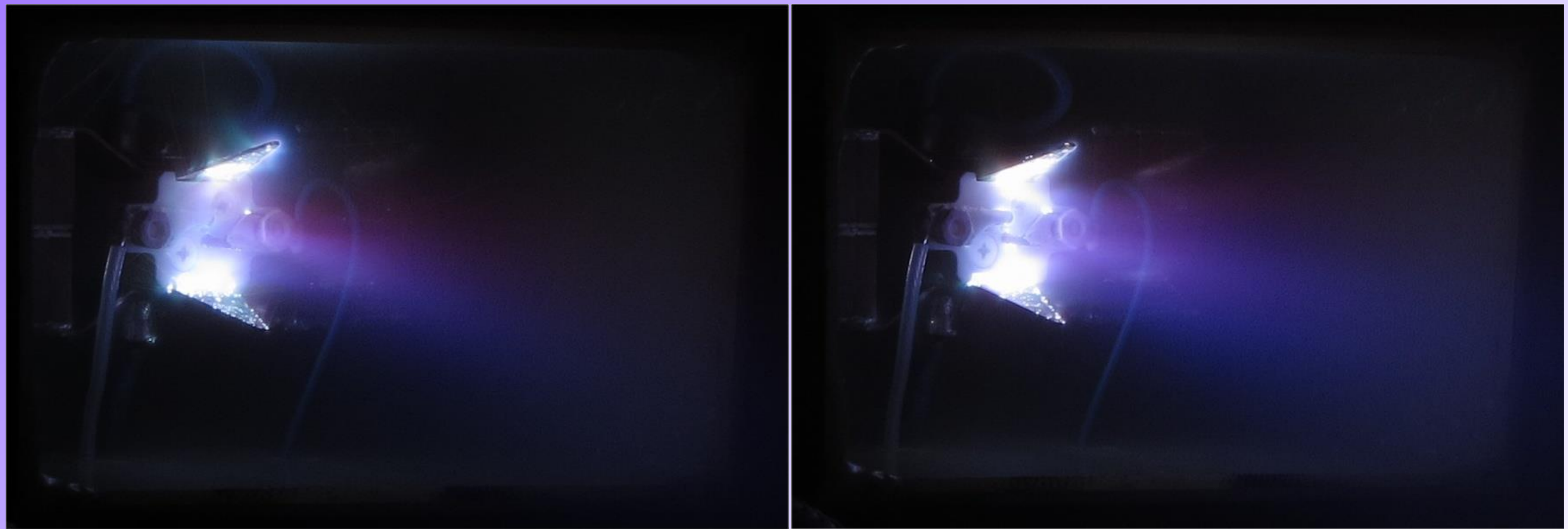
Pictures LμPPT from tests

- **Discharge for two different voltages**



- **With the final prototype**
  - **50 000 pulses achieved**
  - **1000-1400 s Isp measured**
  - **Impulse bit 15-25 μNs measured by impulse thrust balance (and not by equations from some derived parameters)**

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Conclusions

- The main advantages of the Liquid PPT with respect to solid PPT or single other thrusters is on both sides :
  - Operational: very high mass utilisation efficiency, common unified tank for all the thrusters (impossible with Teflon and colloid conductive fluids)
  - Performance: better reproducibility of each pulse because the "ablation" area is mastered
- The L-µPPT is fully compliant with the Cubesat specifications
  - No pressure vessels over 1.2 standard atmospheres
  - No toxic propellant
  - Propellant largely used for space mechanisms
  - No waivers needed for using the propulsion system
- The L-PPT: designed for orbit control and fine attitude control
  - No starting delays
  - Always available
  - Thrust orientation maintained thanks to the active attitude control consistent with the propulsion ➔ No real need of 3 axis RW
  - In view of attitude control of large ComSat (without RW).

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Conclusions

- **It is very important that the propulsion is compatible with the concept of unified propulsion system:**
  - **Almost no loss of unused mass in the system contrary to ionic conductive or solid teflon propellant**
  - **Share of common parts to all thrusters (tanks, etc)**
- **The LPPT is one of the promising concept for orbit and attitude control**
  - **The finding of a suited liquid propellant has been proven by test**
  - **But still a long way before TRL 9**
  - **Millions of pulses : capacitors used with relevant margins**
  - **Design to be optimised: up to now, a replication of Solid PPT has been tested (Isp 1200 s, with same "low" efficiency 10%).**
  - **Hence several areas can be optimised contrary to the Solid PPT: injector size and frequency for higher efficiency and long life**

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Thanks

Ackowledgments

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- IPPLM has also received financial support from the Polish fund for science in years 2012-2014 for the execution of a partially funded international project.

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Electric Propulsion Induced User's Requirements (Cubsat)

- System LPPT works in
  - High vacuum <10-4 torr
  - Weigtlessness < 0.001 g
  - ➔ On ground: system only on flat surface
  - Temperature -20 to + 55°C (operating)
  - COM wrt geom. centre: <10 mm, all axis
- Inputs
  - Wet mass: ½ U with 4 thrusters (TBC)
  - Dimensions: ½ U 100x100x56 mm^3 (TBC)
  - 5 VDC +- 0.1
  - when 1 thruster is ON: 2 W mean power is a goal (worst case 4 W for design)
  - Communication TBD
- Operations
  - Only pulsed mode with 1 thruster among 4
  - Period= capacitors charge + discharge pulse (µs)
  - ➔1 period delay needed between command and effective µs pulse for capacitor charging
  - Period > 0.1s (Frequency : < 10 Hz) (TBC)
- EMC
  - Shielding recommended
- For efficient attitude control
  - Fine angular rate sensor sensibility better than **0.001°/s** on all 3 axis for minimizing the cost of control
  - Attitude sensor sensibility : consistent with the wanted attitude control accuracy
    - 0.02° for 0.2° control
    - or 0.002° for 0.02° control
  - COM wrt geom. centre: to minimize the uncertainties <<10 mm, all axis with all deployed appendices and solar arrays (failure to deploy: possible mission partially abort)

⚠ No pure torques ➔ **always slight thrust** even after using opposite thrusters in 2 pulses

- Thruster System Technical Requirements goals
  - Specific impulse: ≈ 600 s - 12000 s (TBC)
  - Total impulse: 100 up to 200 Ns/thruster (TBC)

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