Electrostatic tether plasma brake module for deorbiting

***Pekka Janhunen**, Petri Toivanen, Jouni Envall,*
Finnish Meteorological Institute, Helsinki, Finland

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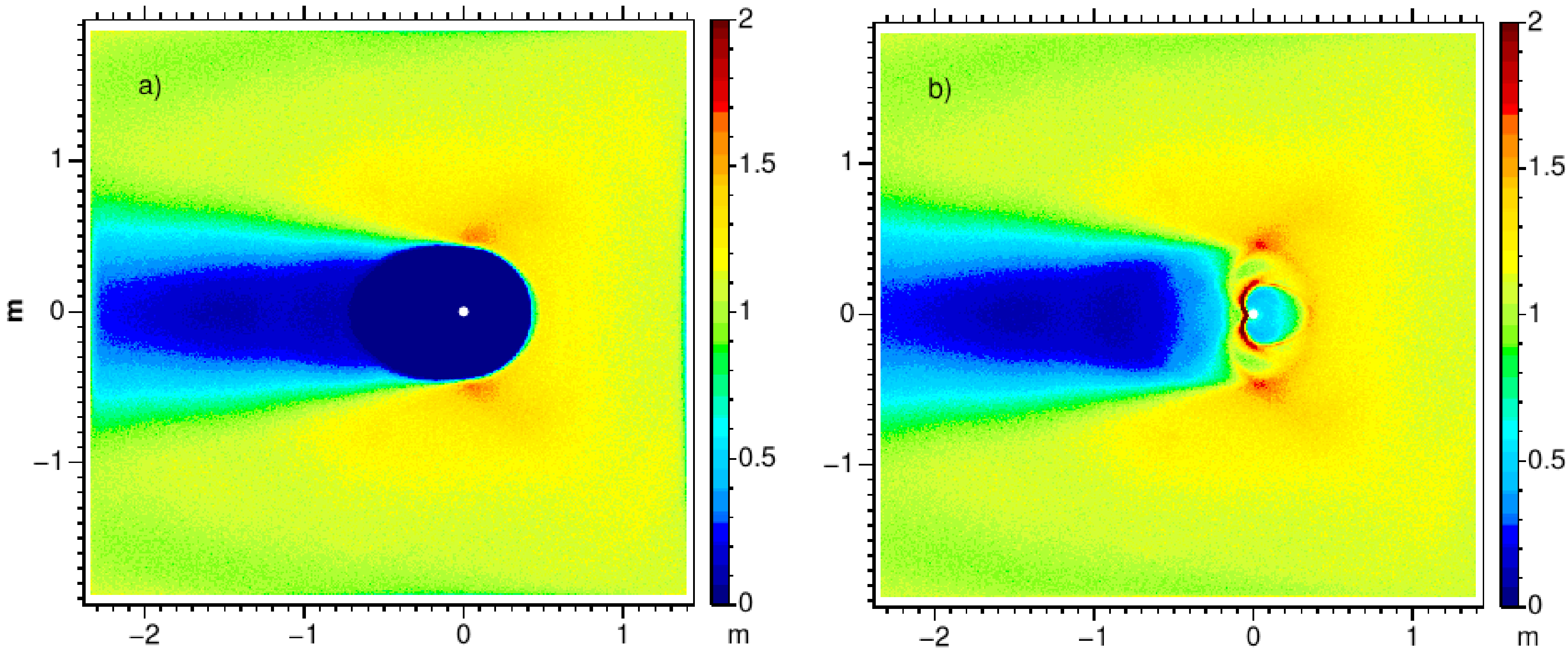
Coulomb drag propulsion

- Way to harness natural space plasma flow for propulsion
  - Charged thin tether taps momentum by deflecting ion flow.
  - One or more tethers: for cubesat, one suffices.
- Two application domains:
  - Solar wind → ***E-sail, interplanetary propulsion***
  - LEO → plasma brake, satellite deorbiting
- At least order of magnitude more efficient than existing methods (efficiency = impulse per propulsion system mass)

PIC simulation of plasma brake



- LEO parameters, -0.34 kV tether polarity
- Electrons left, ions right

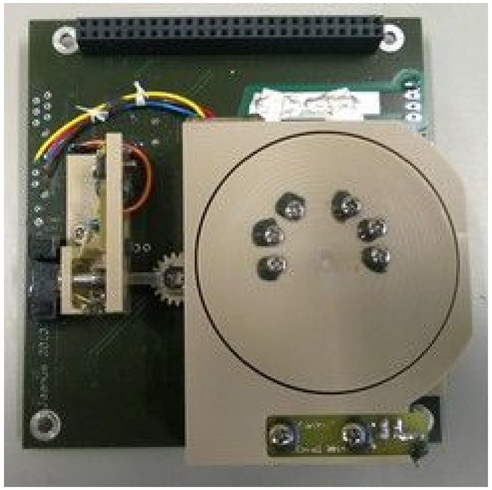
Plasma brake physics

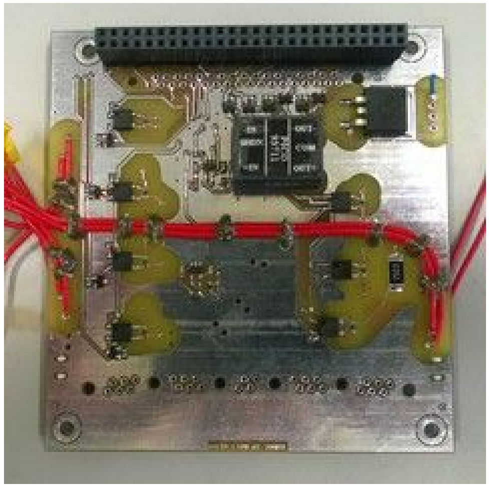
- Negative mode can be simulated well by ordinary PIC because there are no trapped particles (number of low-energy ions is small in the flow, i.e. flow is highly supersonic)
- ***B***-field perpendicular to flow and tether → laminar
- ***B***-field along tether → turbulent, thrust reduced ~27%
- ***B***-field along flow → turbulent, thrust not reduced
- Formula that reproduces simulated thrust very well:

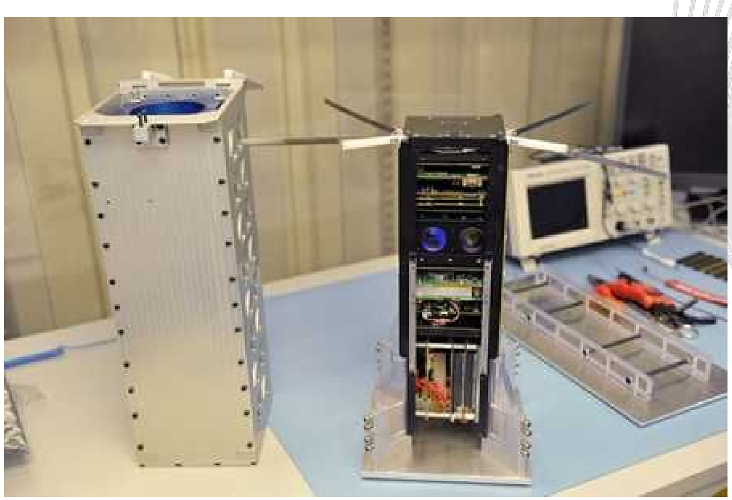
$$\frac{dF}{dz} = 3.864 \times P_{\rm dyn}\sqrt{\frac{\epsilon_o \tilde{V}}{e n_o}} \exp\left(-V_i/\tilde{V}\right) \qquad \tilde{V} = \frac{V_w}{\ln(\lambda_D^{\rm eff}/r_w^*)} \qquad \frac{dI}{dz} = e n_0 \sqrt{\frac{2eV_0}{m_e}} 2r_w$$

Janhunen, P., Simulation study of the plasma brake effect, *Ann. Geophys.*, **32,** 1207-1216, 2014.

Cubesat testing



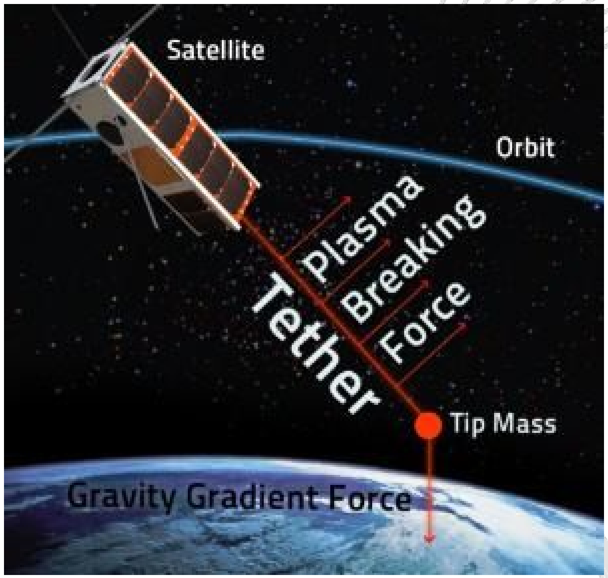


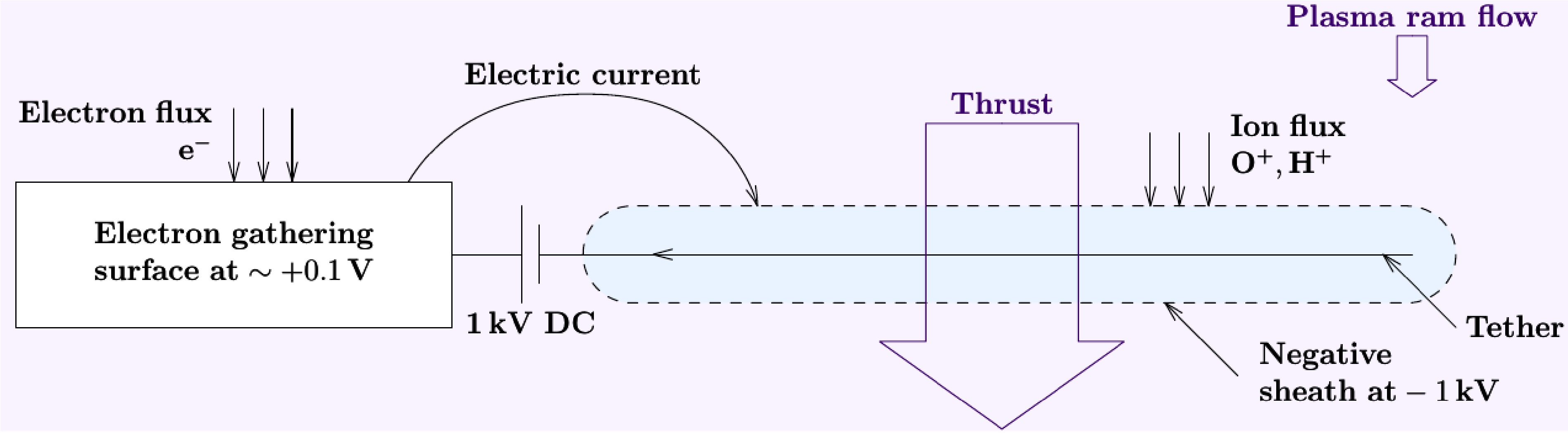


- Aalto-1 (3-U LEO cubesat):
  - 100 m tether
  - 2 PCBs: HV card and motor card, ~300 gram total mass
  - Launched June 23 2017
  - Coulomb drag experiment expected in late autumn/early winter
- Forthcoming: ESTCube-2, 300 m tether

Operating principle

- Charged tether taps momentum from plasma ram flow
- No ion or electron emitter needed, only 1 kV voltage source that forces potential difference between tether and satellite
- Conducting surface area needed

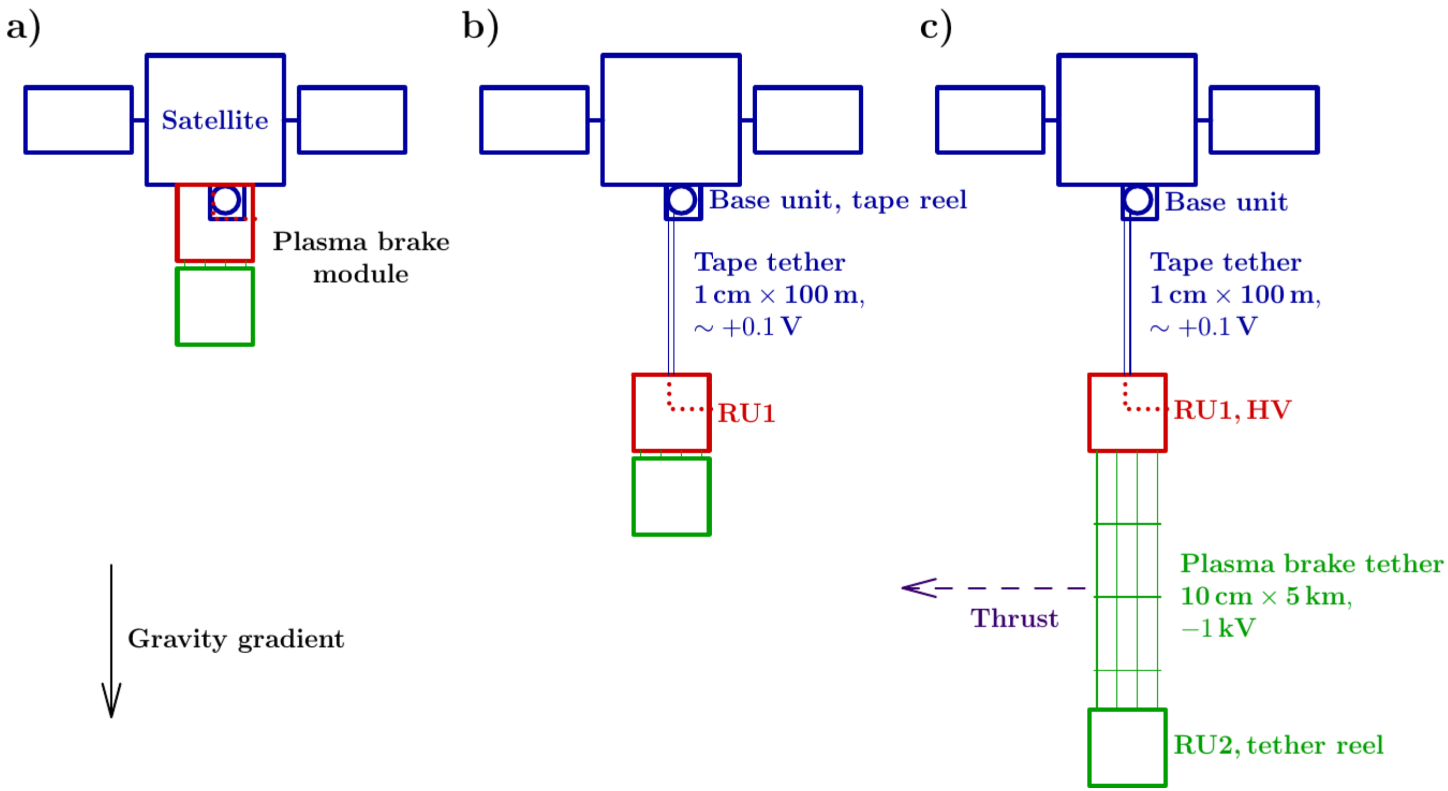




http://www.electric-sailing.fi

Structure and deployment

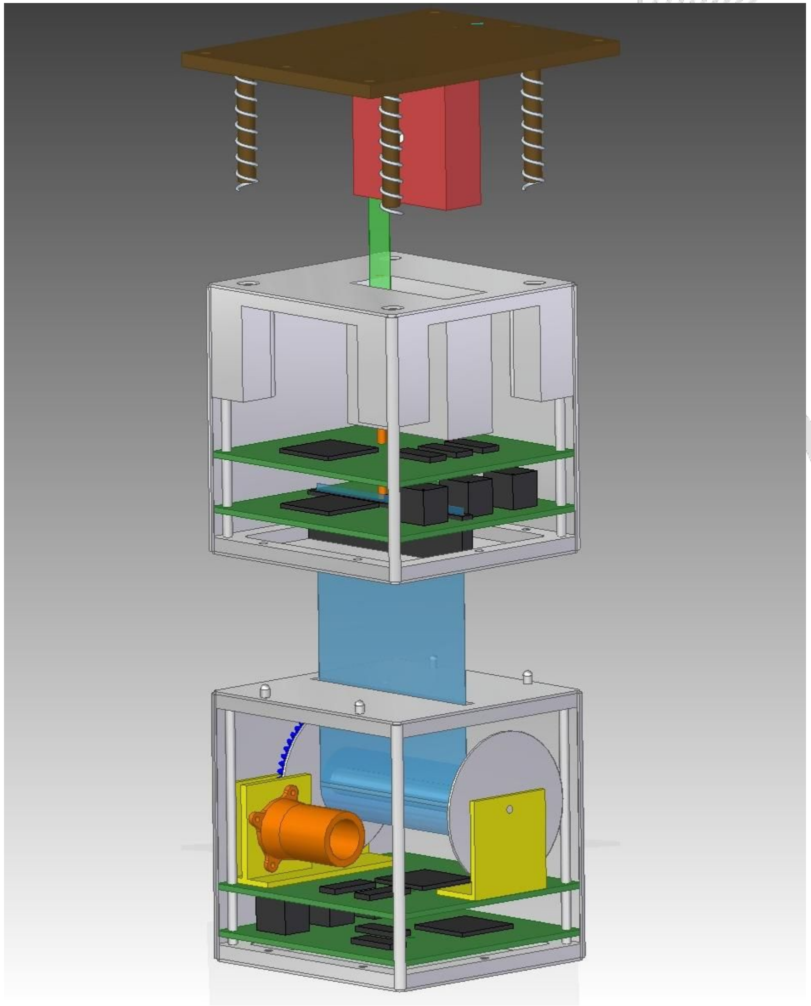
- Aluminised plastic tape tether for seeding gravity gradient deployment and for electron collecting area.



http://www.electric-sailing.fi

2-U module design

- Base unit, RU-1 and RU-2 (RU=remoteunit).
- Springs eject RU1+RU2 combo away, accelerating tape tether spool to rotation.
- Cycle counter triggers smooth braking to avoid bounceback.
- After waiting, RU2 separates from RU1 and its motor starts to slowly turn the main tether reel.
- After deployment is complete, HV source of RU1 turns on.



Features

- One or two modules per satellite. If two, one of them deploys downward and the other one upward.
- Two modules are sufficient for 800 kg sat at 850 km or 200 kg sat a 1200 km.
- No energy storage devices: we hibernate in eclipse.
- Dynamics was simulated and works OK.
- Power for RU1 and RU2 produced by surface solar panels.
- During deployment (~2 days), satellite's ACS must absorb angular recoil of spring ejection(s).
- After deployment, satellite can passivate itself electrically.
- Less than 100 k€ recurrent cost per module.
- Needed: scalable production of tether.

Mass budget of Base Unit

- The Base Unit is permanently attached to the satellite (either bottom or top).

Table 3: Base unit mass budget.

Part	Material	Mass [g]	Margin	Mass /w margin [g]
Frame	Al	179.0	10 %	196.9
6 M6x15 mounting screws	SS	33.6	5 %	35.3
Tape reel	Plastic	4.4	20 %	5.3
Tape reel axis	Al	0.9	20 %	1.1
Tape reel enclosure	Plastic	8.8	20 %	10.6
Brake mechanism		3.0	20 %	3.6
Cycle counter		2.0	20 %	2.4
Tape	Kapton	19.0	20 %	22.8
Cables and harnesses		10.0	20 %	12.0
Springs	SS	4.5	10 %	5.0
Screw M4x4	SS	1.7	5 %	1.8
		266.9		296.8

Mass budget of Remote Unit 1

- Remote Unit 1 is made as lightweight as possible to reduce tether oscillations.

Table 4: RU1 mass budget.

Part	Material	Mass [g]	Margin	Mass /w margin [g]
Frame	Al	87.2	10 %	95.9
1.0 mm side panels	Al	96.1	5 %	100.9
6 side solar panels		174.0	5 %	182.7
Top and bottom panels	Al	67.1	10 %	73.8
EPS PCB		47.0	20 %	56.4
HV PCB		55.0	20 %	66.0
8 M3x8 screws	SS	8.6	5 %	9.0
Cables and harnesses		8.0	20 %	9.6
Other structural		14.0	20 %	16.8
		557.0		611.1

Mass budget of Remote Unit 2

- Remote Unit 2 mass is set to 1.0 kg to give sufficient tension for main tether during deployment.

Table 5: RU2 mass budget.

Part	Material	Mass [g]	Margin	Mass /w margin [g]
Frame	Al	87.2	10 %	95.9
1.0 mm side panels	Al	96.1	5 %	100.9
6 side solar panels		174.0	5 %	182.7
Top and bottom panels	Al	67.1	10 %	73.8
EPS PCB		47.0	20 %	56.4
HV PCB		55.0	20 %	66.0
Motor phySPACE19		55.0	5 %	57.8
Motor driver electonics		30.0	20 %	36.0
Tether reel	Al	30.7	20 %	36.8
Tether reel mount	Plastic	17.0	20 %	20.4
Pinions	Plastic	9.0	20 %	10.8
Tether 5 km, 5×35 μm	Al	65.0	20 %	78.0
8 M3x8 screws	SS	8.6	5 %	9.0
Cables and harnesses		8.0	20 %	9.6
Other structural		14.0	20 %	16.8
Ballast mass		–	–	149.1
		763.7		1000.0

Conclusions

- The Coulomb drag Plasma Brake is an efficient and low-cost way of deorbiting LEO satellites up to 800 kg mass.
- One module is 2-U form factor, 2 kg mass, below 100 k€ recurrent cost.
- Performance with two modules: 800 kg from 850 km orbit, or 200 kg from 1200 km orbit.
- The satellite's ACS must be functional during deployment, but after that the satellite can perform electric passivation.
- The tether is safe to other space assets.
- Needed: scalable production of tether.