FINNISH METEOROLOGICAL INSTITUTE

Coulomb drag device: long, thin and highly biased cylindrical “probe”

Pekka Janhunen,
Finnish Meteorological Institute

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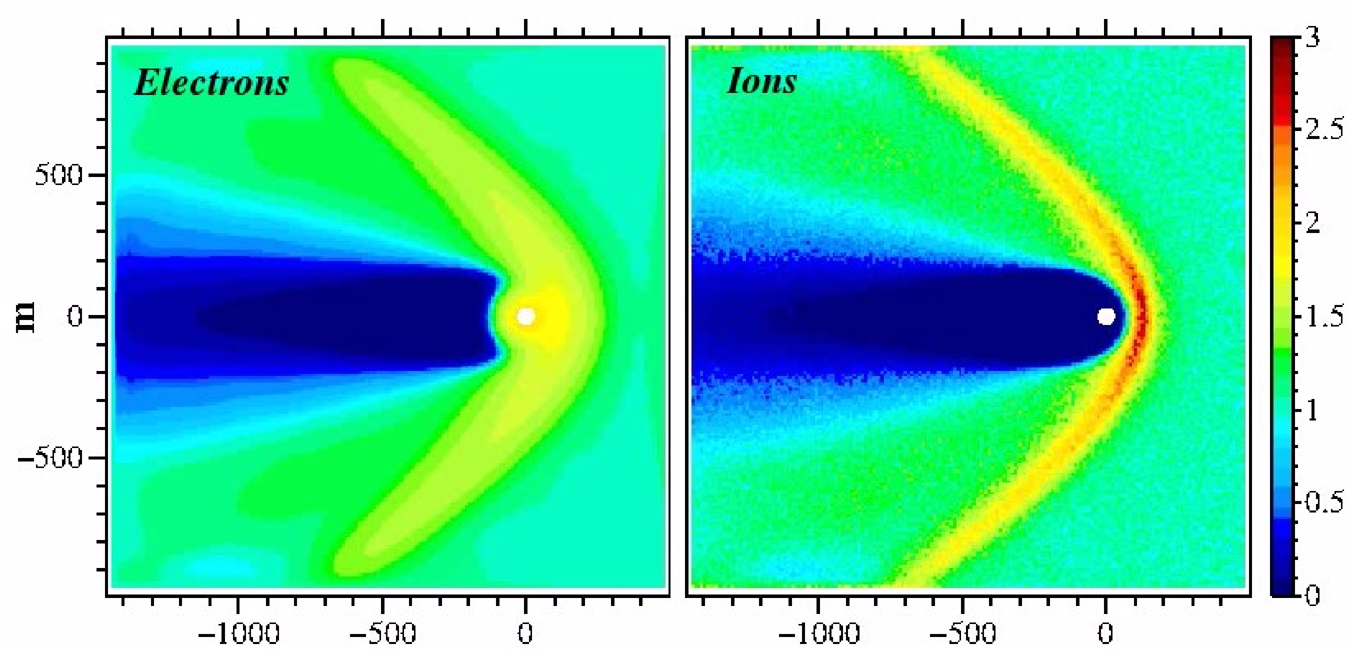
Coulomb drag effect

- Way to harness natural space plasma flows for propulsion
  - Discovered at Finnish Meteorological Institute in 2004-2006
  - Enhanced drag between spacecraft and natural plasma flow
- Two main application domains
  - Solar wind → E-sail, general propulsion outside magnetosphere
  - LEO, ionosphere → satellite deorbiting, space debris elimination
- At least order of magnitude more efficient than existing methods (efficiency = impulse per propulsion system mass)
  - E-sail works like photonic sail, but much higher thrust per mass ratio
  - Plasma brake also has very good performance

Positive polarity case (E-sail)

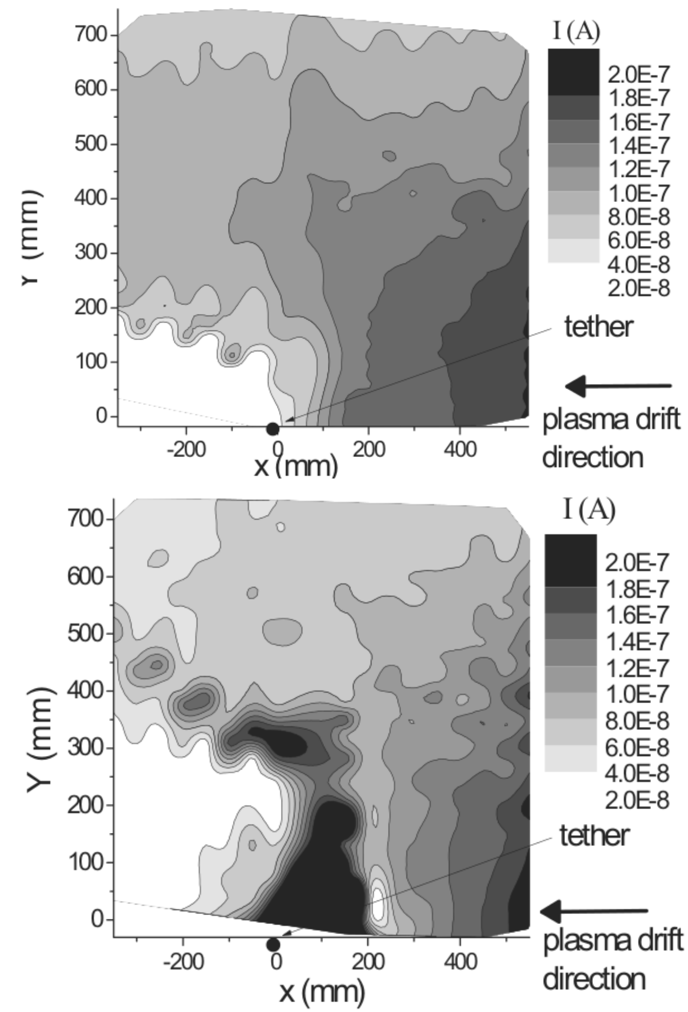


Thrust=350 nN/m

- Boltzmann electron PIC with two additional tricks: 1) power law for attractive & iterate parameter, 2) filter out frequencies higher than ω_{pi}
- Also full PIC simulations done, but slow calculation...
- Trapped electron modelling is the challenge

Positive mode lab experiment

- Siguier et al. (2013): measurement of sheath width around positive (+100 V, +400 V) tether in LEO-like flow
- Estimate thrust from obstacle size==>good agreement with theory if trapped electrons are absent
- This is consistent with “maximal” strength of E-sail effect (no extra shielding by trapped electrons)



Positive mode physics

- We think that Orbital Motion Limited (OML) theory describes electron collection well, because the tether is very thin:

$$\frac{dI}{dz} = en_0\sqrt{\frac{2eV_0}{m_e}}2r_w$$

- Population of trapped electrons forms when voltage is turned on
- In multi-tether E-sail, orbit chaotisation removes trapped electrons in few minute timescale
- Plasma waves might affect the trapped population much faster, although this is hard to model
- In Boltzmann-PIC, we search the least amount of trapped electrons that produces a solution with a single bow shock

Positive mode thrust

- Based on PIC, the following thrust formulas were fitted to it:

$$R = \frac{\tilde{V}\sqrt{2\epsilon_0/P_{\rm dyn}}}{1+\sqrt{1+en_e\tilde{V}/P_{\rm dyn}}} \qquad \tilde{V} \equiv \frac{\max[0, V_0 - V_1 - (en_e/(4\epsilon_0))R^2]}{\log(R/r_w^*)}$$

$$P_{\rm dyn} = m_i n_0 v^2$$

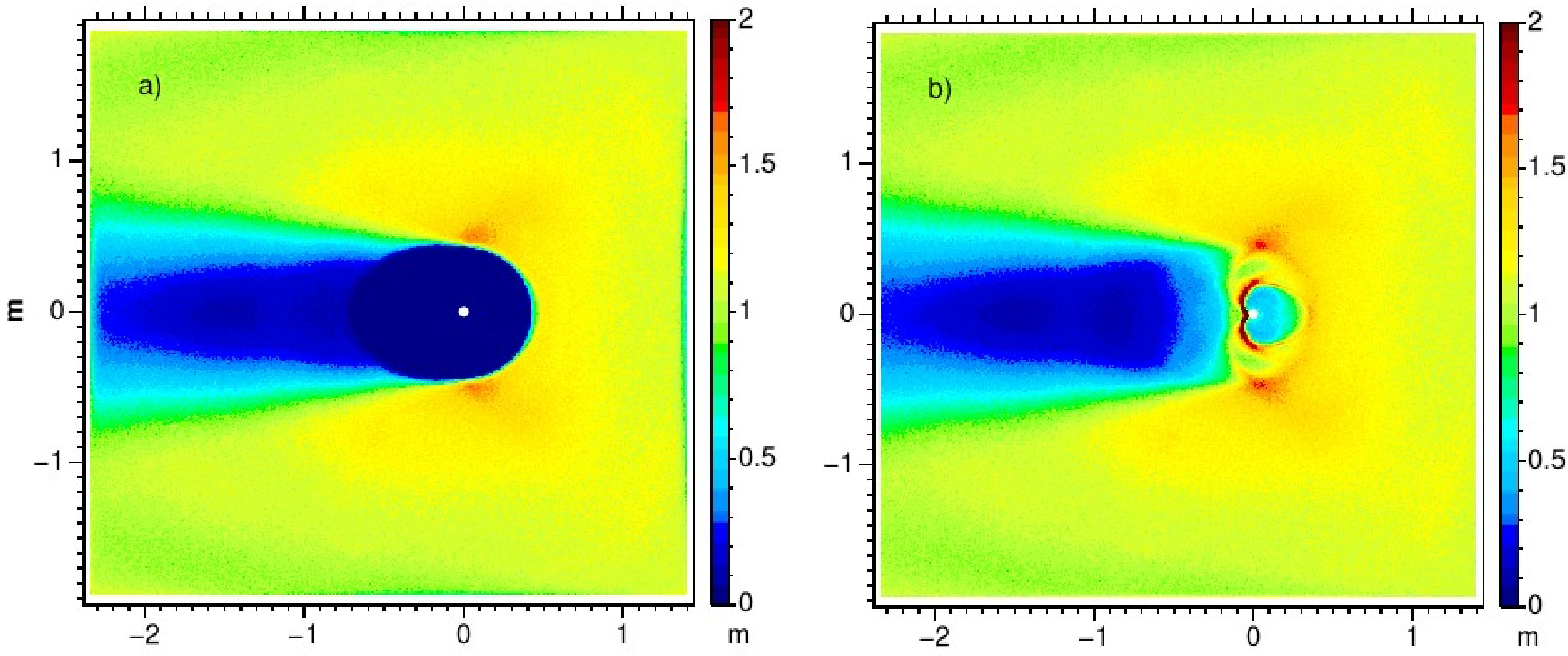
$$\frac{dF}{dz} = K P_{\rm dyn} R, \qquad K = 3.09$$

- Approximation valid for typical solar wind parameters:

$$\frac{dF}{dz} \approx 0.18 \max(0, V_0 - V_1)\sqrt{\epsilon_0 P_{\rm dyn}} \qquad V_1 = (1/2) m_i v^2/e \approx 1 \ \mathrm{kV}$$

- At 1 au and for V_0=20kV, *dF*/*dz*=500 nN/m
- Then raw tether thrust per mass is 45 mN/kg, system thrust 4.5 mN/kg (12 km/s per month, without payload), spacecraft thrust per mass 1 mN/kg=30 km/s/year (if E-sail propulsion system has 20% mass fraction)

Negative polarity (plasma brake)



- LEO parameters
- Electrons left, ions right

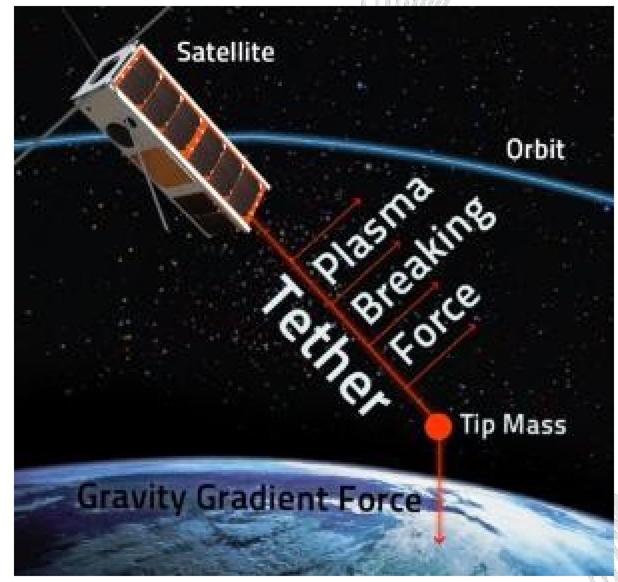
Negative mode physics

- 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:

$$\frac{dF}{dz} = 3.864 \times P_{\rm dyn}\sqrt{\frac{\epsilon_{\rm o}\tilde{V}}{e n_{\rm o}}}\exp\left(-V_i/\tilde{V}\right) \qquad \tilde{V} = \frac{V_w}{\ln(\lambda_D^{\rm eff}/r_w^*)}$$

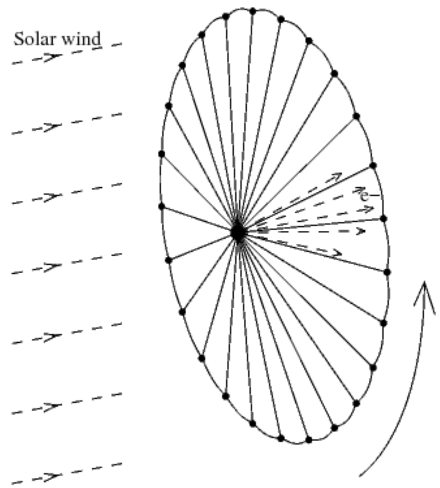
Plasma brake particulars

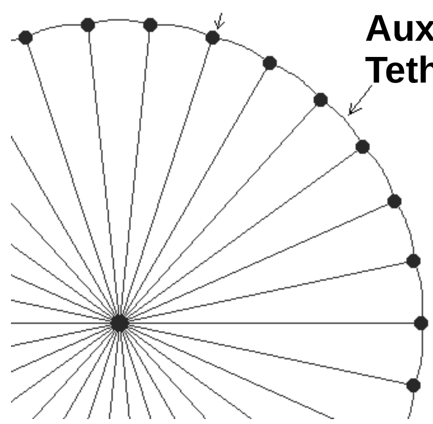
- Equatorial orbit gravity-stabilised tether: laminar
- Polar orbit gravity-stabilised tether: turbulent everywhere; thrust reduced ~27% in high latitudes
- Spinning tether: typically similar behaviour, although depends on spin axis orientation
- Numerical example: 5 km tether, mass 55 grams, 0.43 mN braking force at 800 km, enough to reduce altitude of 260 kg mass by 100 km per year



How to construct E-sail

- Use centrifugal force to stretch tethers
- Use auxtethers to stabilise dynamics
- 20 kV voltage, 0.5 mN/km thrust
- 100x20 km tethers: 1 N thrust at 1 au
- Gives 30 km/s delta-v per year to 1000 kg spacecraft
- Tethers weigh 20 kg, whole E-sail system 100-200 kg
- Modest amount of power: ~700 W





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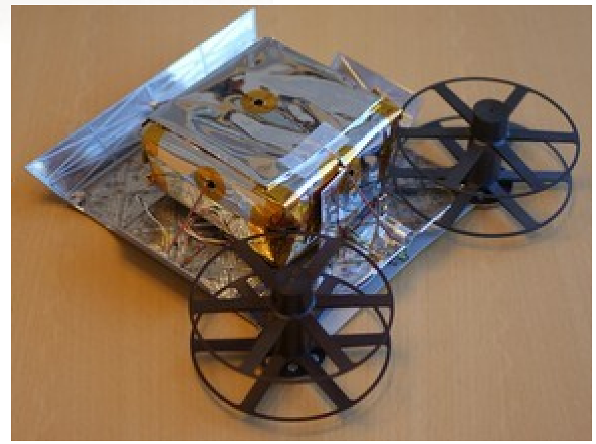
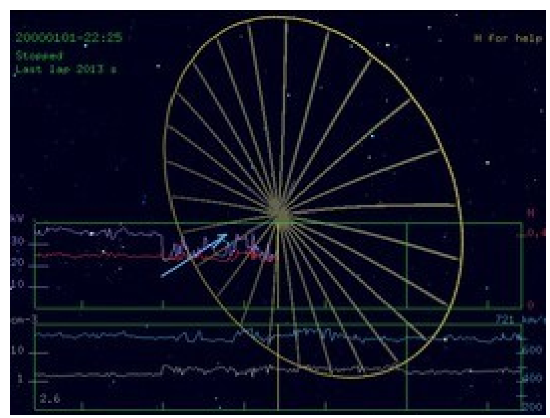
Engineering

- Made 1 km tether

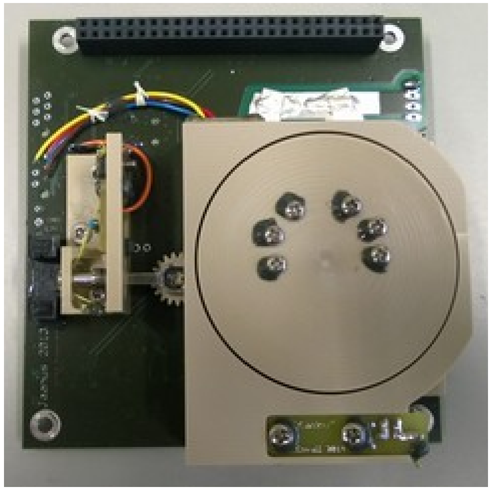
- Made “Remote Unit” for 0.9-4 au

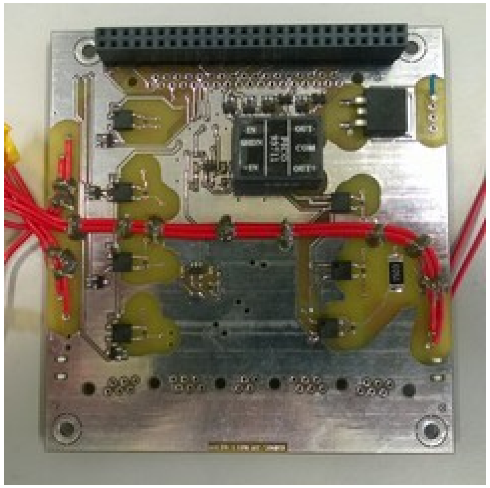


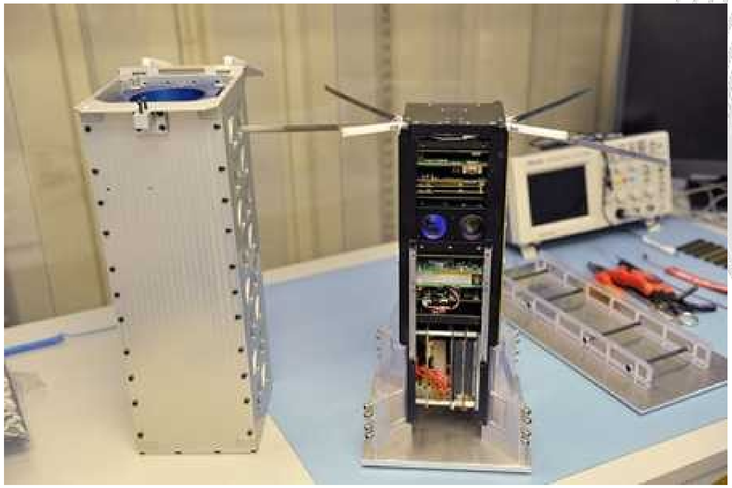
- Made “Flight Simulator”



Aalto-1 3-U cubesat







- Carries 3 experiments (hyperspectral camera, radiation monitor, 100 m tether)
  - Measurement of positive and negative mode Coulomb drag in LEO
    - Positive mode result can be compared with lab experiment and simulation
    - Negative mode experiment can be compared with simulation
  - Mission is also demonstration of Plasma Brake device in orbit
  - 100 m tether can cause clear orbit lowering, full deorbiting is a marginal possibility
- Expected launch June 2016 (Falcon 9)

SC-charging topics of E-sail

- Different tethers have different voltages (requirement of the control algorithm)
- Spacecraft chassis can be either floating or biased at some positive voltage (which is less than lowest tether voltage)
- Metallic tethers experience 20-40 keV accelerated solar wind electron bombardment ==> not a problem
- ~30 μA/m² tether-incident electron current density typical at 1 au (like strong auroral inverted-V event)
- Deep dielectric charging is not an issue
- ~5-10 keV potential differences exist:
    - Across remote units at tips of tethers
    - Between different tethers at main spacecraft
    - Triple junctions must be avoided, as usual

Coulomb drag projects

- *(completed)* ESAIL FP7 project, 2011-2013
- *(completed)* Academy of Finland projects, 2008-2015
- “Asteroid Touring by Electric Sail Technology” ESA TRP project, 2016-2018
- “CleanSat” plasma brake study ESA GSP project, 2016
- NASA Marshall Space Flight Center NIAC Phase 2 project “Heliopause Electrostatic Rapid Transit System” (HERTS), 2015-2016
  - try to measure Coulomb drag in plasma chamber
- Aalto-1 (ready, to be launched in June 2016)
- *(planned)* ESTCube-2: 300 m tether to demonstrate full deorbiting of a cubesat in LEO

Conclusions

- Coulomb drag propulsion is an interesting new concept
- Two application domains: 1) E-sail for interplanetary propulsion, 2) plasma brake for LEO deorbiting
- In both cases, calculations predict very high performance
- E-sail uses positive polarity ~ +20kV, plasma brake uses negative polarity ~ -1kV
- Aalto-1 cubesat (to be launched in May or June) will attempt to measure the magnitude of both positive and negative polarity effects (thrust per tether length) in LEO conditions

E-sail

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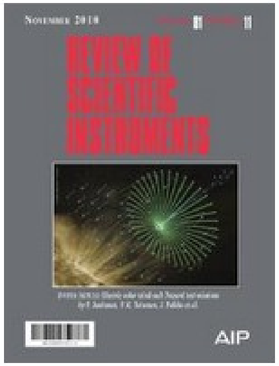

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