FINNISH METEOROLOGICAL INSTITUTE

Electrostatic plasma brake for deorbiting

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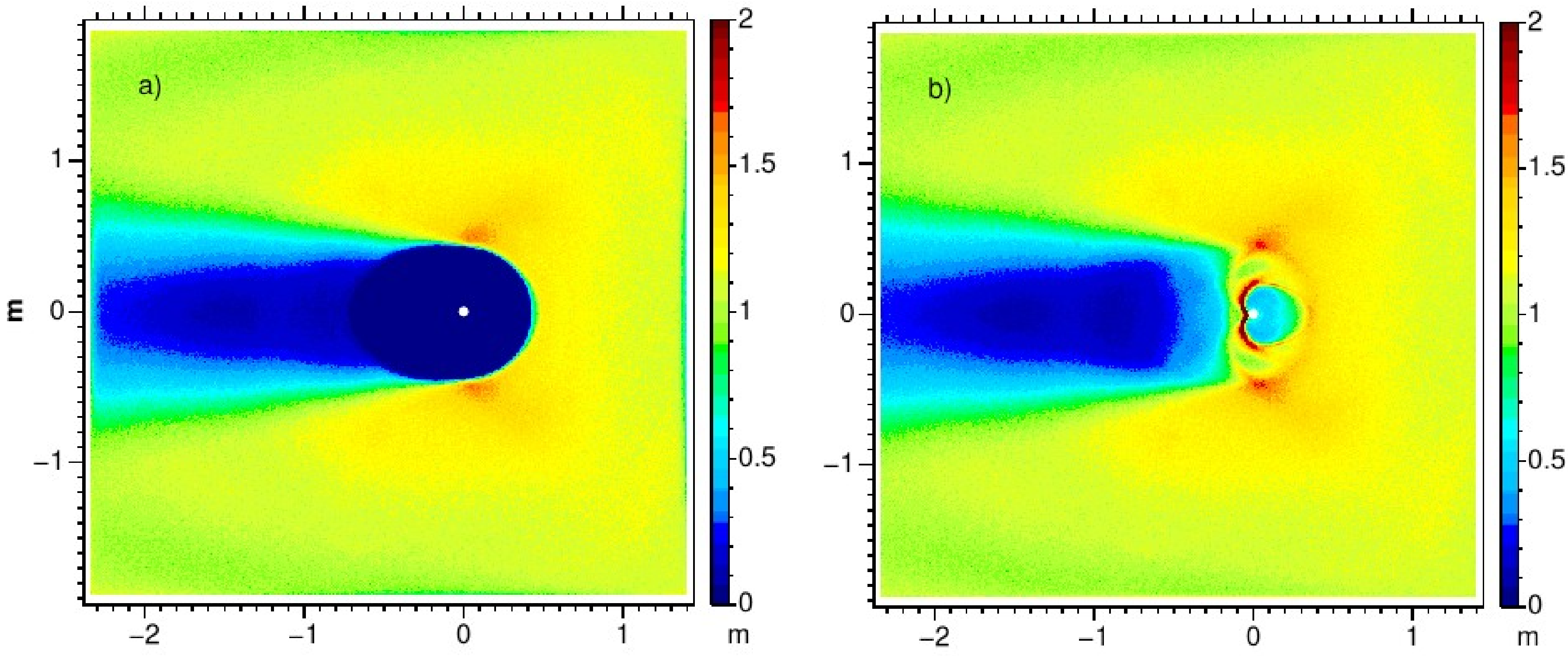
Coulomb drag effect

- 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
    - Using positive tether polarity
  - **LEO, ionosphere → satellite deorbiting, space debris elimination**
    - **Using negative tether polarity**
- Coulomb drag is efficient and propellantless (efficiency = impulse per propulsion system mass)
  - The plasma brake is also ***safe to other space assets***

PIC simulation of plasma brake



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

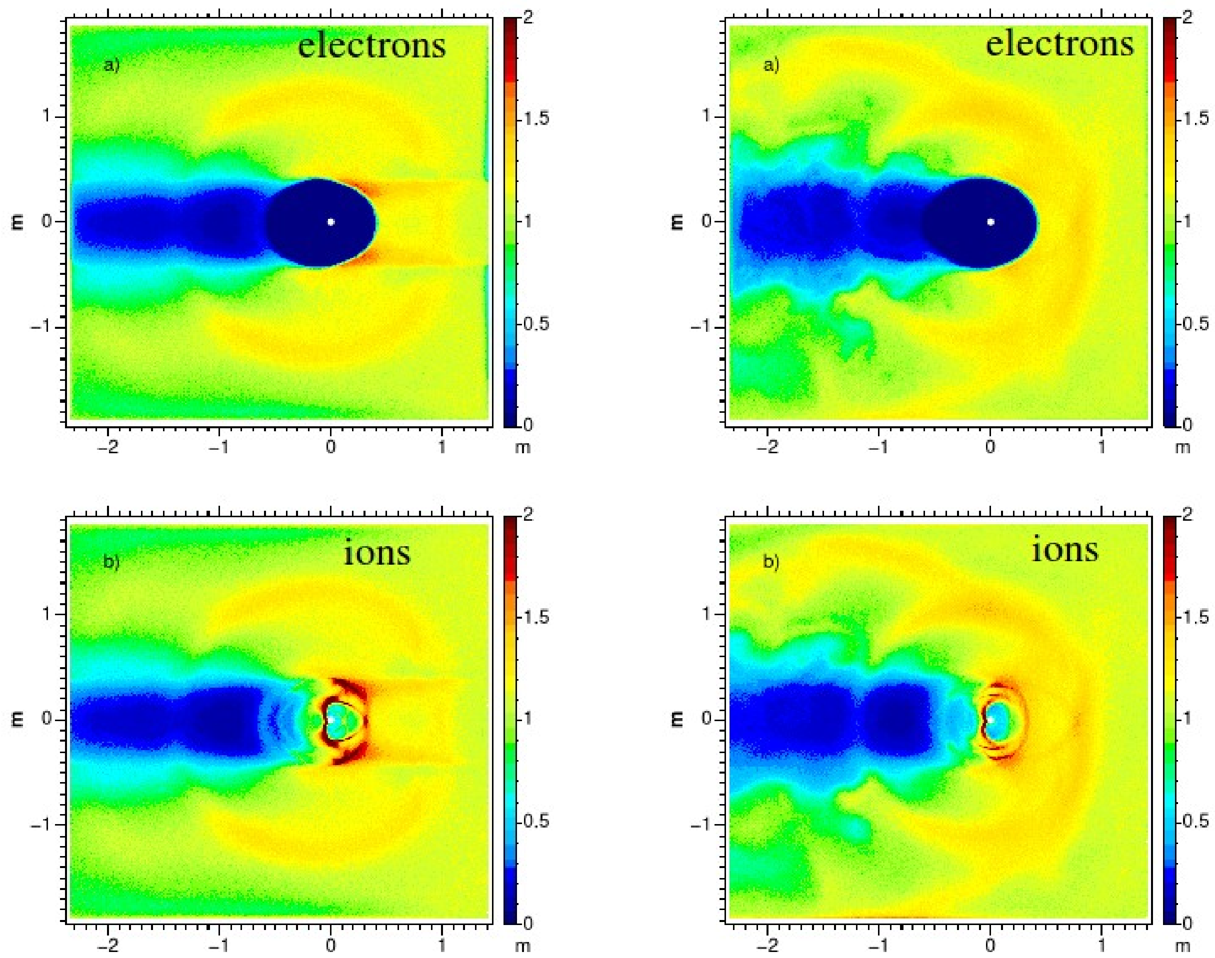
Plasma brake physics

- 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:

$$\frac{dF}{dz} = 3.864 \times P_{\rm dyn}\sqrt{\frac{\epsilon_{\rm o}\tilde{V}}{en_{\rm o}}}\exp\left(-V_i/\tilde{V}\right) \qquad \tilde{V} = \frac{V_w}{\ln(\lambda_D^{\rm eff}/r_w^*)} \qquad \frac{dI}{dz} = en_0\sqrt{\frac{2eV_0}{m_e}}2r_w$$

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

Plasma brake turbulent cases



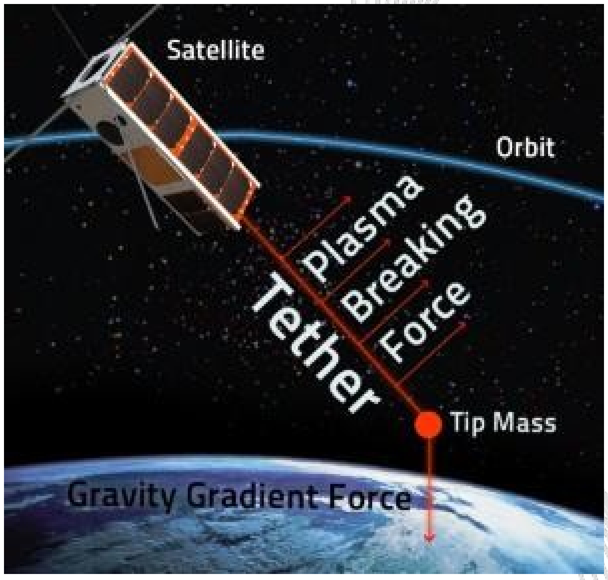
B along flow

B ⊥ to plane

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

Plasma brake particulars

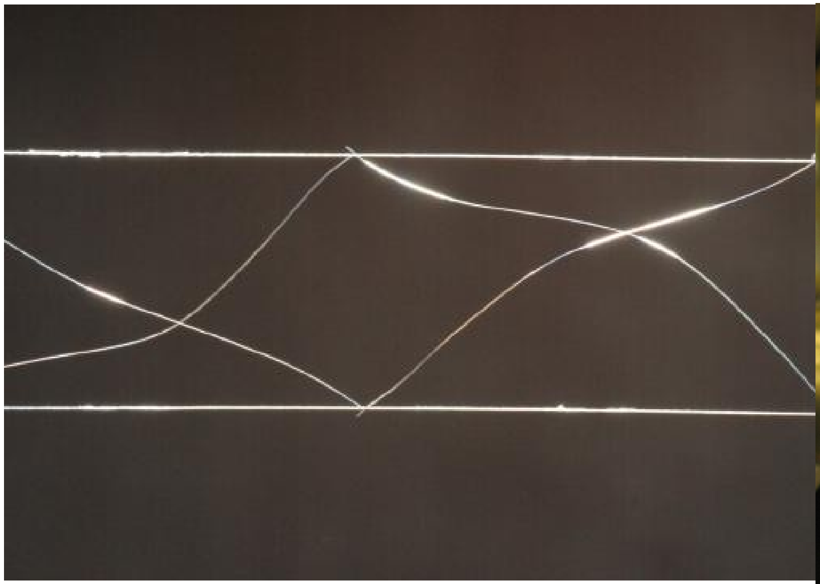
- Equatorial orbit gravity-stabilised tether: laminar
- Polar orbit gravity-stabilised tether: turbulent everywhere; thrust reduced ~27% in high latitudes
- Spinning tether: typically similar behaviour, although depends on spin axis orientation
- <u>Numerical example</u>: 5 km tether, mass 55 grams,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

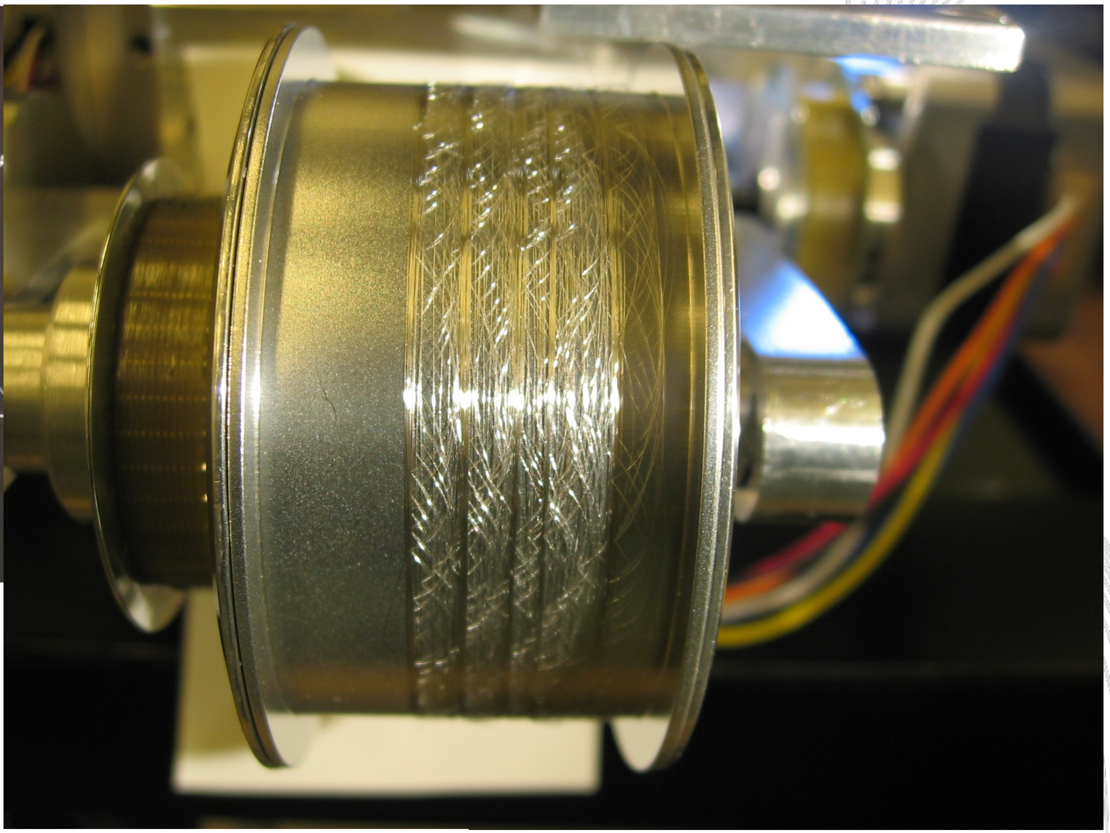


Plasma brake types

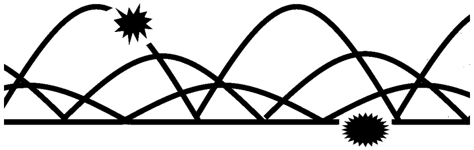
- Single gravity-stabilised tether
  - Up to ~300 kg mass
  - Up to ~1 mN of braking thrust at 800km
- Multi-tether gravity-stabilised configurations
  - Various possibilities, e.g. a cone formed by tethers hanging from spacecraft (downward or upward)
  - Tether mutual distance should be >~1m, otherwise their potential structures overlap and efficiency is reduced
- Spinning multi-tether configurations
  - Use brief positive polarity periods to induce Lorentz force, to control spinrate and spinplane orientation

Plasma brake tethers





- Different tether geometries with 1 or 2 parallel wires

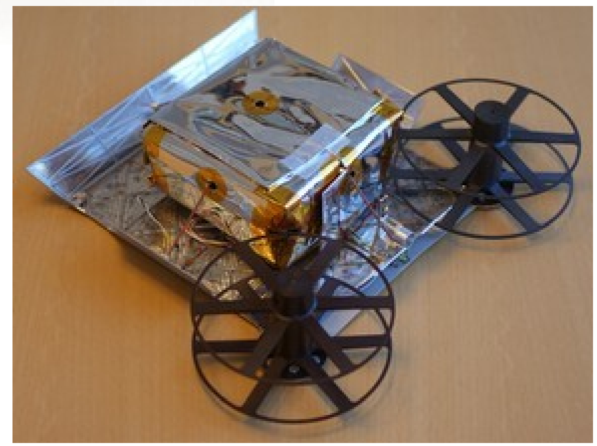


http://www.electric-sailing.fi

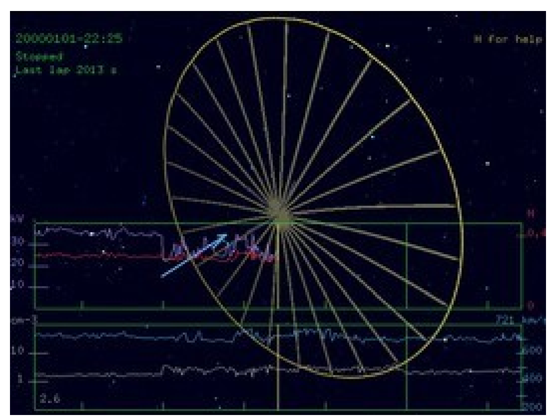
"ESAIL" FP7 project (2011-2013)

- 1 km tether

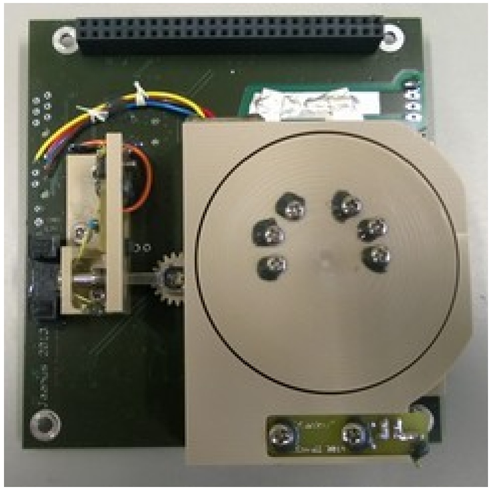
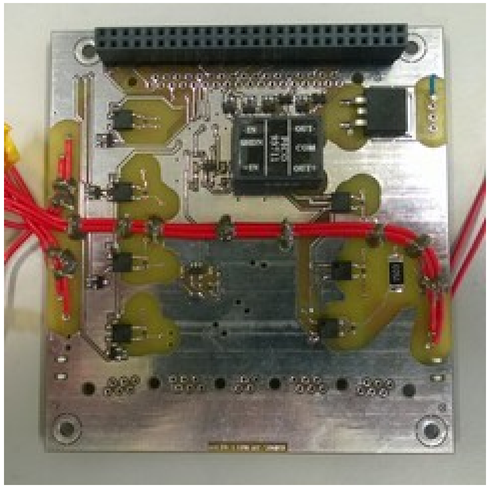
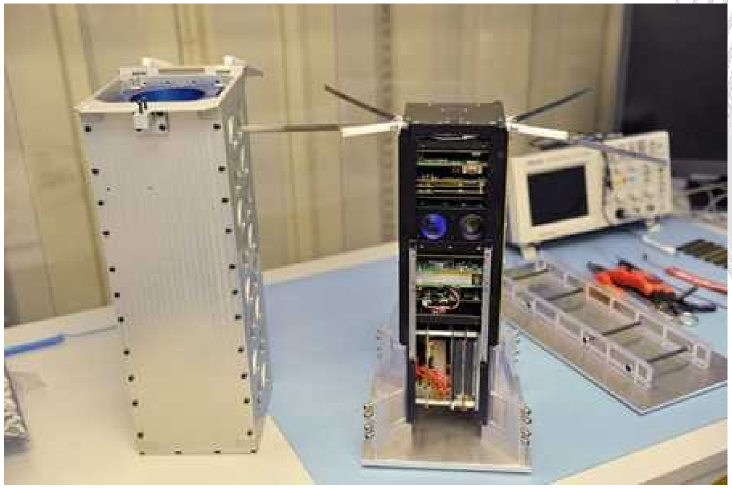
- "Remote Unit" for 0.9-4 au



- "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)

Plasma brake benefits

- Benign system:
  - No chemicals, no SRM dust, no pressure, no tanks, no D4D burden
- Low mass
  - Tether weighs few tens of grams per kilometre
  - Each kilometre produces ~0.1 mN of thrust at 800 km
- Low power consumption, of order 0.5 W per kilometre
- Reduces $\int A dt$, unlike neutral drag augmentation
  - Tether is so thin that it should be safe to other space assets
- Up to ~15 km (1.5 mN) with single tether, higher thrust needs multiple tethers
- (1 mN reduces 600 kg body altitude by 100 km per year.)

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
- The plasma brake seems to be an efficient, safe and benign way of deorbiting primarily smallish masses, although scaling to higher masses is also possible with somewhat more complicated system (many ways to do it, details were omitted).

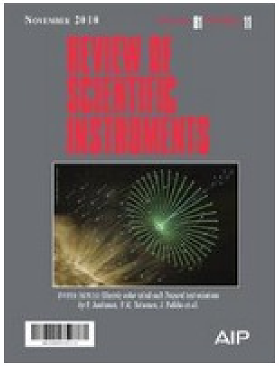
E-sail

www.electric-sailing.fi/publications.html

Electric Solar Wind Sail (E-sail)

Main page | Theory | Technology | Projects | **Publications** | Media | FAQ

Papers, press releases and workshop material



Scientific papers

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2. Janhunen, P. and A. Sandroos, Simulation study of solar wind push on a charged wire: basis of solar wind electric sail propulsion, Ann. Geophys., 25, 755-767, 2007.
3. Mengali, G., A. Quarta and P. Janhunen, Electric sail perfromance analysis, J. Spacecr. Rockets, 45, 122-129, 2008.
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5. Mengali, G., A. Quarta and P. Janhunen, Considerations of electric sail trajectory design, J. British Interpl. Soc., 61, 8, 326-329, 2008.
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7. Janhunen, P., On the feasibility of a negative polarity electric sail, Ann. Geophys., 27, 1439-1447, 2009.
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