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Coulomb drag propulsion

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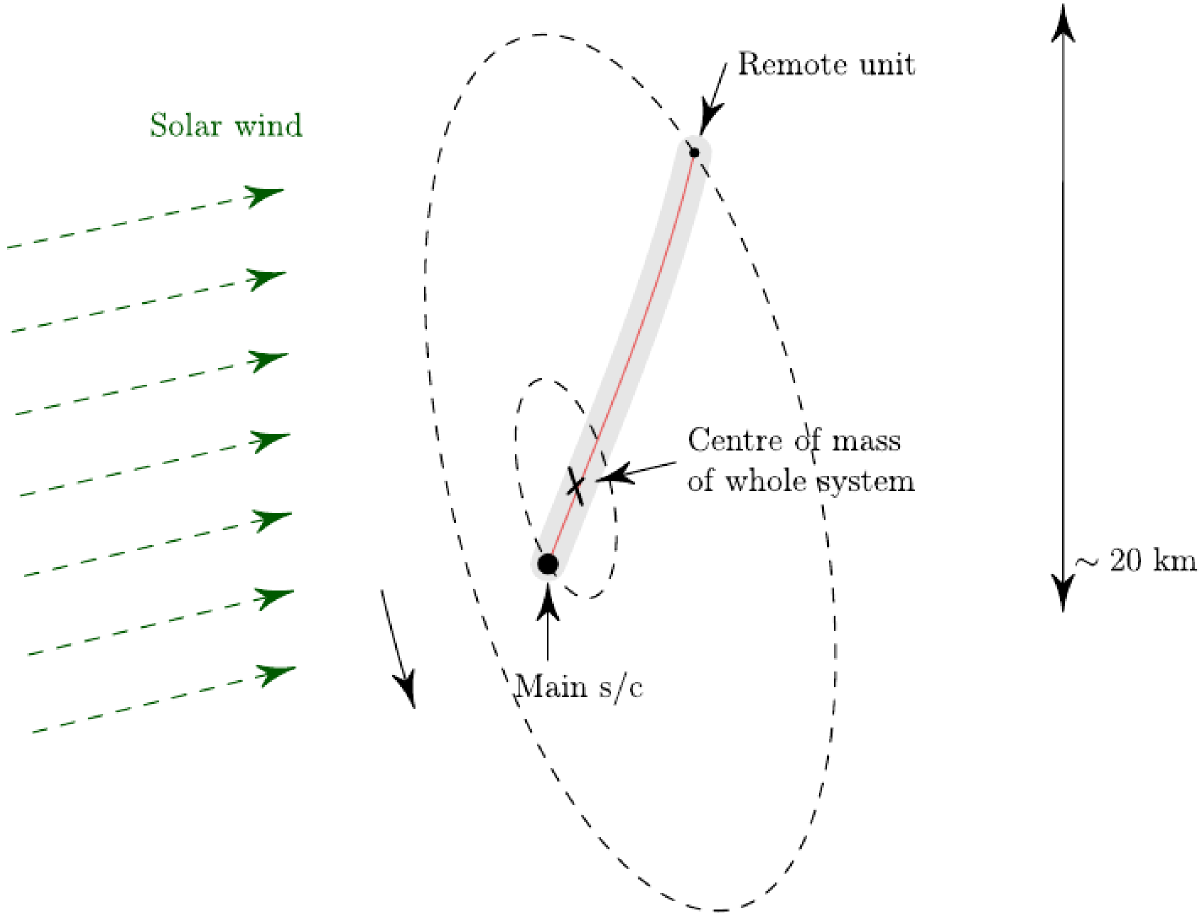
Coulomb drag propulsion

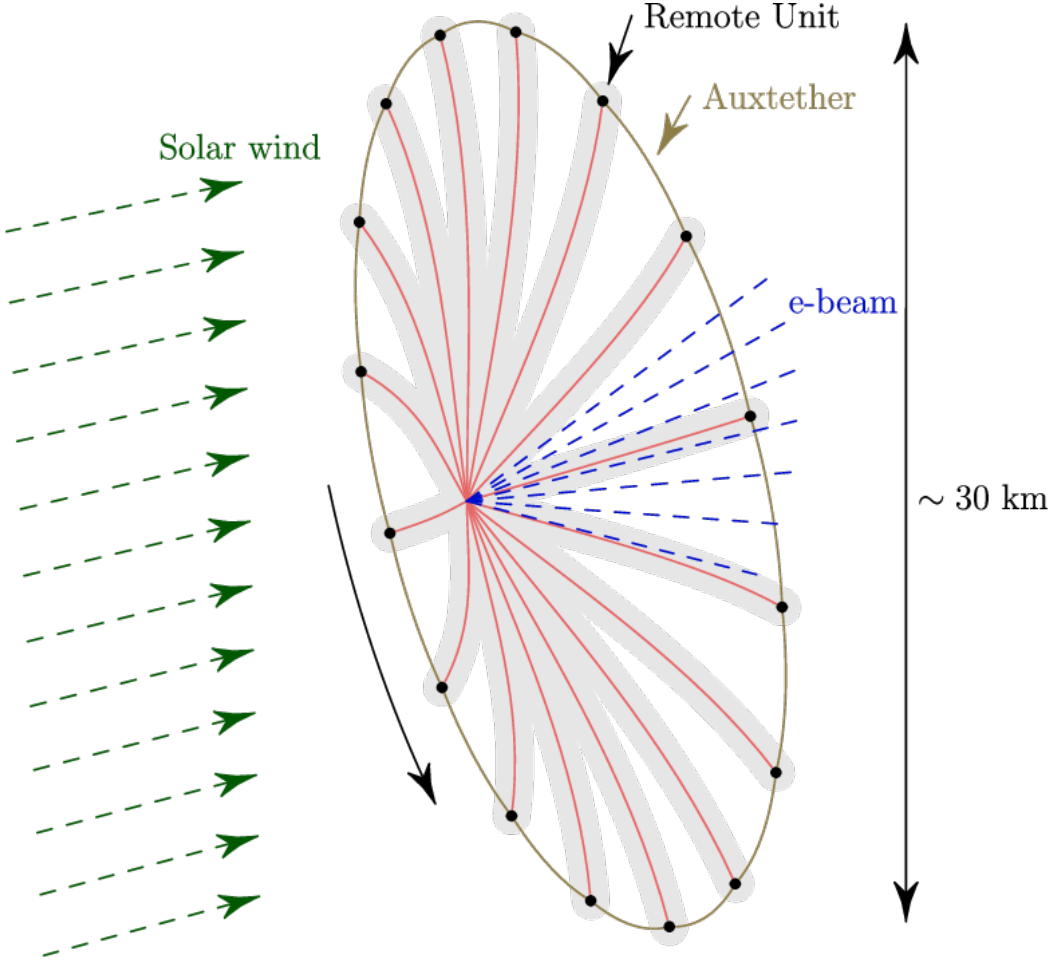
- Charge a tether to high voltage so that its electrostatic field acts as a plasma sail
- Need a natural plasma flow: solar wind, orbital ram flow, etc.
- The tether can be thin, resulting in potentially high intrinsic acceleration
- Small current collection occurs, but is a side product, not a goal
- Maintaining the charge requires power, but the amount is not large
- The process is independent of the magnetic field
  - Works in the solar wind
  - When used in LEO, has (nearly) uniform efficiency at all inclinations
- The process works for both positive and negative tether polarity

Selection of polarity

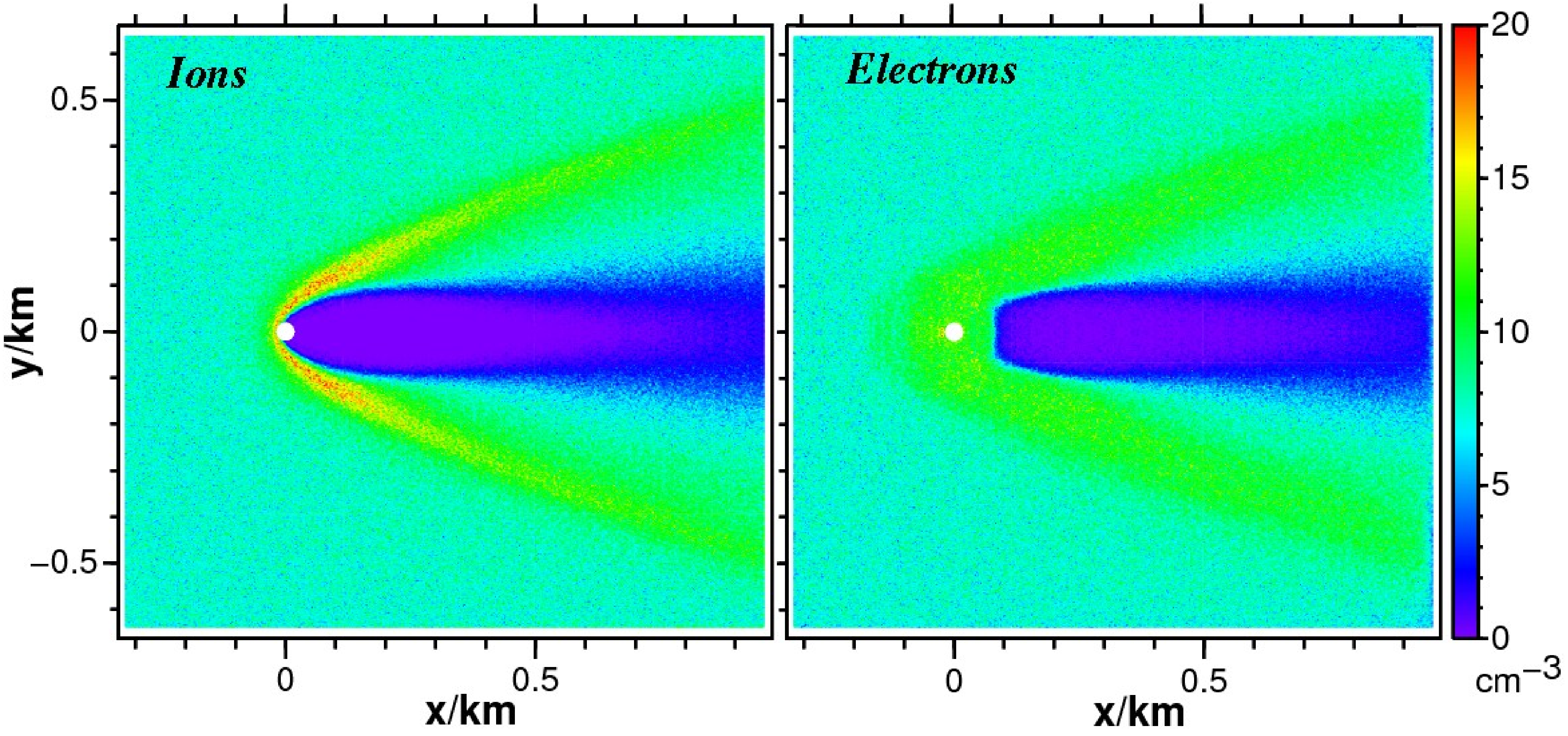
- Negative polarity consumes less power than positive, because ion current collection is much smaller than electron current collection
- But negative polarity is limited to ~ 1 kV due to electron field emission from the surface of thin metallic wires (Fowler-Nordheim emission)
- Solar wind proton kinetic energy is 1-4 keV ==> 1 kV negative tether would deflect ions only weakly ==> use positive polarity in the solar wind (electric sail, E-sail)
- In LEO we can use negative polarity, because 7.8 km/s ram flow oxygen ion kinetic energy is only 5 eV
- Positive polarity (E-sail) needs electron gun
- Negative polarity (Plasma Brake) needs HV source and electron-gathering surface

Single-tether and multi-tether E-sail





PIC simulation of E-sail



E-sail thrust

- Approximate thrust:

$$\begin{aligned} \frac{dF}{dz} &= 0.18\,(V_0 - V_1)\sqrt{\epsilon_0 P_{\text{dyn}}} \\ P_{\text{dyn}} &= \rho v^2 \\ V_1 &\approx 1\ \text{kV} \\ V_0 &\sim 20\ \text{kV} \end{aligned}$$

- 500 nN/m (average solar wind at 1 au, at 20 kV voltage)
- More accurate formula exists (Janhunen et al., 2010), but requires iteration
- Thrust scales as 1/*r* !

E-sail power consumption

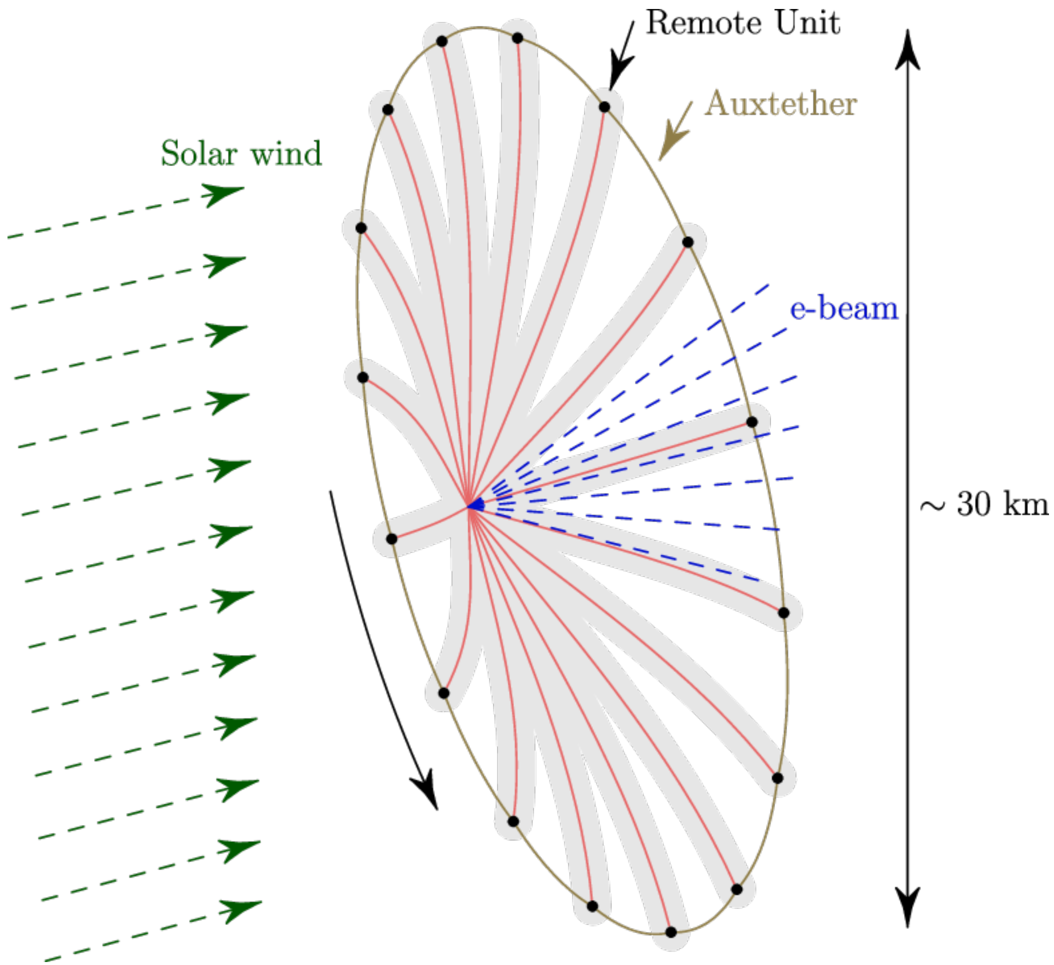
- OML theory electron current collection:

$$\frac{dI}{dz} = en_0\sqrt{\frac{2eV_0}{m_e}}4.3(2r_w)$$

- 20 nA/m (average solar wind at 1 au, at 20 kV voltage)
- Power consumption 0.4 mW/m
- Power per thrust: (0.4 mW/m) / (500 nN/m) = 800 W/N
  - ~ 25 times less than for Hall thrusters which have typically ~ 20 kW/N
- Power consumption scales the same as solar panel power: ~ $1/r^2$

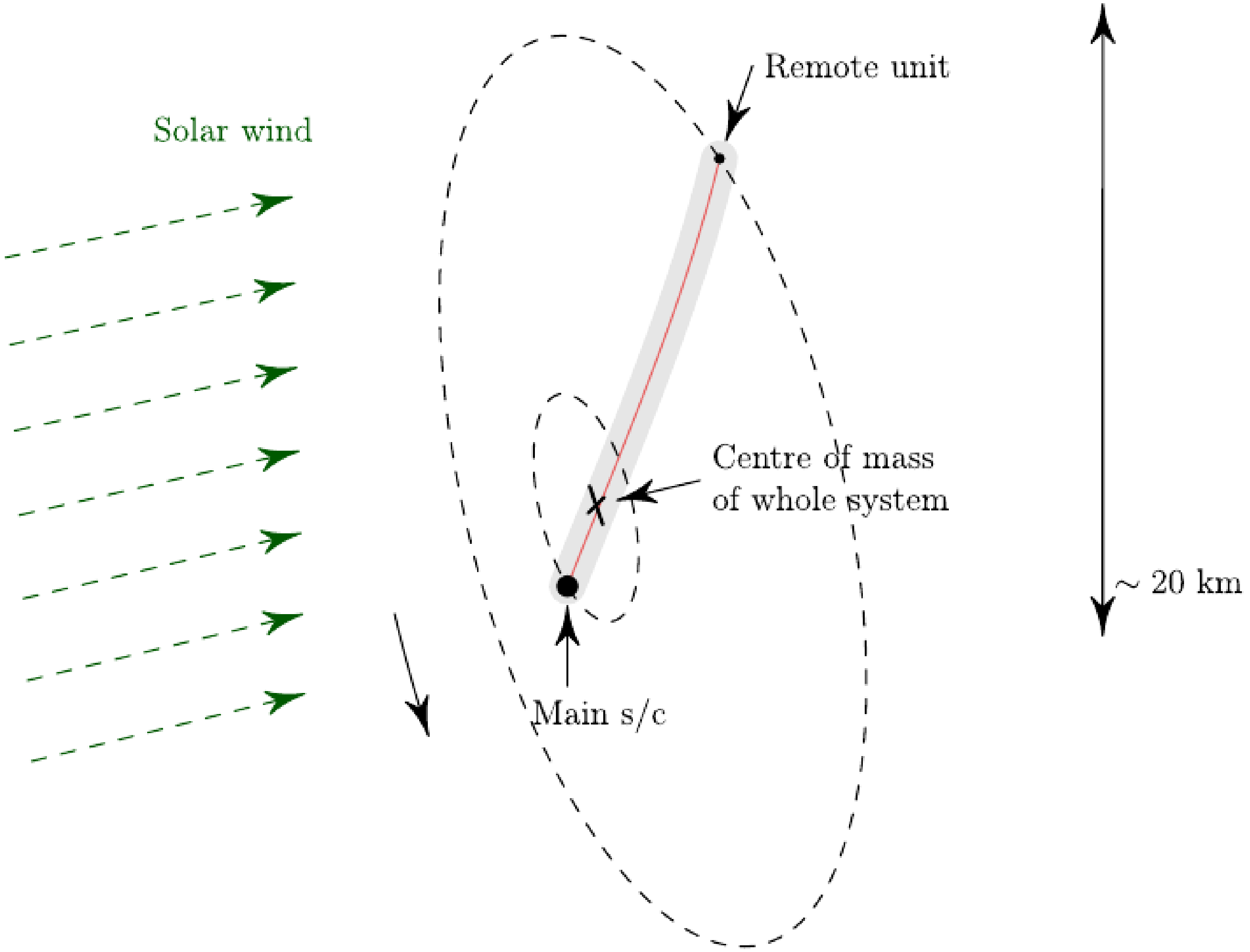
Control of multi-tether E-sail

- Thrust magnitude is controlled by changing the voltage and/or current of the electron gun
- Thrust vectoring = spin plane turning by differential voltage modulation
- Secular spin rate change if orbiting Sun with inclined sail ~ exp(Ω t tan α)
- Can be overcome by modulating auxtether voltages (”TI-modulation”)



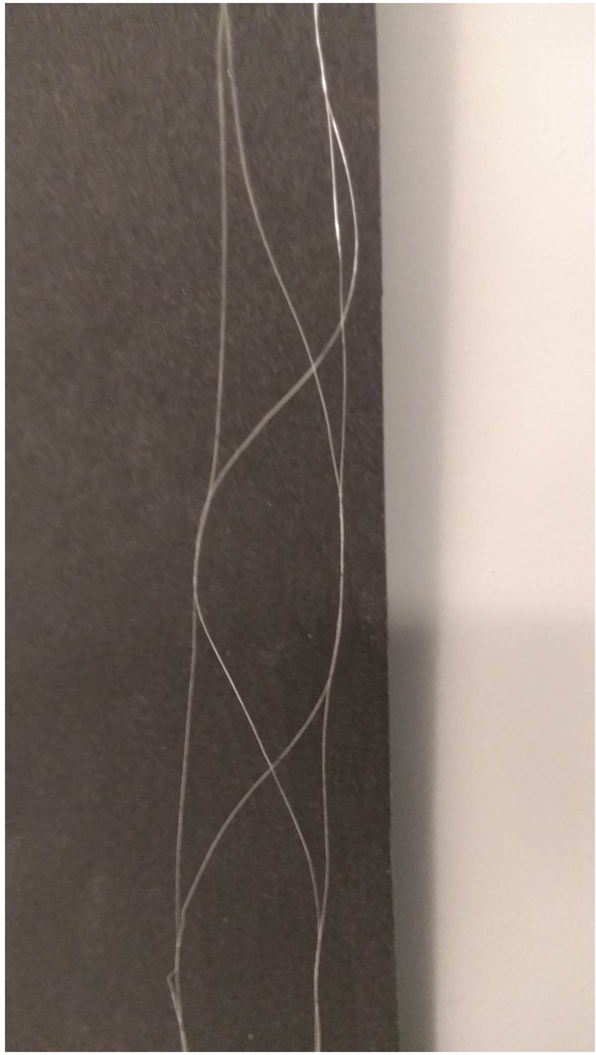
Control of single-tether sail

- Single-tether sail for Interplanetary Cubesat
- Remote Unit needs auxiliary propulsion to start spin (and to overcome secular spin rate change if angle around Sun is significant)
- The main spacecraft can do pointing freely, if tether is attached at its centre of mass
- Multi-Asteroid Touring (MAT): flyby imaging

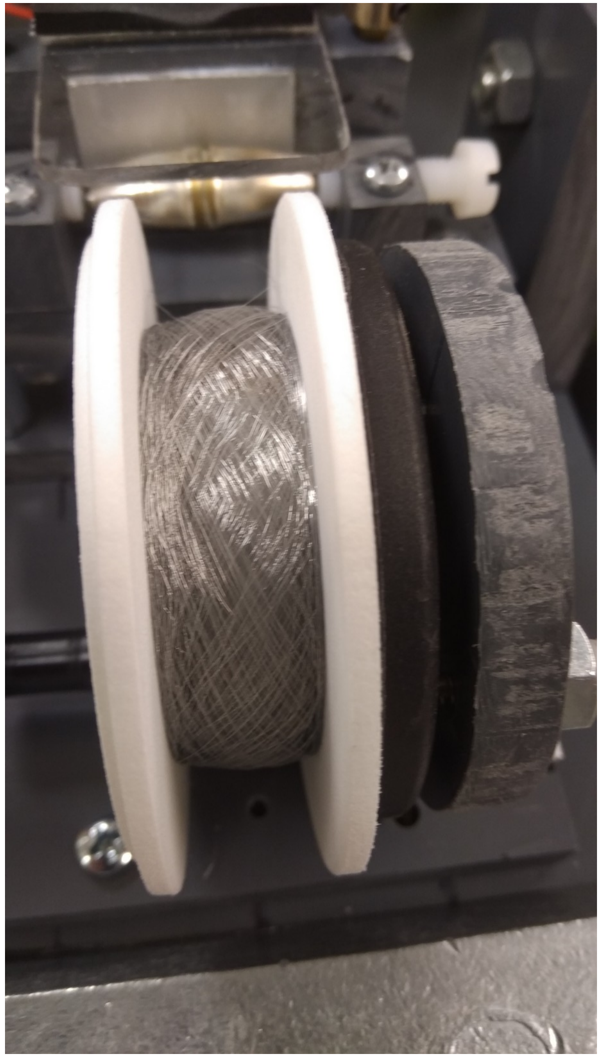


Microtether

- 4-wire Hoytether made of 50 µm aluminium wire (Al-2024)
- Micrometeoroid-resistant
- The bonds are made by twisting
- Can reduce wire thickness to 32 µm, then 25 µm, we started with 50 µm to ease handling

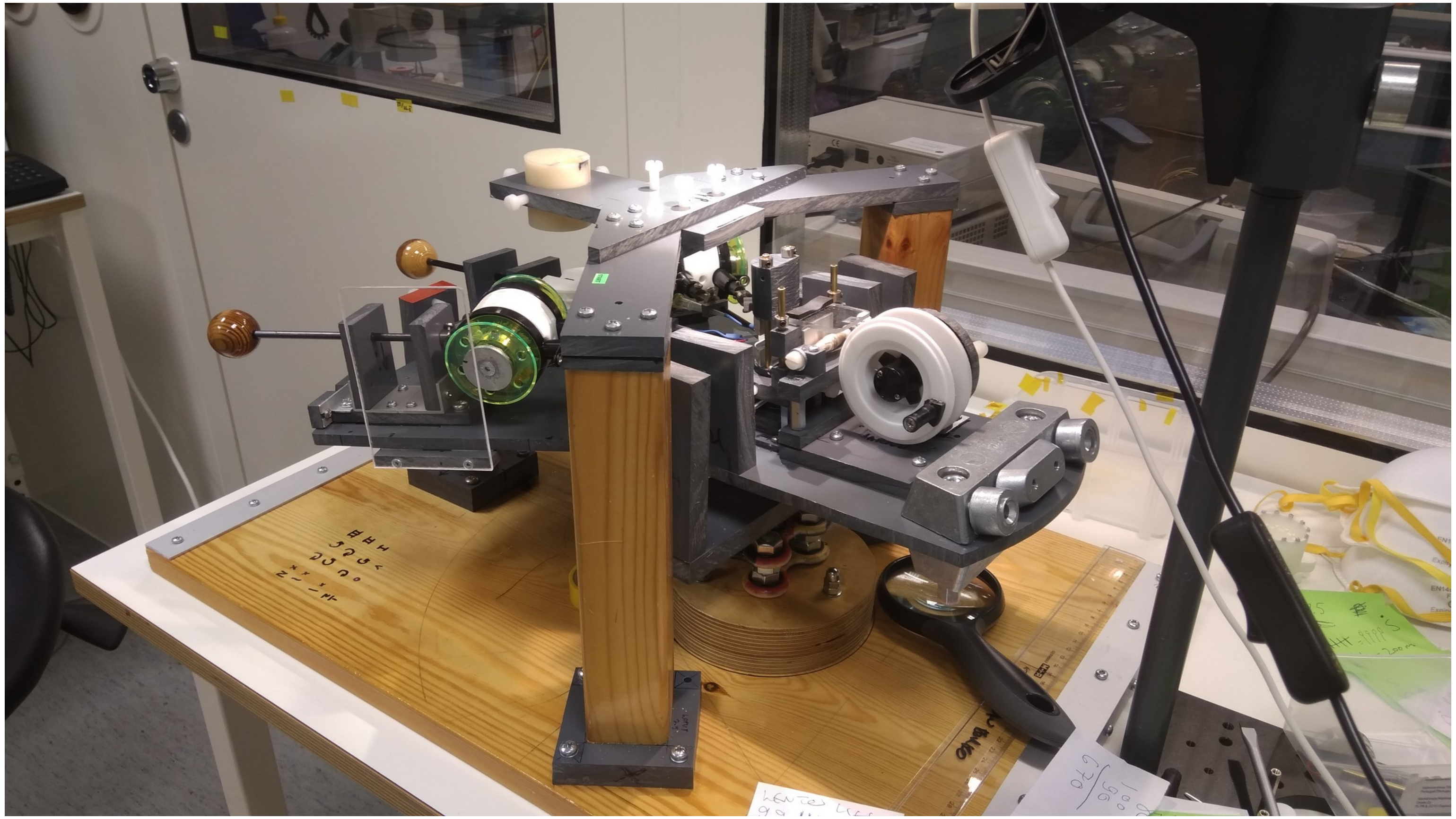


Tether width 1.5 cm



Tether length 60 m

FMI’s manual tether factory



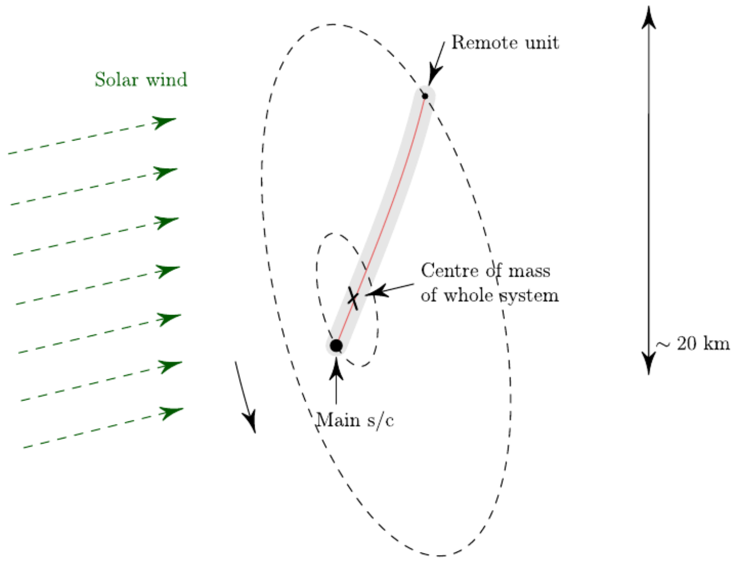
- In progress: automation

ESTCube-2 experiment

- CubeSat experiment payload of ESTCube-2 satellite
- ESTCube-2 is multi-payload Estonian 3-U cubesat built at Tartu University
- Launch schedule: Aug-Sep 2023
- Launcher: Vega

Exemplary missions

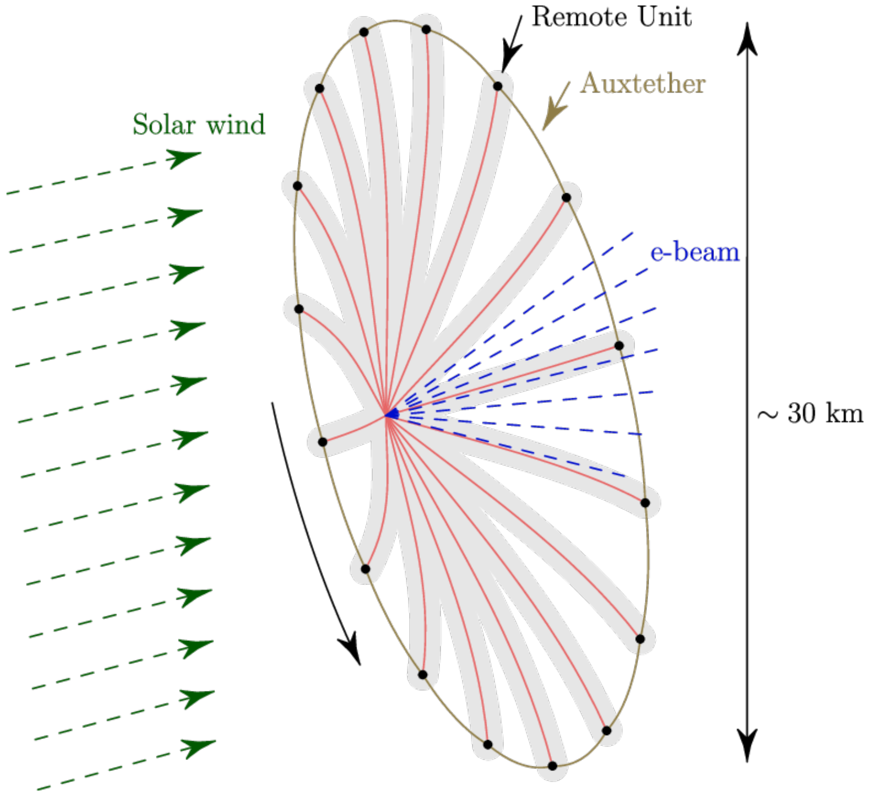
- Multi-Asteroid Touring (MAT)
  - flyby imaging of 500 asteroids by fleet of 50 3-U sats using single tether E-sails
  - data returned at end by Earth flyby
  - ESA proposal 2016, developed since then (Iakubivskyi et al., *Adv. Space Res.,* 2021)
- ”NorthStar” (Aurora Propulsion Technologies, https://aurorapt.fi)
  - multi-tether sun-powered 25 kg mission at 100 km/s speed out of solar system
  - triple-use inflatable solar collector as parabolic dish antenna and E-sail frame
  - stays functional up to 30 au



- Off-Lagrange point solar wind monitoring
  - longer warning time for space weather
- Plasma Brake – ongoing ESA ARTES ”Dragliner” project
  - LEO satellite deorbiting

Flying fast outward

- 0.5 mN/kmTether at 1 au, if voltage is 20 kV
- E.g., 30 tethers, 20 km long, 0.3 N
- Tether 5.7 gram/km (4-fold 25 µm Al), total 3.4 kg
- HV power consumption 220 mW/km, 130 W
- Thrust ~ 1/*r*, Power ~ $1/r^2$
- Assume reels+HV+remoteunits+auxtethers weigh 7x tether ==> total mass 25 kg, acceleration 12 mm/s^2 = 32 km/s/month
- Roughly, 100 km/s and 25 kg payloads are within reach
- Solar manoeuvre probably not needed



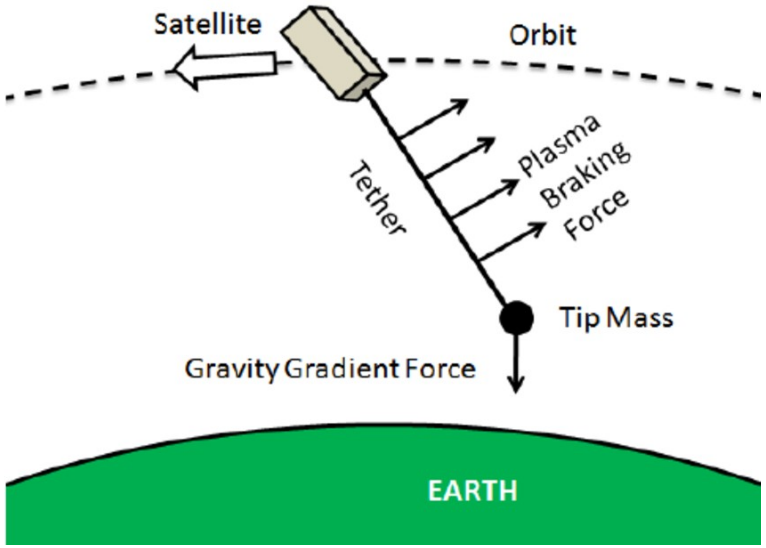
100 kg payload to 200 au by E-sail

(My calculation from 2010)

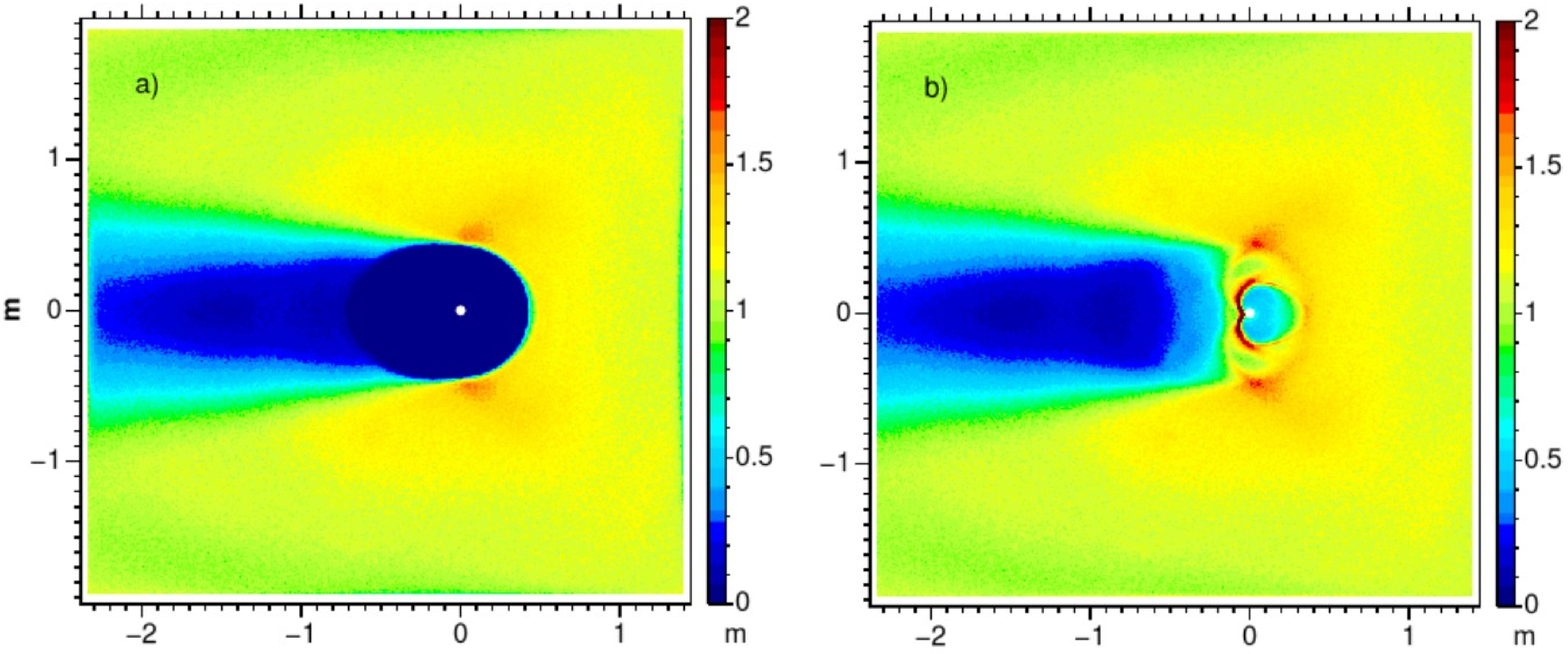
Payload	Total	Final v	Time to 200 AU	
0 kg	69 kg	112 km/s	8.6 years	
25 kg	94 kg	98 km/s	9.9 years	
50 kg	119 kg	88 km/s	11.0 years	
75 kg	144 kg	81 km/s	12.0 years	
100 kg	169 kg	75 km/s	12.9 years	<-- preferred case with zero payload margin
125 kg	194 kg	70 km/s	13.8 years	<-- preferred case with 25% paload margin
150 kg	219 kg	66 km/s	14.7 years	<-- preferred case with 50% payload margin
200 kg	269 kg	56 km/s	16.3 years	<-- still acceptable case, 100% payload margin
250 kg	319 kg	52 km/s	17.8 years	
300 kg	369 kg	48 km/s	19.3 years	
350 kg	419 kg	46 km/s	20.8 years	
400 kg	469 kg	43 km/s	22.2 years	
450 kg	519 kg	41 km/s	23.7 years	
500 kg	569 kg	38 km/s	25.1 years	

Plasma brake

- Negative polarity Coulomb drag sail in LEO
- For deorbiting of satellites and upper stages
- Max ~5 km tether (limited by material conductivity and tensile strength)



PIC simulation of Plasma Brake



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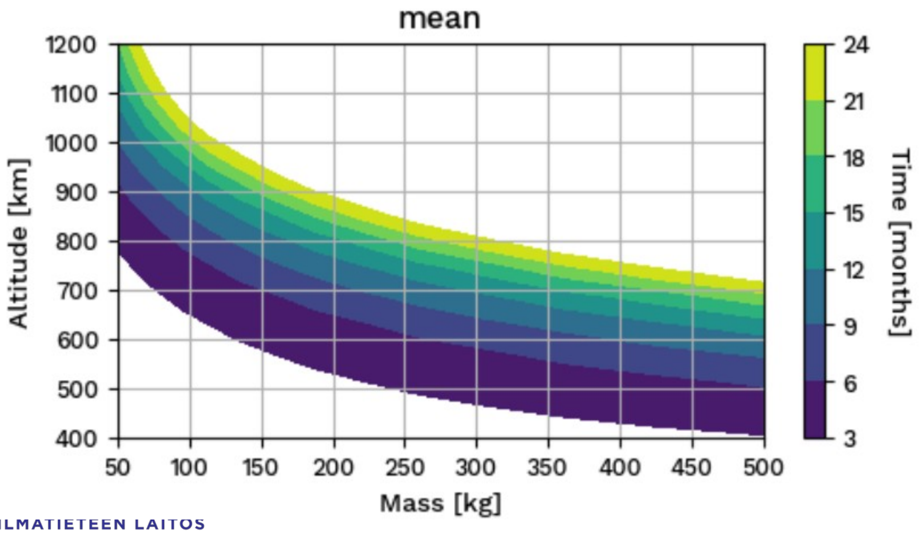
Plasma Brake thrust

- Approximate thrust:

$$\frac{dF}{dz} = 3.864 \times P_{\rm dyn} \sqrt{\frac{\epsilon_{\rm o} \tilde{V}}{e n_{\rm o}}} \exp\left(-V_i/\tilde{V}\right)$$

- ~ 87 nN/m (at $3 \cdot 10^{10}$ m^{-3} plasma density and 10 amu mean ion mass, at 1 kV)



Plasma Brake power consumption

- OML theory ion current collection:

$$\frac{dI}{dz} = \chi \cdot e n_0 \sqrt{\frac{2eV_0}{m_i}} 4.3(2r_w), \qquad \chi = 1..2$$

- 200 nA/m (at $3 \cdot 10^{10}$ m^{-3} plasma density and 10 amu mean ion mass, at 1 kV)
- Power consumption 0.2 mW/m
- Power per thrust: (0.2 mW/m) / (87 nN/m) = 2 kW W/N
  - ~ 10 times less than for Hall thrusters which have typically ~ 20 kW/N

Safety of Plasma Brake tether

- Collision of the 5 km long Plasma Brake tether with a debris satellite or active satellite is unlikely, but cannot be excluded (the probability is ~1 % per year)
- But 50 µm tether makes only a ~0.1mm scratch to satellite surface
- Scratches of this depth occur all the time in satellites by the natural micrometeoroids and existing orbital debris
- Thus we consider the Plasma Brake essentially safe to other space assets
- (Except if two Plasma Brake tethers collide, then both are severed. But that starts to be a concern only if there are ~10000 Plasma Brakes in orbit simultaneously.)

Coulomb drag projects and events

- E-sail (Janhunen, 2006)
- Plasma Brake (Janhunen, 2010)
- EU project ”ESAIL” (2011 - 2013)
  - Ultrasonically bonded 1 km long tether (Seppänen et al., 2013)
- ESTCube-1 launch (2013)
- ESA TRP project ”Asteroid touring by electric sail technology” (2015 - 2019)
- ESA CleanSat Plasma Brake study: TRL 3 of Plasma Brake Module (2017)
- Aurora Propulsion Technologies (https://aurorapt.fi) founded (2018)
- ESA ”Dragliner”: TRL 4 Plasma Brake Module for Telecom satellites (2022 -)
- ESTCube-2 (2023) and FORESAIL-1 Prime (2024)

Other studies and related activities

- NASA MSFC ”HERTS” SBIR project (~ 2014 - 2015): plasma lab experiment etc.
- Pisa University (Italy) E-sail trajectory optimisation calculations (~ 2008 -)
- Chinese E-sail control algorithm studies (~ 2018 -)
- Tartu University (Estonia) student satellite programme
  - ESTCube-1 (2013)
  - ESTCube-2 (2023 (?))
  - ESTCube-3 (lunar orbit – under planning)
- FORESAIL – Finnish Centre of Excellence of Research of Sustainable Space
  - Includes FORESAIL cubesats (Foresail-1, Foresail 1 Prime, Foresail-2 & 3)
- Etc.

Coulomb drag summary

- Single-tether E-sail for interplanetary cubesats
- Multi-tether E-sail for up to ~ 0.3-1 N thrust
- E-sail thrust decays only as 1/*r*
- Plasma Brake to deorbit any D4D satellite or upper stage using few kilogram package
- Plasma Brake microtether is safe to other orbital assets (except to other Plasma Brakes)