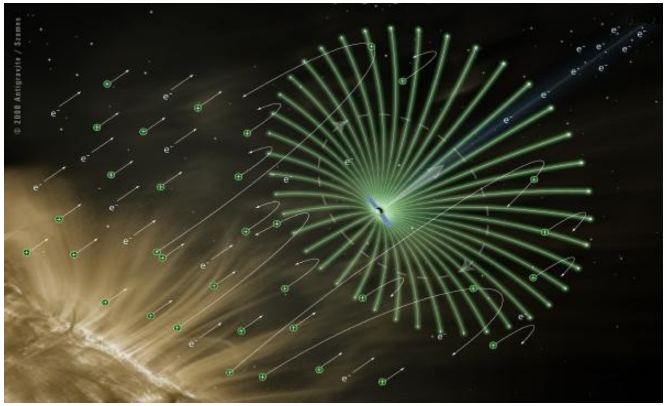

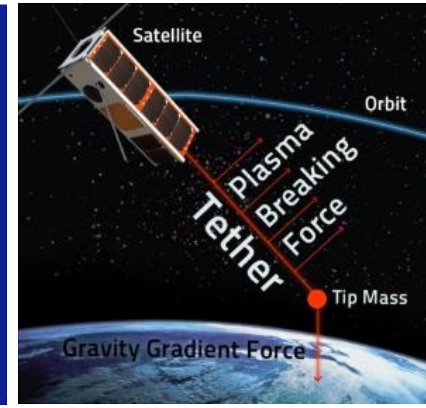

Space exploration with electric solar wind sail

Tartu Conference on Space Science and Technology, 22-24 September, 2014, Tõravere, Estonia

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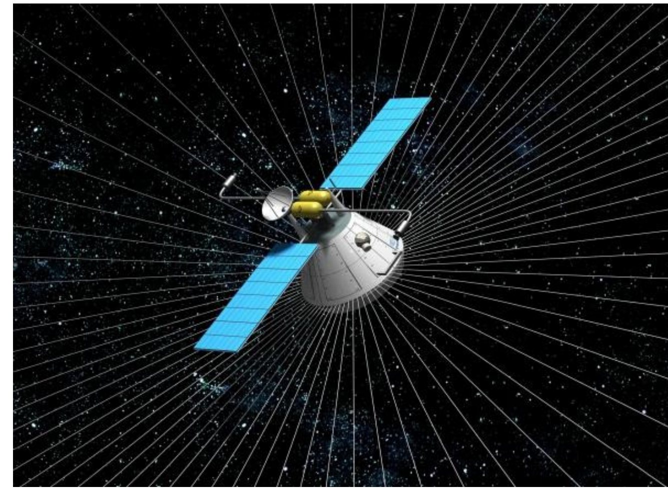
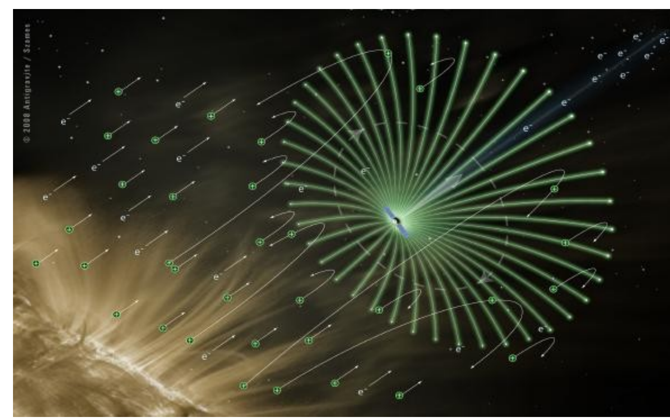
Contents

- Positive and negative polarity Coulomb drag phenomena
- Positive polarity E-sail
- Negative polarity plasma brake
- ESTCube-1 and Aalto-1 CubeSats
- E-sail applications
- Conclusions





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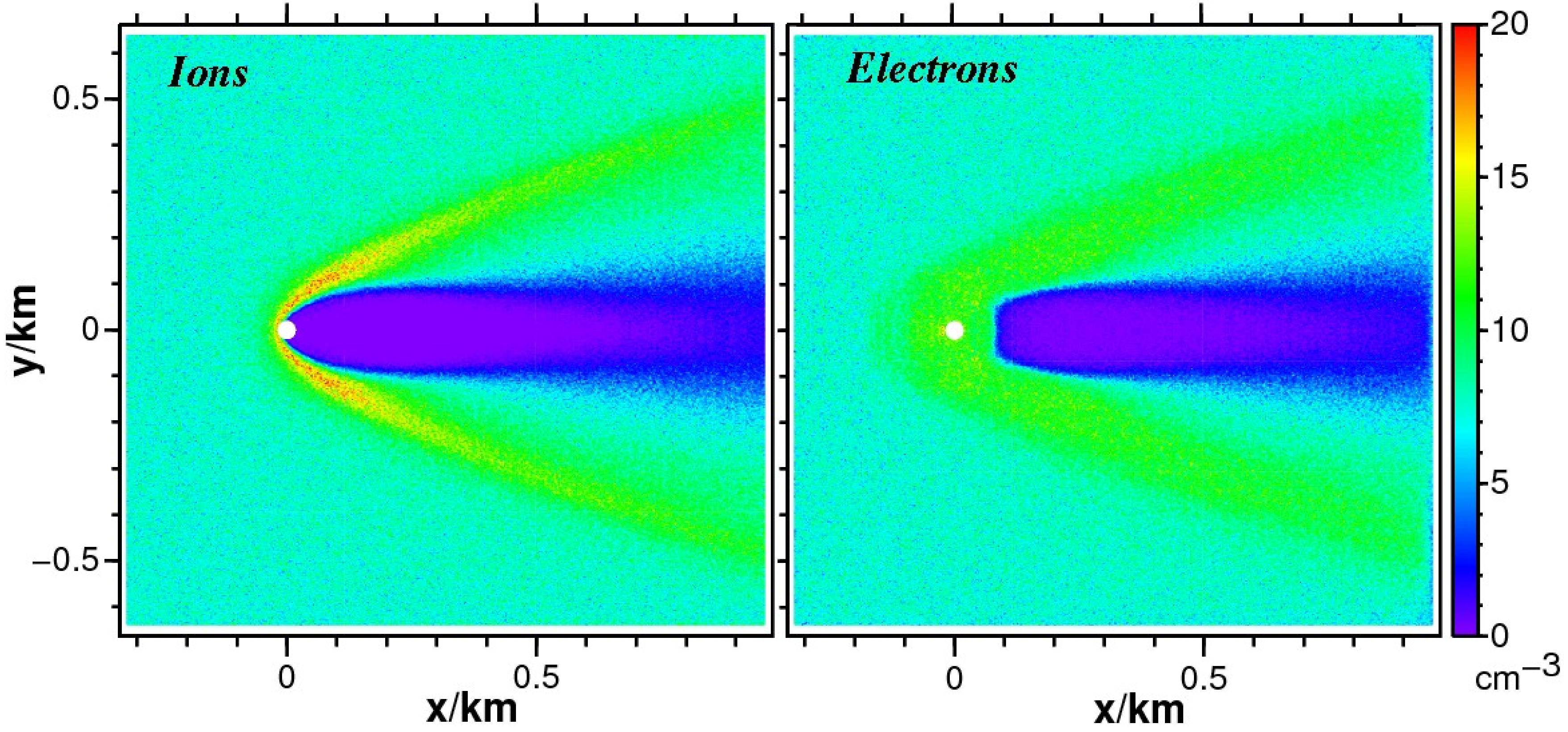
Positive polarity Coulomb drag



- PIC simulation, solar wind parameters, +5 kV tether

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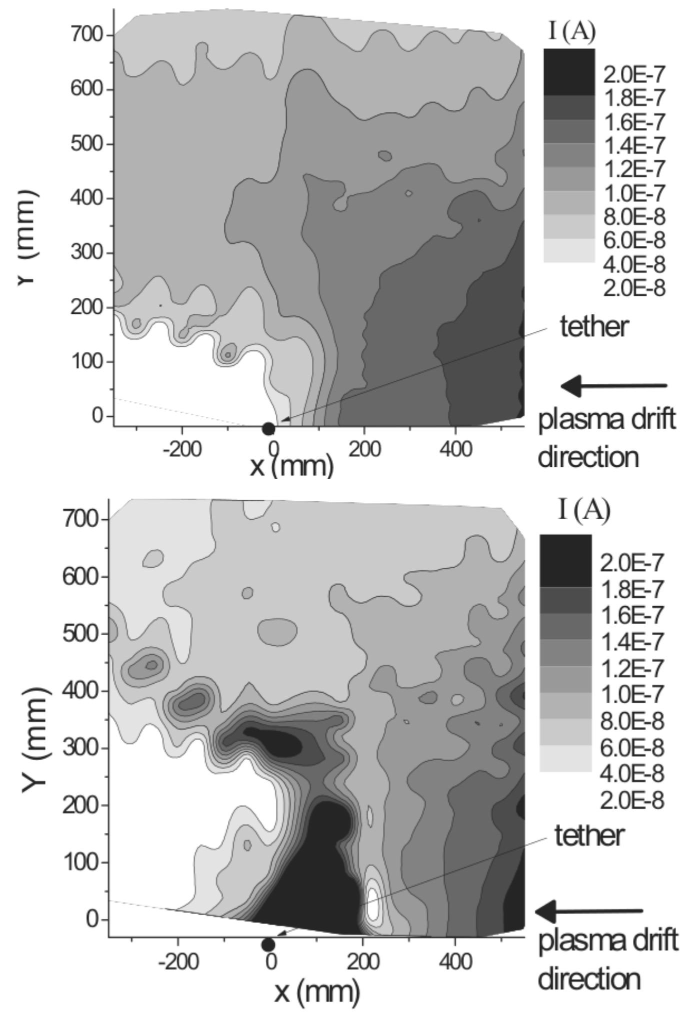
Laboratory measurements ($V_o>0$)

- 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 supports the idea that E-sail force is maximal (no extra shielding by trapped electrons)



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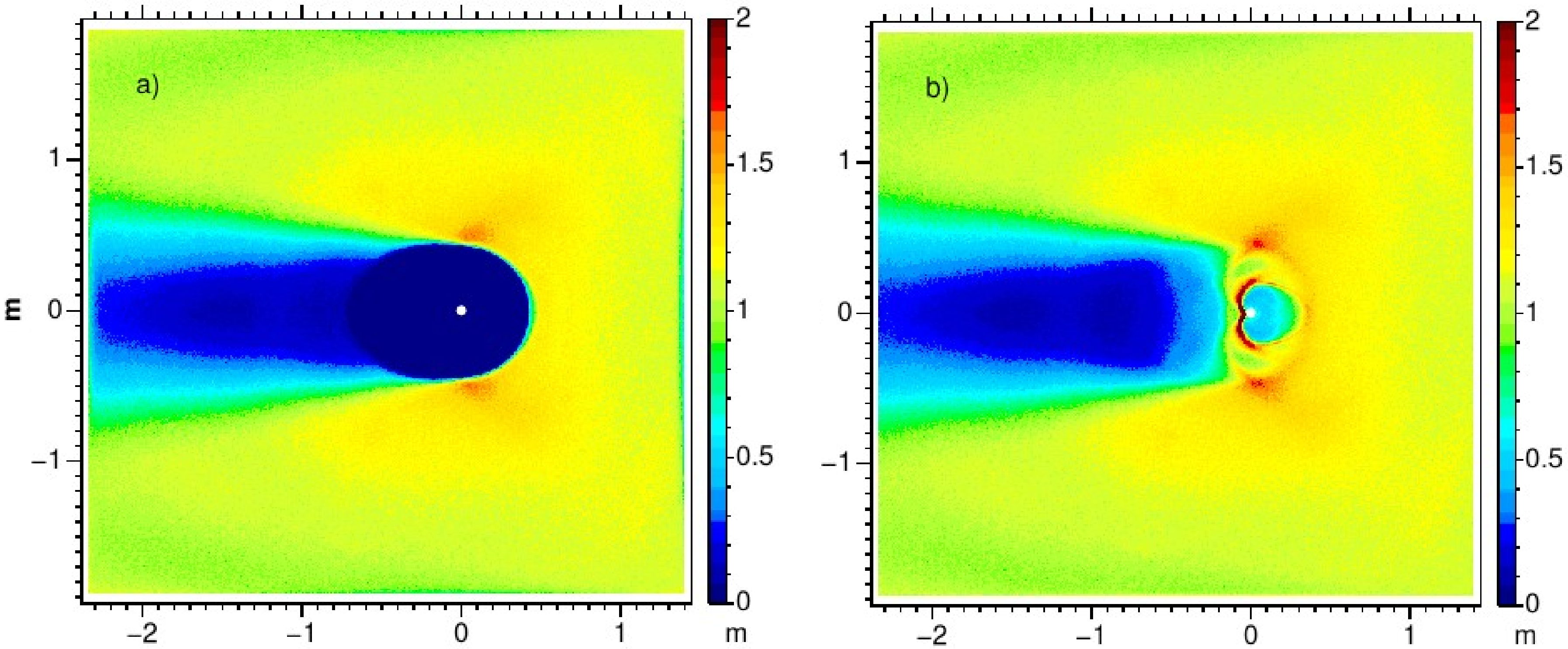
Negative polarity Coulomb drag



- LEO parameters (electrons left, ions right)

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Positive or negative polarity?

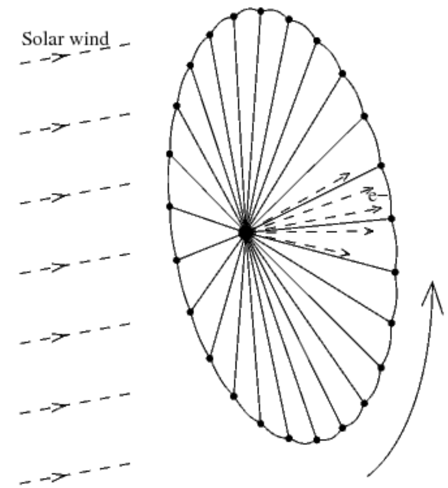
- Positive tether polarity preferred in solar wind:
  - Electron gun is simpler than ion gun
  - No limitation on voltage by electron field emission
  - No photoelectron emission
- Negative tether polarity preferred in LEO:
  - Usually can use satellite body as balancing electrode
  - Negative tether gathers less plasma current (ions versus electrons)
  - Photoelectron current is much less than plasma current
- Other combinations remain possible, in principle

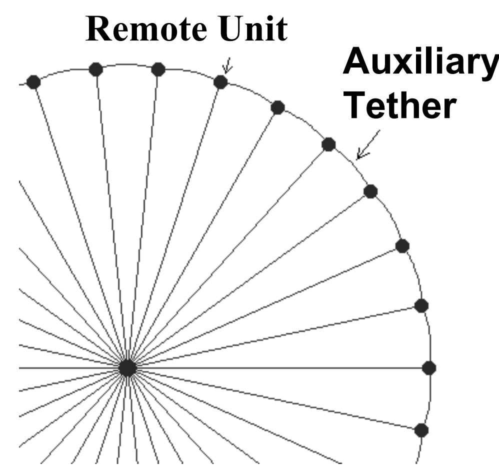
Thrust and power consumption

- Positive polarity (E-sail):
  - Thrust 0.5 mN/km at 20 kV in average solar wind at 1 au
  - Thrust scaling ~1/r (r=solar distance)
  - Electron gun power consumption ~0.7 W/mN, scales ~1/r^2
- Negative polarity (plasma brake):
  - Thrust ~0.05-0.1 mN/km at 1 kV at 800 km LEO
  - Power consumption ~2 W/mN
  - Thrust likes oxygen ($P_{dyn} \sim m_i$ where $P_{dyn}=m_i n_o v^2$)
- Roughly: dF/dz ~ $P_{dyn}[\varepsilon_o V_o/(e n_o)]^{1/2}$ in both cases (effective Debye length)

E-sail construction

- Positive tethers (10-20 km length made of 25-50 um wire, +20-40 kV voltage)
- Up to 1 N thrust (scales as *1/r*) from 100-200 kg unit (30 km/s delta-v per year to 1000 kg spacecraft)
- Power consumption modest, scales as *1/r²*
- Baseline approach uses non-conducting **Auxiliary Tethers** to stabilise flight without active control
- "**Remote Units**" at tips contain auxtether reels and spinup propulsion/spin control





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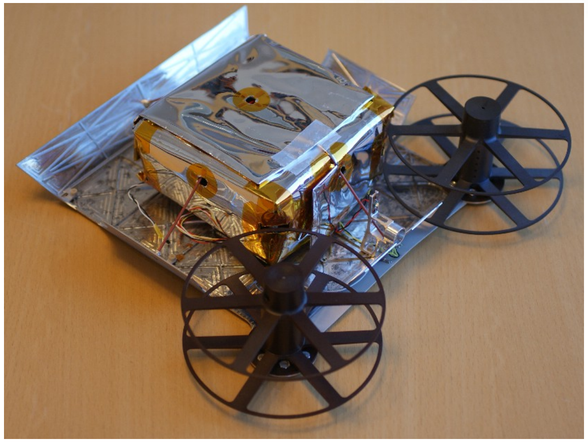
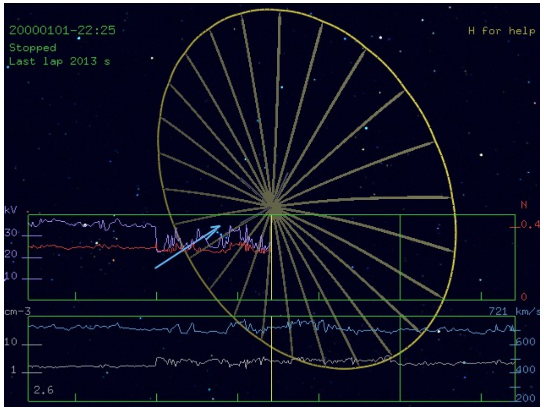
FINNISH METEOROLOGICAL INSTITUTE

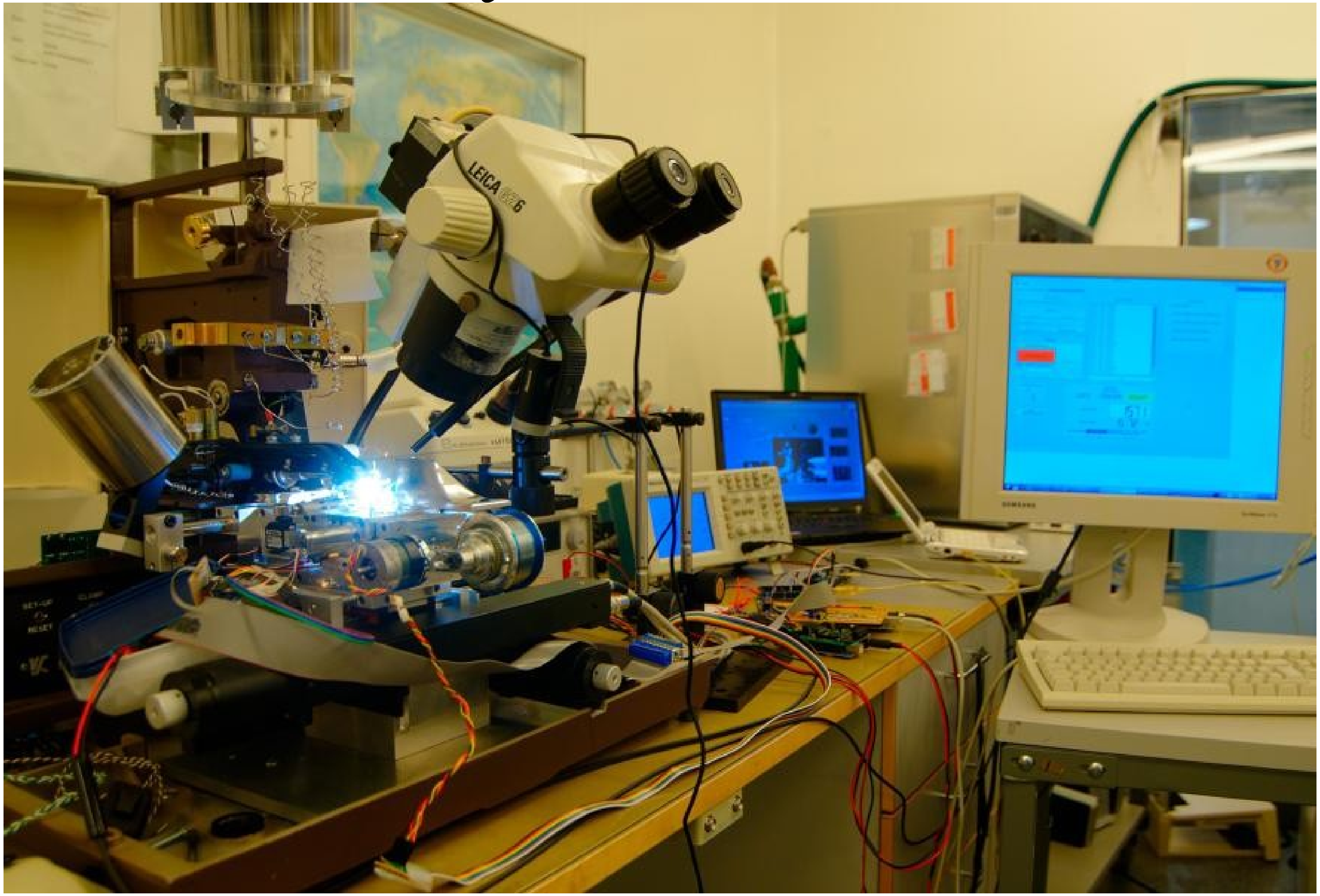
ESAIL FP7 project results

- Produced **1 km tether**
- Demonstrated unreeling after vibration test
- Tested in vacuum & under HV
- Prototyped and tested the **Remote Unit**
- E-sail “**flight simulator**”





Tether factory



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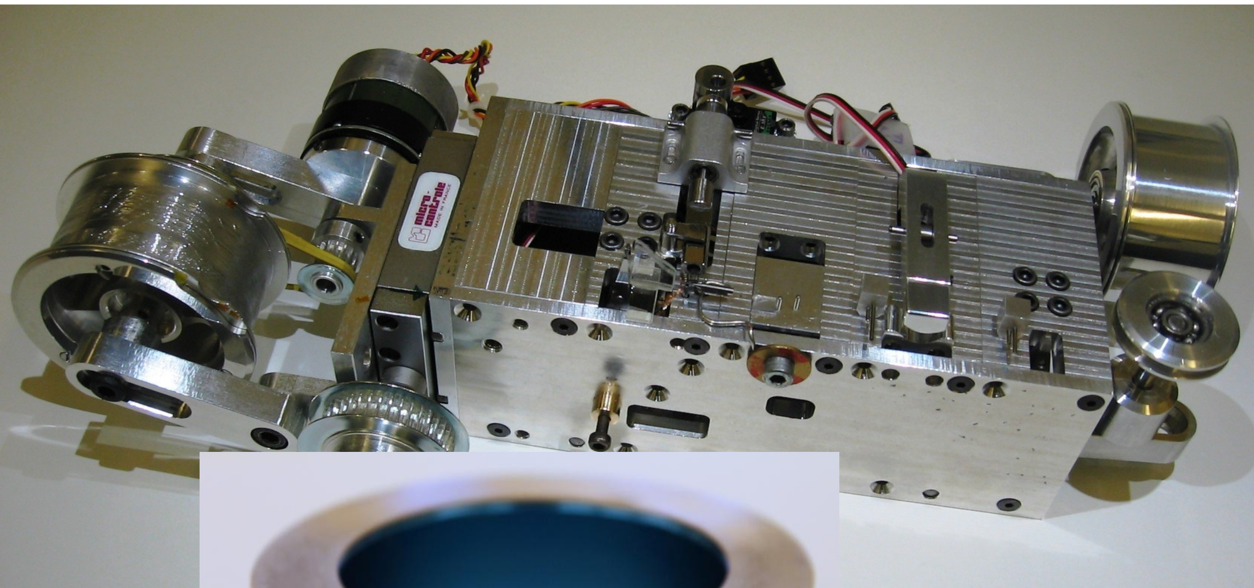
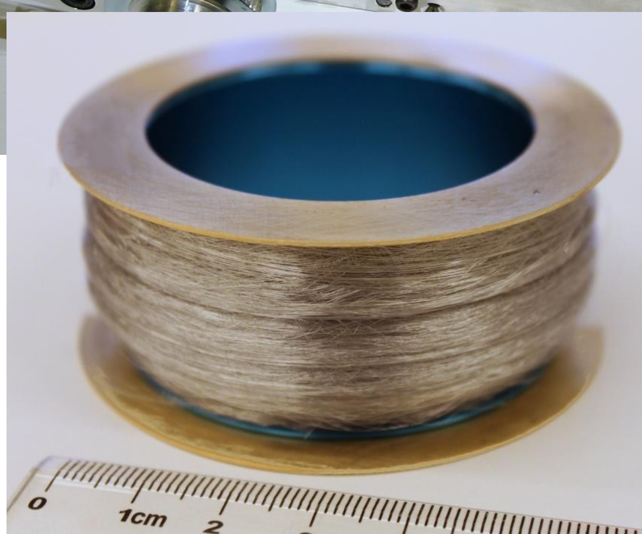
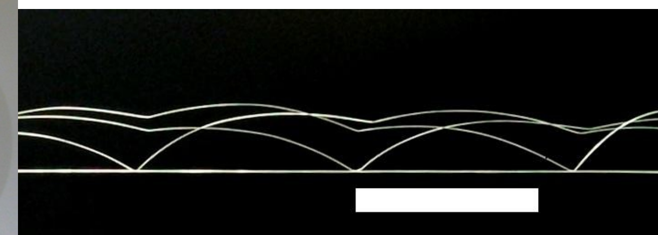
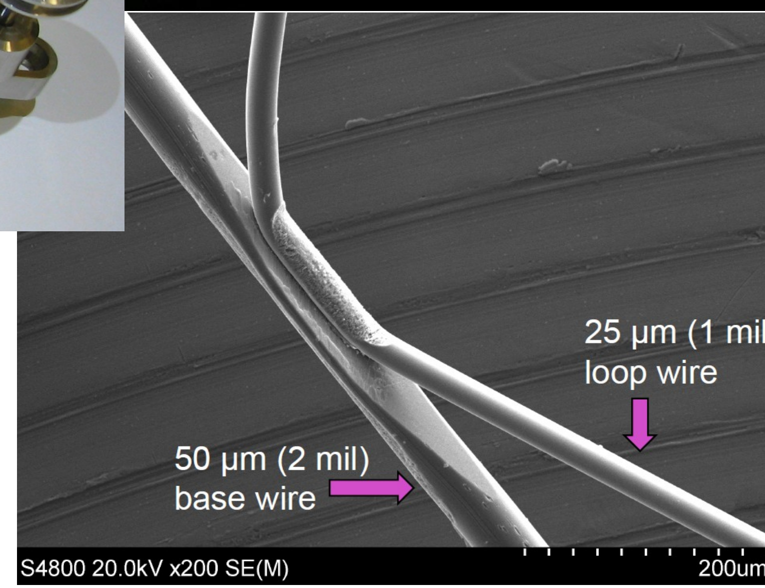
Tether factory and its products









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FMI dynamical simulation

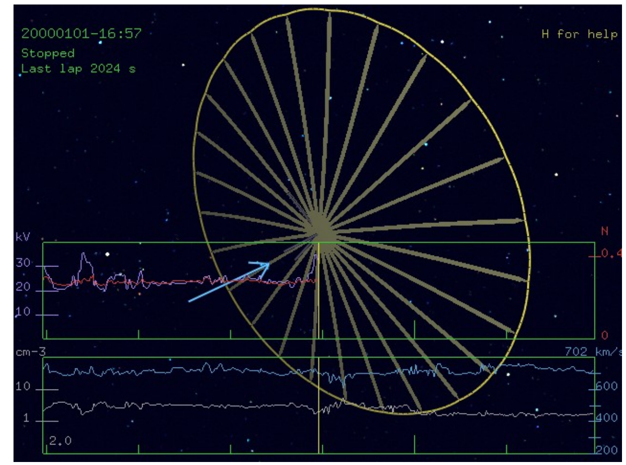
Solve Newton's laws for elastic, bending wires

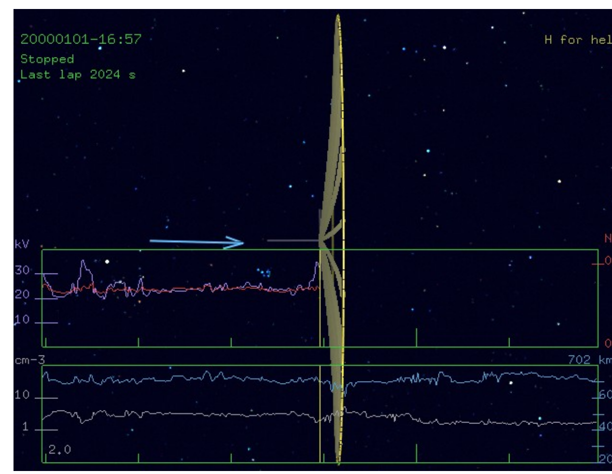
Include E-sail force under real solar wind

Can model manoeuvring by differential potential control

Can test “flight behaviour” of tether rig

→ “Stretched auxtether model” works





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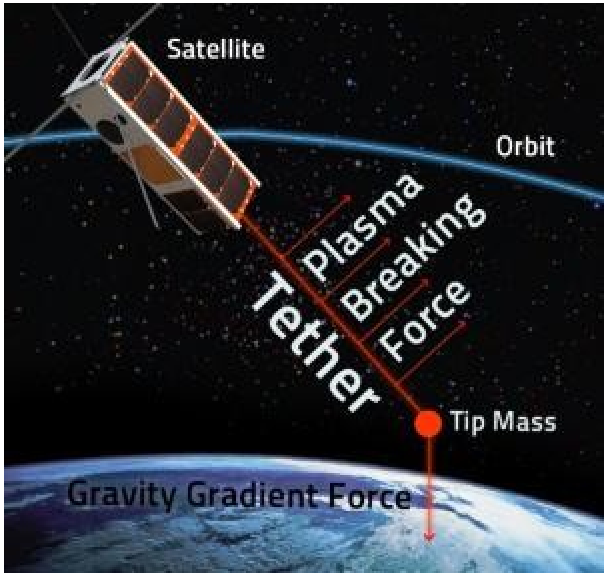
Plasma brake construction

- Negative tether, uses s/c conducting body as balancing electrode
  - Voltage “low” (~1 kV), photoelectron current negligible ==> can use negative tether
  - Negative polarity uses less power than positive
- Up to ~15 km length, ~50 gr. tip mass
- Thrust formula fitted to simulations:



$$\frac{dF}{dz} = 3.864 \times P_{\text{dyn}} \sqrt{\frac{\epsilon_o \tilde{V}}{e n_o}} \exp\left(-V_i/\tilde{V}\right)$$

$$\tilde{V} = \frac{|V_0|}{\ln(\lambda_D^{\text{eff}}/r_w^*)}$$

$$\lambda_D^{\text{eff}} = \sqrt{\epsilon_o |V_0|/(e n_o)}$$

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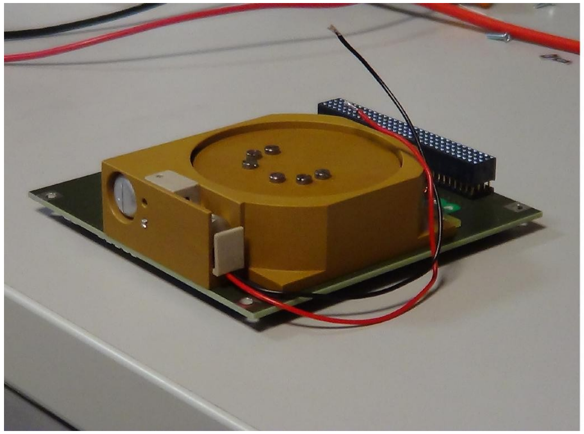
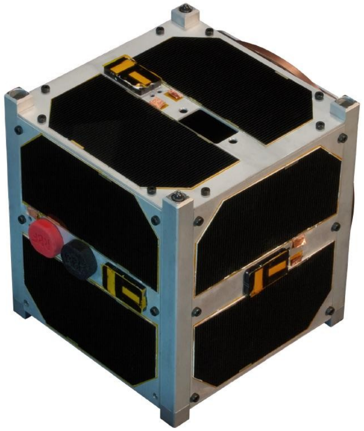
ESTCube-1 test mission





- 1-U CubeSat, 670 km orbit
- 10 m tether, ±500 V
- Launched May 7, 2013 (Vega/Kourou)
- Tether experiment started on September 16, more info in next presentation (Mart Noorma)...

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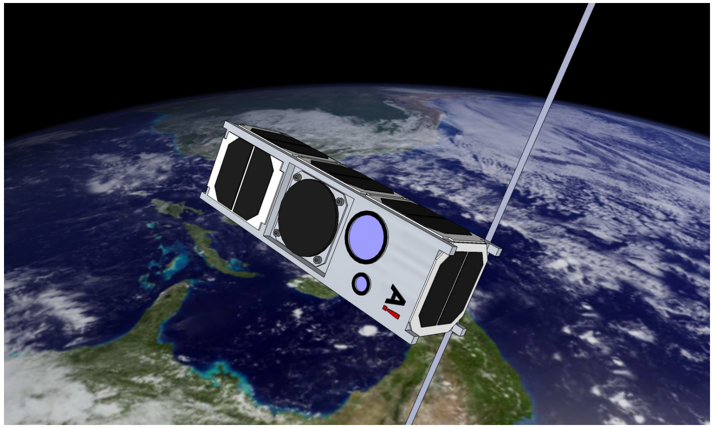
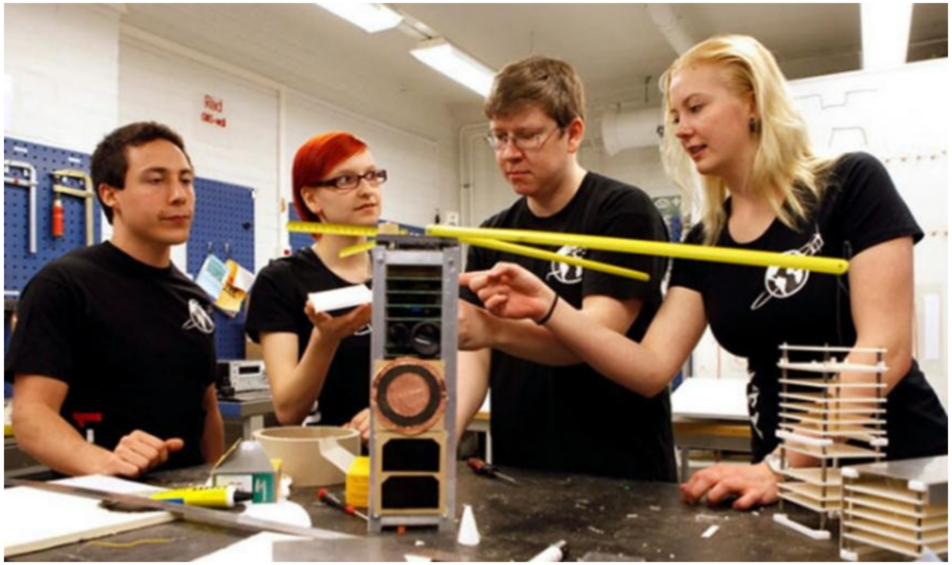
Aalto-1 E-sail test mission

- 3-U CubeSat, work led by Aalto University, Finland
- 100 m tether, similar orbit as ESTCube-1
- Satellite carries also other payloads
- Planned launch 2015





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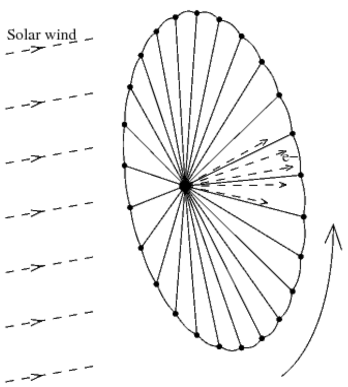
Electric Sail applications

- Almost any interplanetary mission faster, cheaper, better
  - Only needs solar wind to work
  - Thrust direction controllable 0-30° off radial
  - Thrust magnitude ~1/*r*, 100% throttling capability
- Here we'll look into the following:
  - Giant planet entry & flyby
  - Non-Keplerian orbits
  - Sample return and “data clippers”
  - Asteroids: Touring, Protection, Mining



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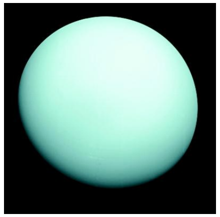
Giant planet entry & flyby

- E-sail can one-way-boost payloads to outer solar system at high speed
- Simple possibilities: atmospheric entry, flyby, orbit capture by small/modest chemical burn
- Travel time in years for 1 N E-sail:



	Jupiter	Saturn	Uranus	Neptune
500 kg	1.0	1.7	3.1	4.6
1000 kg	1.6	2.8	5.3	8.0
1500 kg	2.5	4.6	9.6	14.9

Non-Keplerian orbits

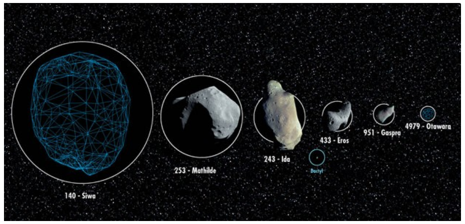
- Earth observation:
  - Off-Lagrange point solar wind monitoring (space weather forecasting with longer than 1 hour warning time)
  - Watching Earth-approaching NEOs and pseudomoons
  - High elliptic orbit whose apogee is locked to morning sector
  - Various orbits having view to polar regions
- Solar system science:
  - Lifted orbit above ecliptic plane (helioseismology of Sun's poles)
  - Jupiter aurora study: Stay above Jupiter-Sun Lagrange L1 point: continuous view to Jupiter's polar aurora and in-situ solar wind measurement (for other giant planets as well)

Sample return and "data clippers"

- With E-sail, return trip has no additional cost
- One could return physical samples, or flash memory chips containing terabytes of data (Joel Poncy)
- Returning data gets around the telemetry problem
- For example, high-res images and video of asteroids

Multi-asteroid touring mission

- E-sail does not consume propellant and can produce large delta-v (30 km/s/year or even more)



- Enables touring the asteroid belts
- NEO, main belt, Jupiter Trojans
- Flybys: 40-50 days per asteroid $\Delta t_{\rm FB} = 1.47\ (nv)^{-1/5}\, a^{-2/5}$
- Rendezvous: 4-6 months per asteroid + proximity ops

$$\Delta t_{\rm R} = 2.073\ n^{-1/9} v^{1/3} a^{-2/3}$$

- Instrumentation: Remote sensing, penetrator, impactor ...

Asteroid direct deflection by E-sail

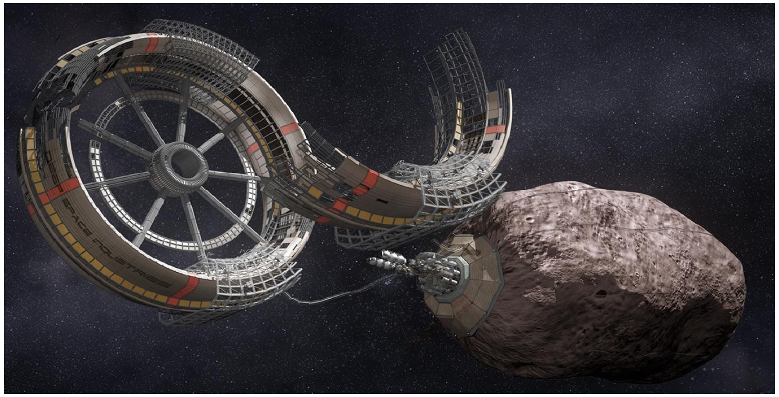
- 1 N E-sail thrust could move 150 m asteroid (3e9 kg) by one R_E over 7 years (Merikallio and Janhunen, 2010)
  - Gravitational keyholes might make situation better...
- Attachment remains important challenge. Harpooned tether might work in cases where pulling from the pole is geometrically feasible.
- However, low-thrust deflection methods require sufficiently long warning time, which is not always available...

Retrograde E-sail planetary defence

- Use E-sails to push ~1-5 ton masses to retrograde heliocentric orbits (requires large delta-v of ~60 km/s)
- The masses are spacecraft capable of impulsive propulsion (liquid propellant, chemical or cold-gas)
- If an Earth-threatening asteroid is found, the masses are commanded to collide with it
- Rationale: Impact energy $(1/2)mv^2$ ~1 kt, v ~ 60 km/s
- Intrinsic safety: the masses are mostly liquid and can be *designed for demise* in case of accidental collision with Earth

E-sail for asteroid mining

- Asteroid mining can enable qualitatively different space activity: large assets with asymptotically low €/kg
- Main product categories:
  - H_2O and other volatiles, for use as impulsive propellant in space
  - Platinum group metals, for selling on Earth
  - Iron-nickel, for constructions in space (3-D printing..)
- 2013: *deepspaceindustries.com*, *planetaryresources.com*



Conclusions

- E-sail technology status:
  - Theory is consistent with lab experiment (2013)
  - 1 km tether production was demonstrated (2012)
  - “Remote Unit” for 1 N, 0.9-4 au E-sail is at TRL 4-5 (2013)
  - ESTCube-1 tether experiment started (Sept 16, 2014)
- E-sail technology applications:
  - Plasma Brake for solving LEO space debris problem
  - Revolutionising solar system science missions
  - Protection of Earth against impact threat
  - Enabler of Asteroid Mining → solar system colonisation

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