Cosmic Squid:
A Giant Spinning CubeSat Solar Sail

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Why Go Small?
(i.e. CubeSat Solar Sails)

- Want to launch sooner than 2030

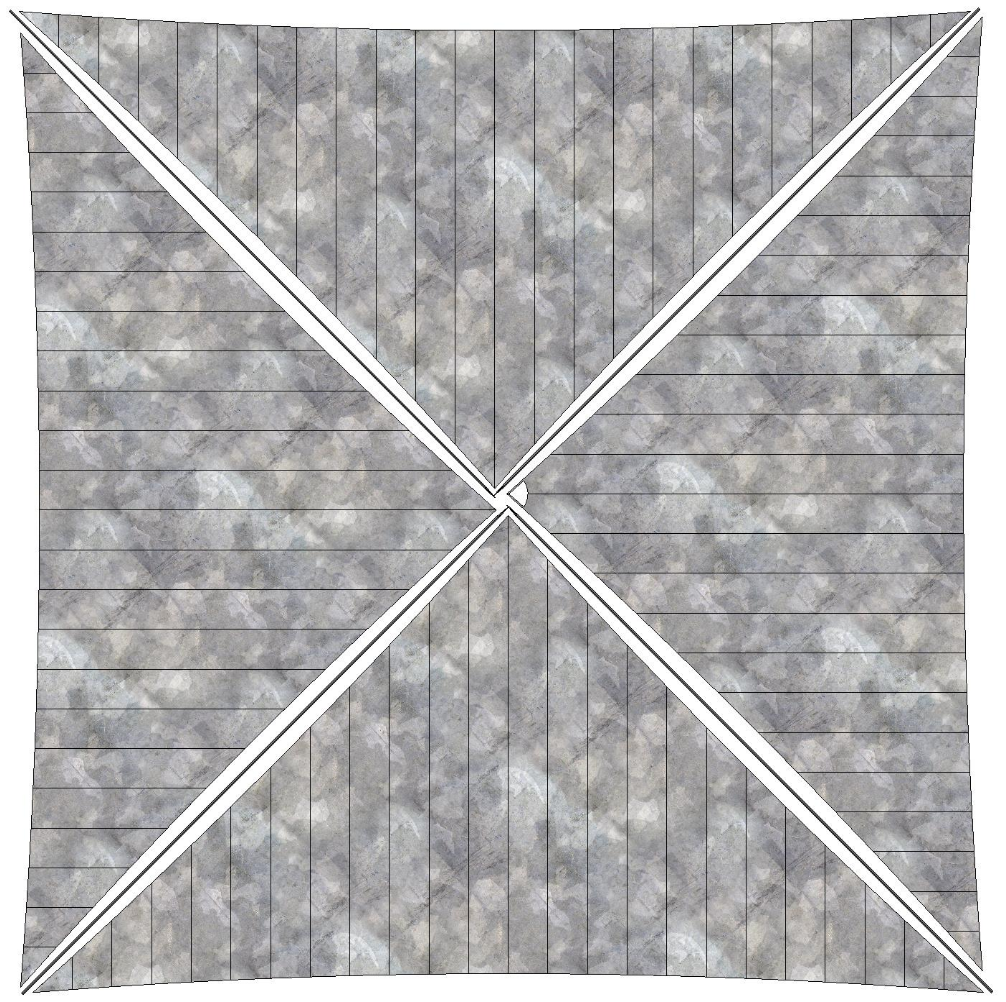
- Want to keep costs low

- Want more than one shot into the ISM

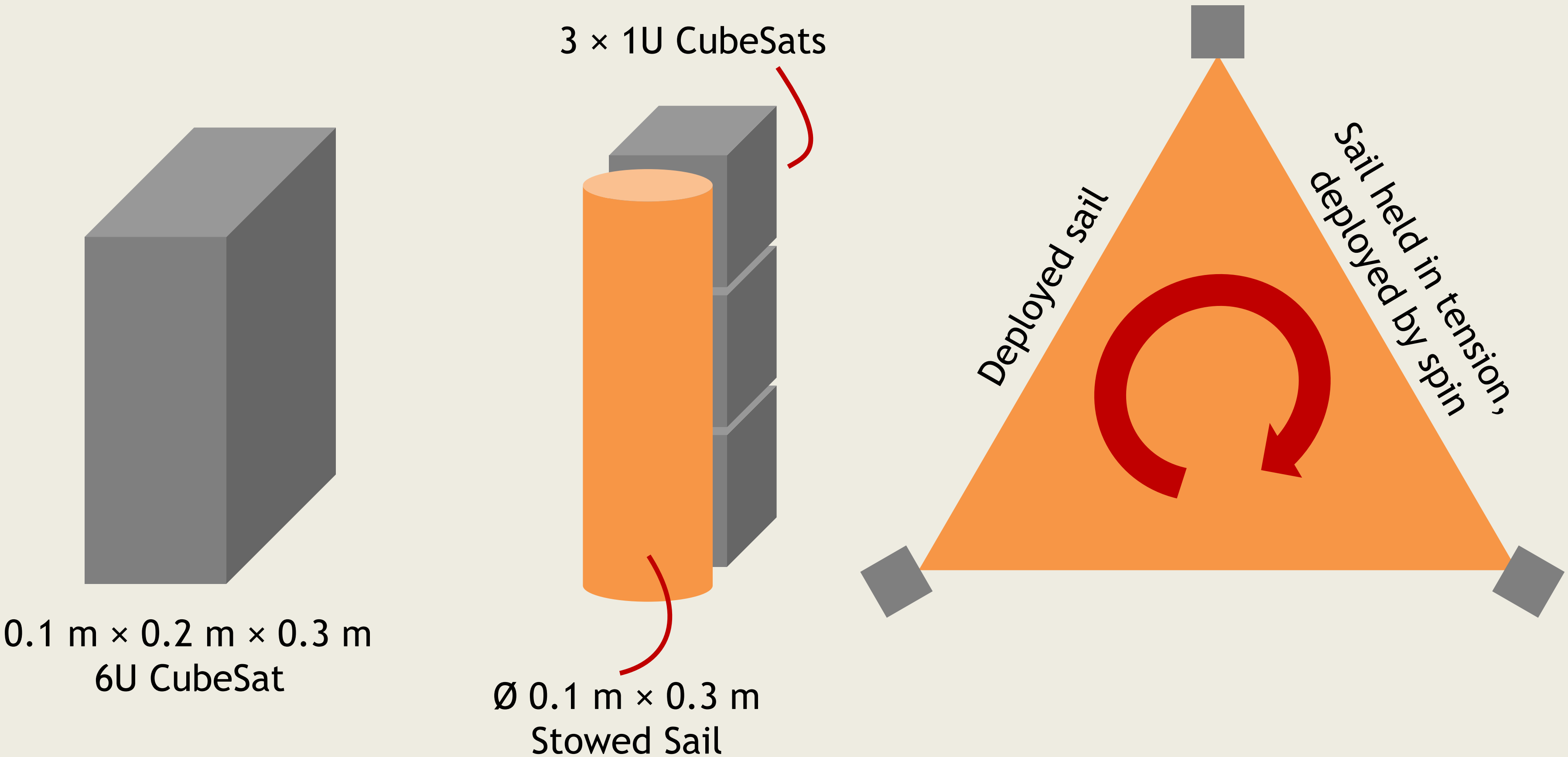
- Want a continuous series of probes into the ISM/to KBOs

Solar Sails

- “Traditional” architecture: four booms, four sail quadrants
- Deployed size limited by boom packaging volume, not sail packaging
- Can increase area/mass (or char. accel.) by removing booms
- Spin to deploy + preload



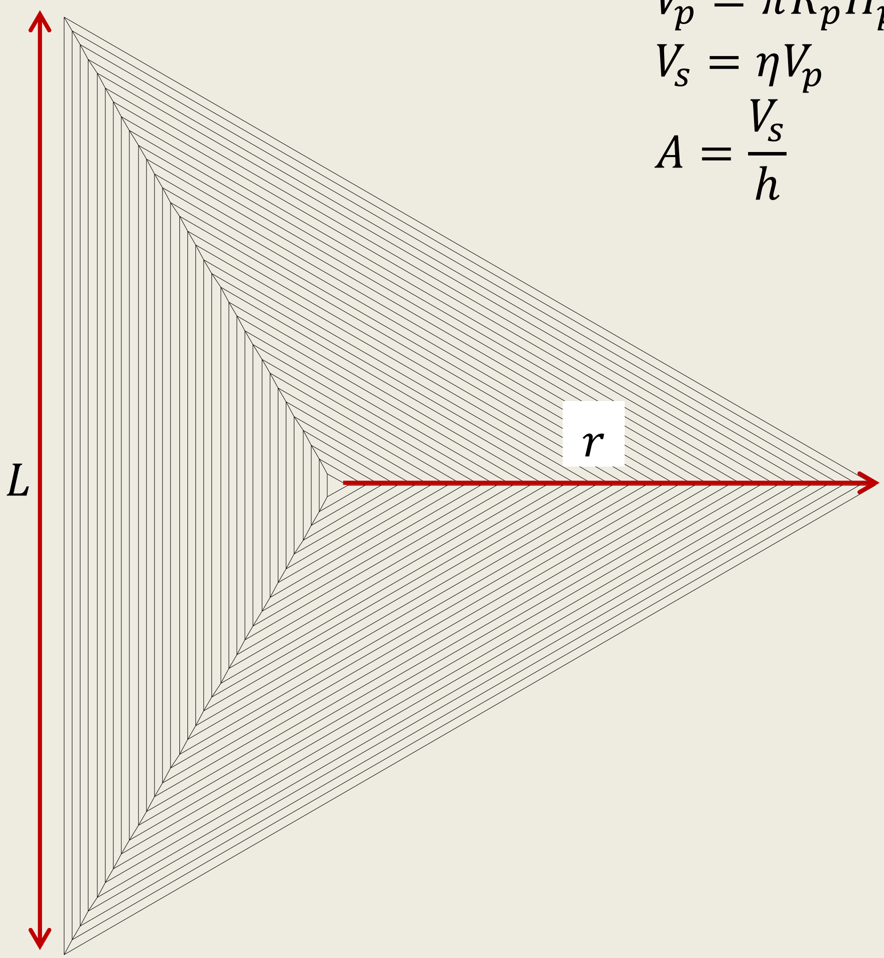
Cosmic Squid

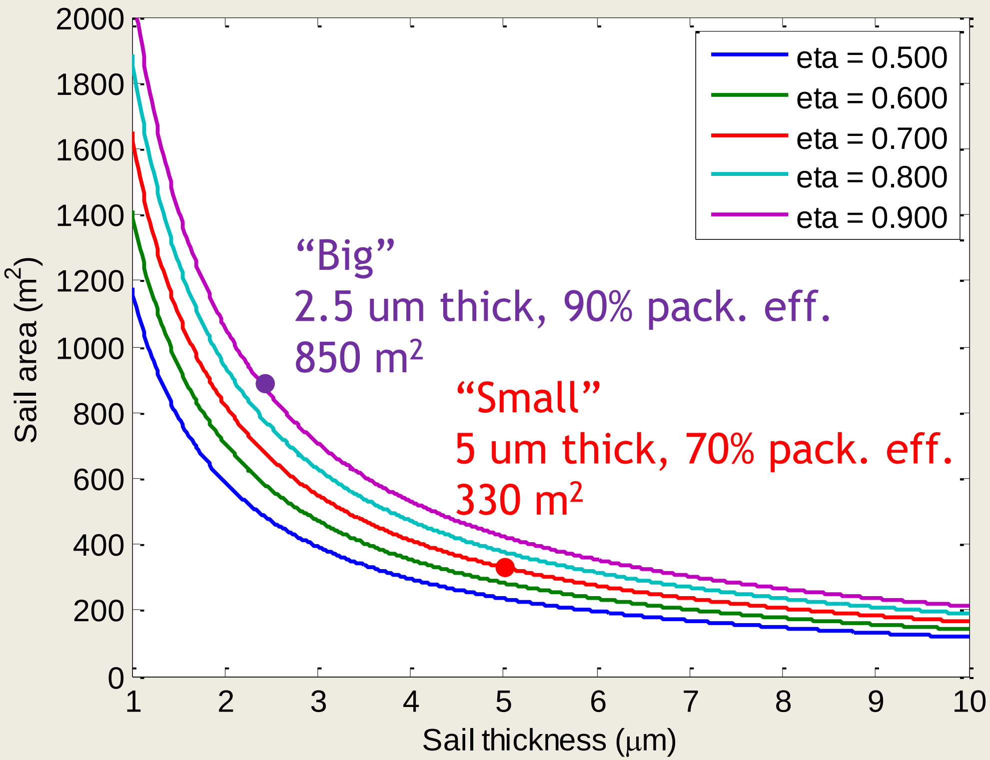


Sail Packaging → Sail Size

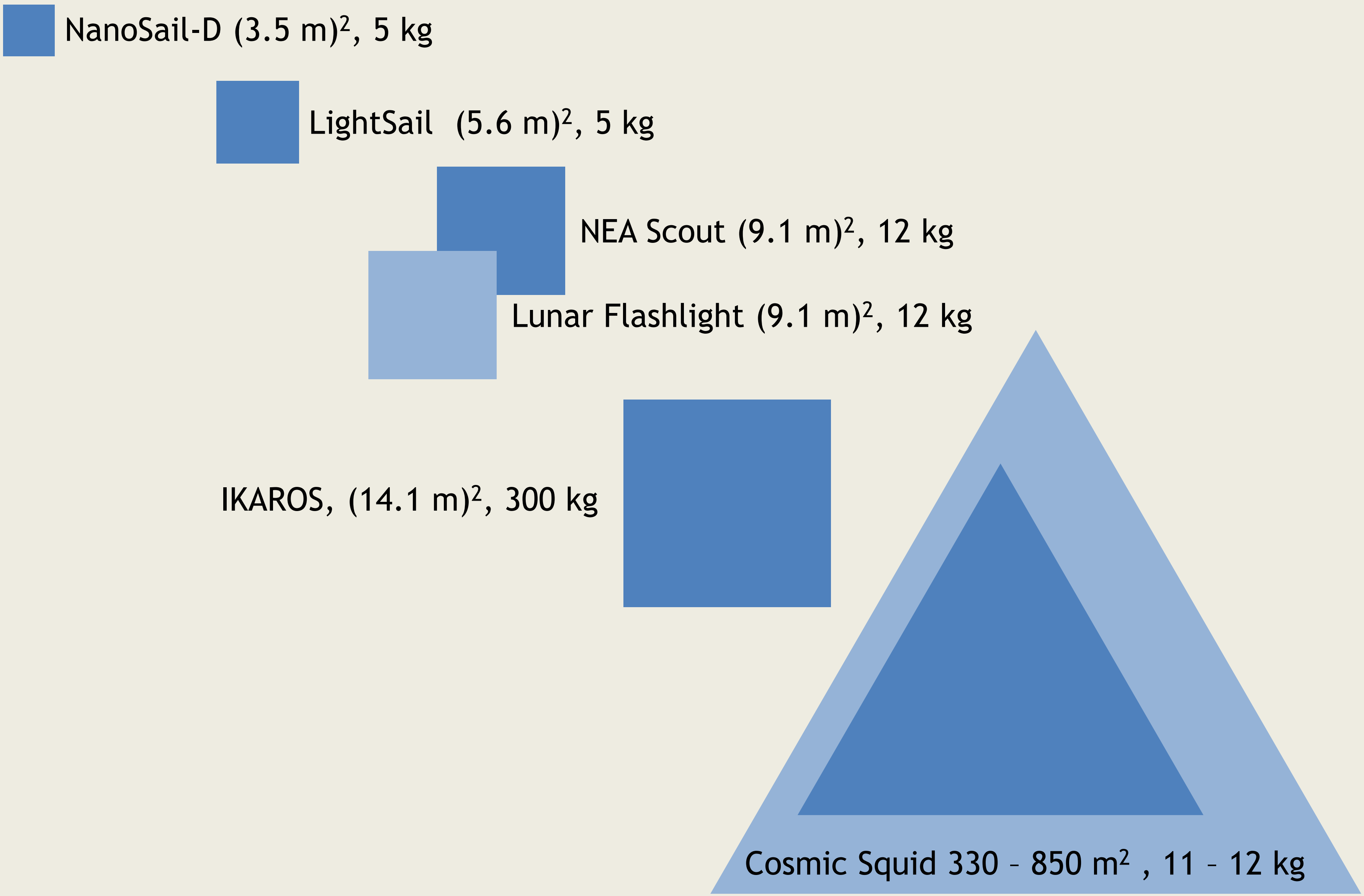
$$V_p = \pi R_p^2 H_p = 0.00236\,m^3$$
$$V_s = \eta V_p$$
$$A = \frac{V_s}{h}$$

$$L^2 = 3r^2$$
$$A = \frac{\sqrt{3}}{4} L^2 = \frac{3\sqrt{3}}{4} r^2$$



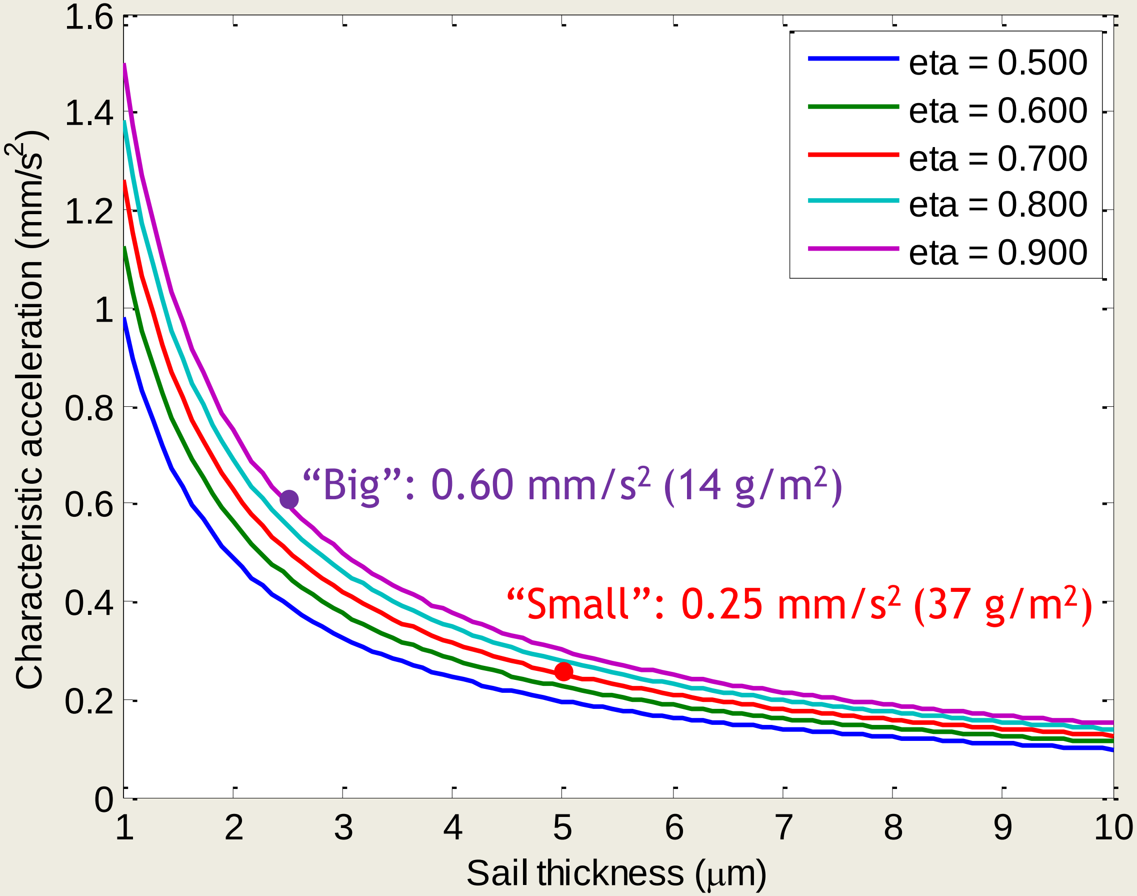


Size Comparison



Performance

- Mass of each 1U CubeSat $m_u = 2\ kg$
- Sail mass $m_s = V_s \times 1420\ kgm^{-3} = 2.4\ - 3.0\ kg$
- Total accelerated mass $m = (3m_u + m_s) \times 1.3 = 11\ - 12\ kg$
- Characteristic acceleration $a_c = (8.3\ \mu Pa)A/m$



$$a_c = \frac{P_{srp}A}{m}$$

$$m = m_s + 3m_u$$

$$= \eta V_p \rho + 3m_u$$

$$\Rightarrow a_c = \frac{P_{srp}\left(\frac{\eta V_p}{h}\right)}{\eta V_p \rho + 3m_u}$$

$$= \frac{P_{srp}}{h}\left(\rho + \frac{3m_u}{\eta V_p}\right)^{-1}$$

Char. accel. depends mainly on material thickness

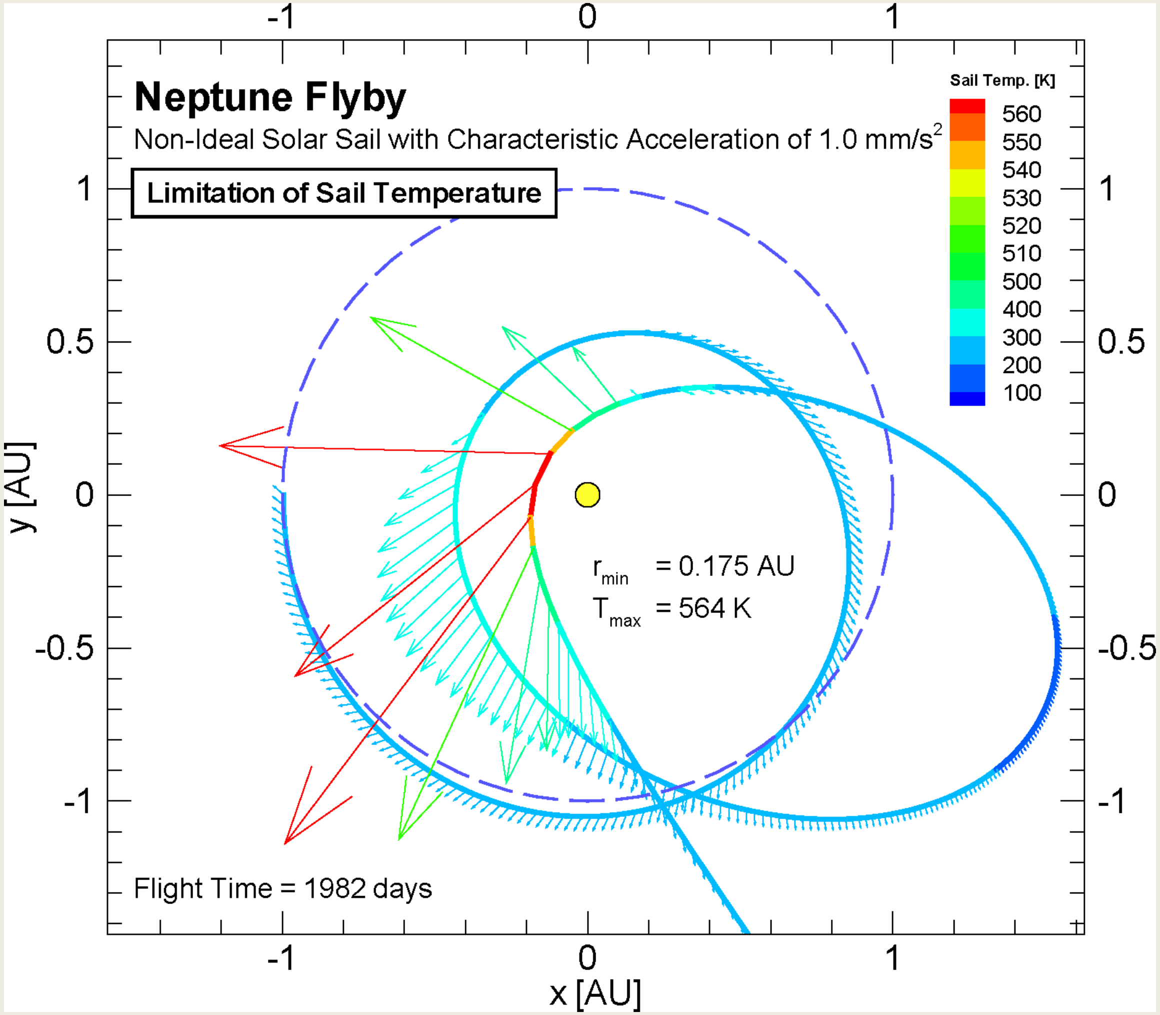
Trajectory Design

Optimal Solar Sail Trajectories for Missions to the Outer Solar System

Bernd Dachwald*

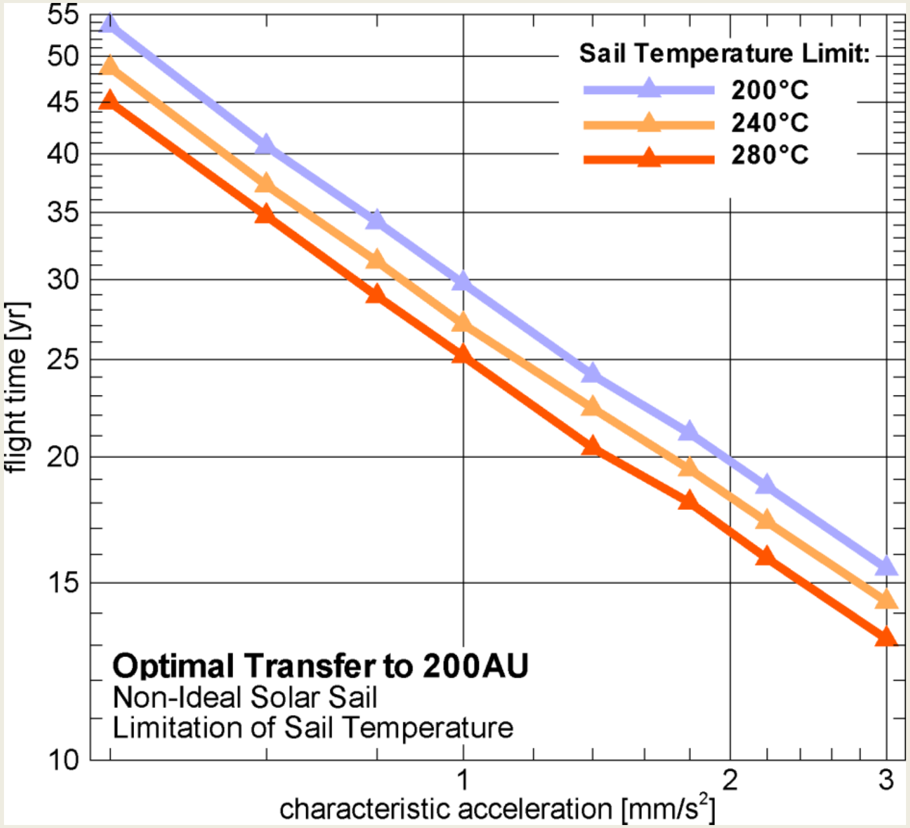
German Aerospace Center (DLR), Cologne, Germany

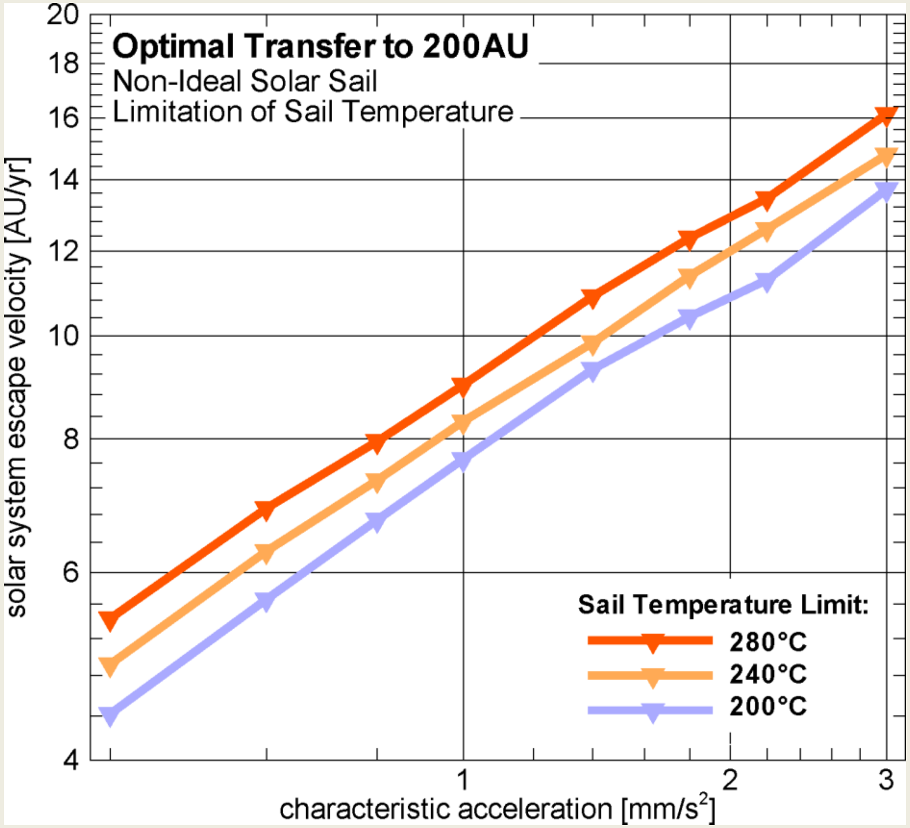
Trajectory Design



Dachwald, Optimal Solar Sail Trajectories to the Outer Solar System, 2004

Escape Velocities and Flight Times





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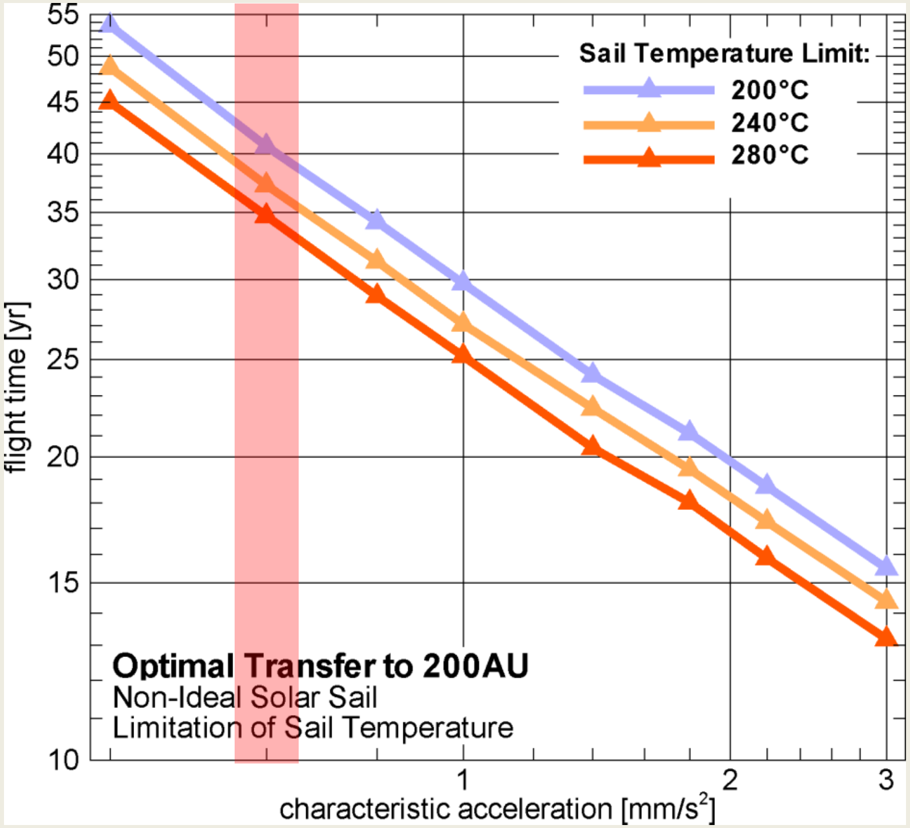

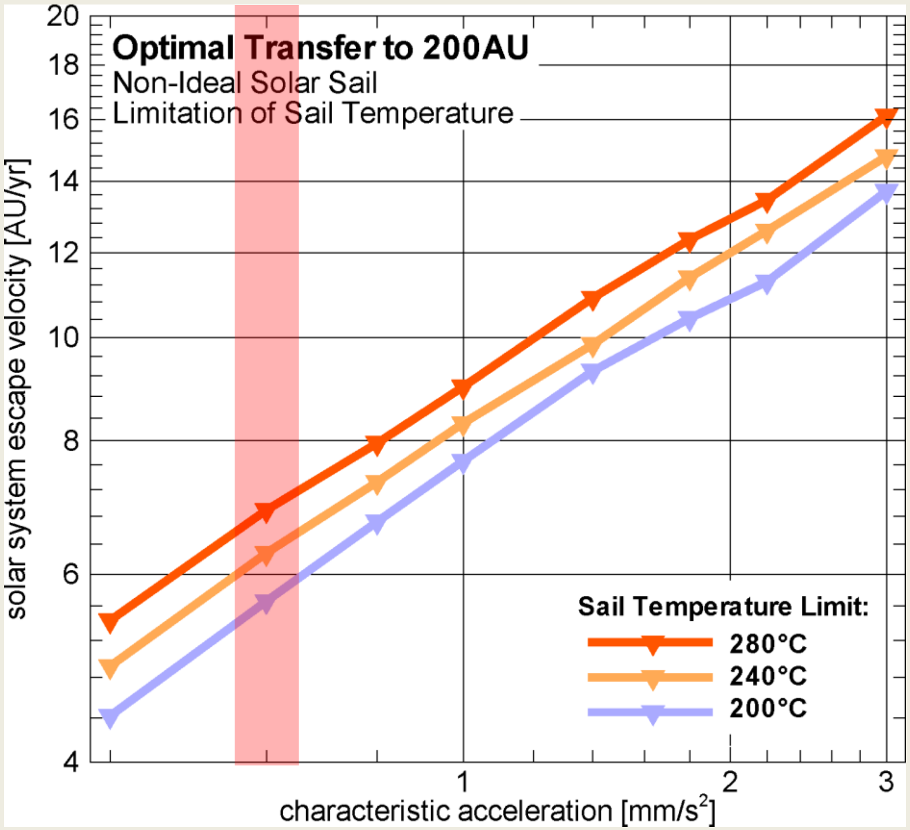

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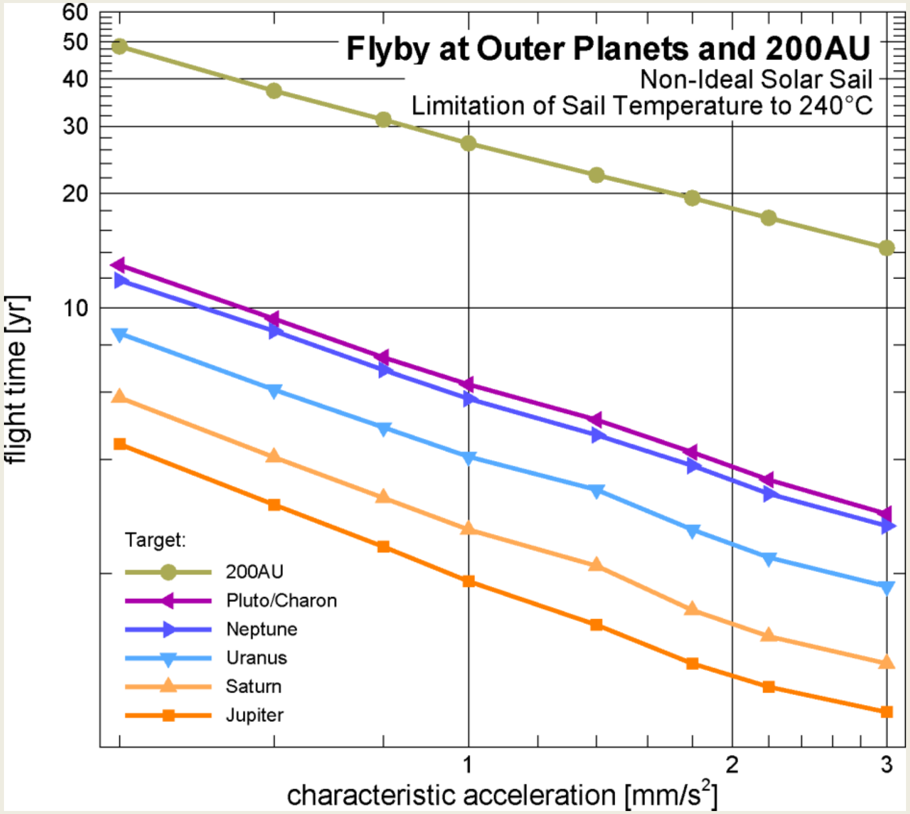

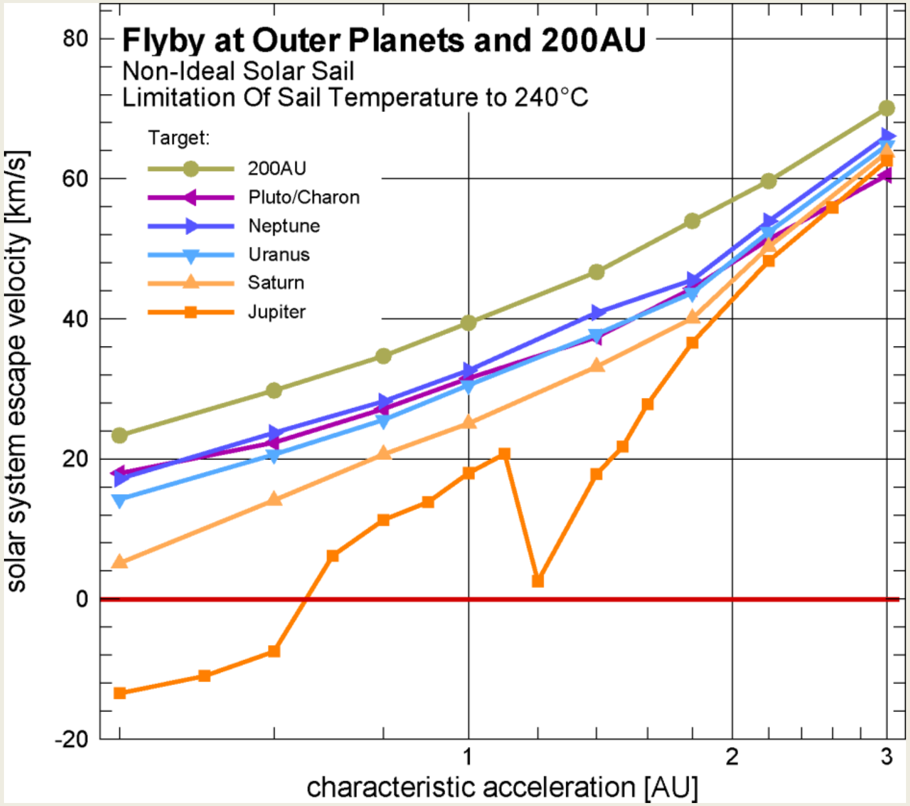

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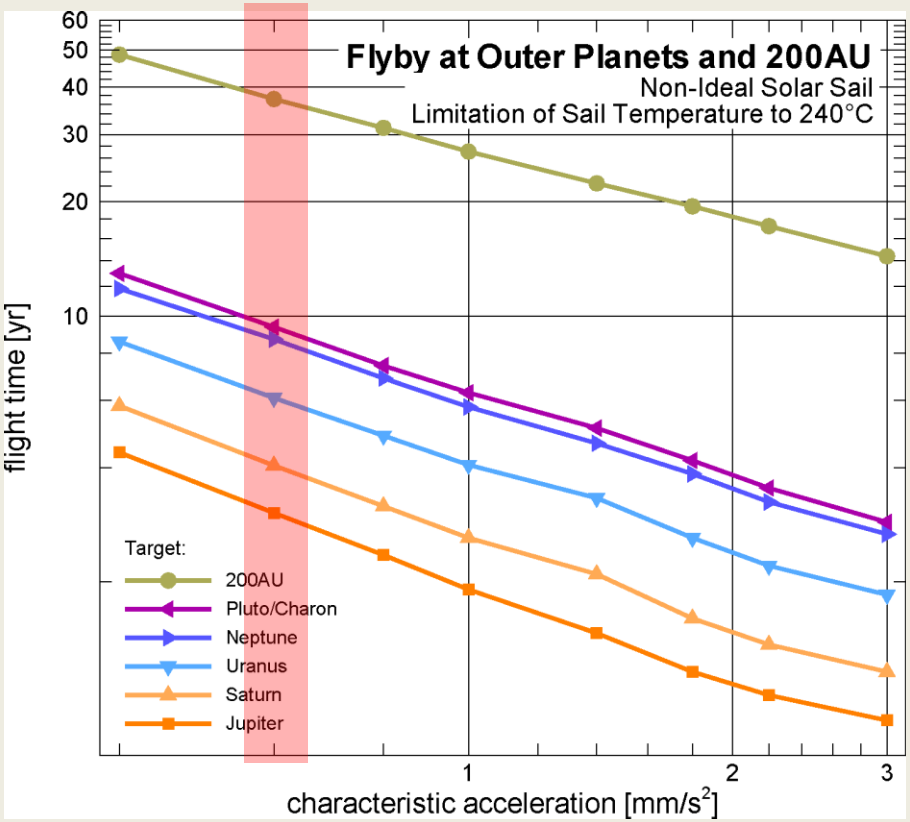

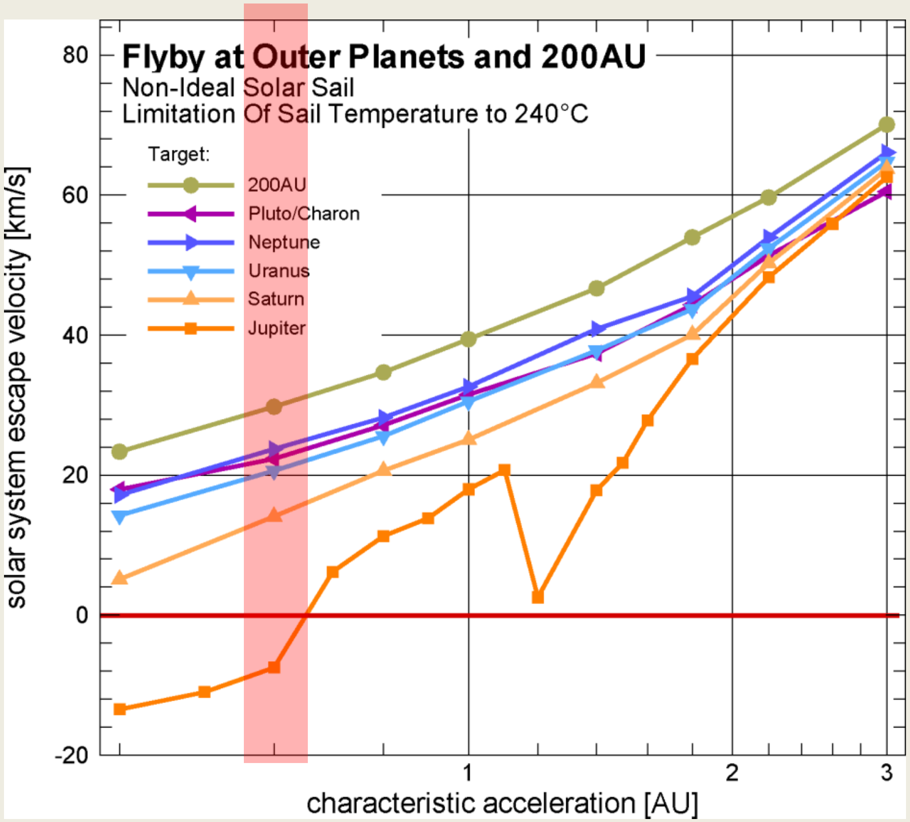

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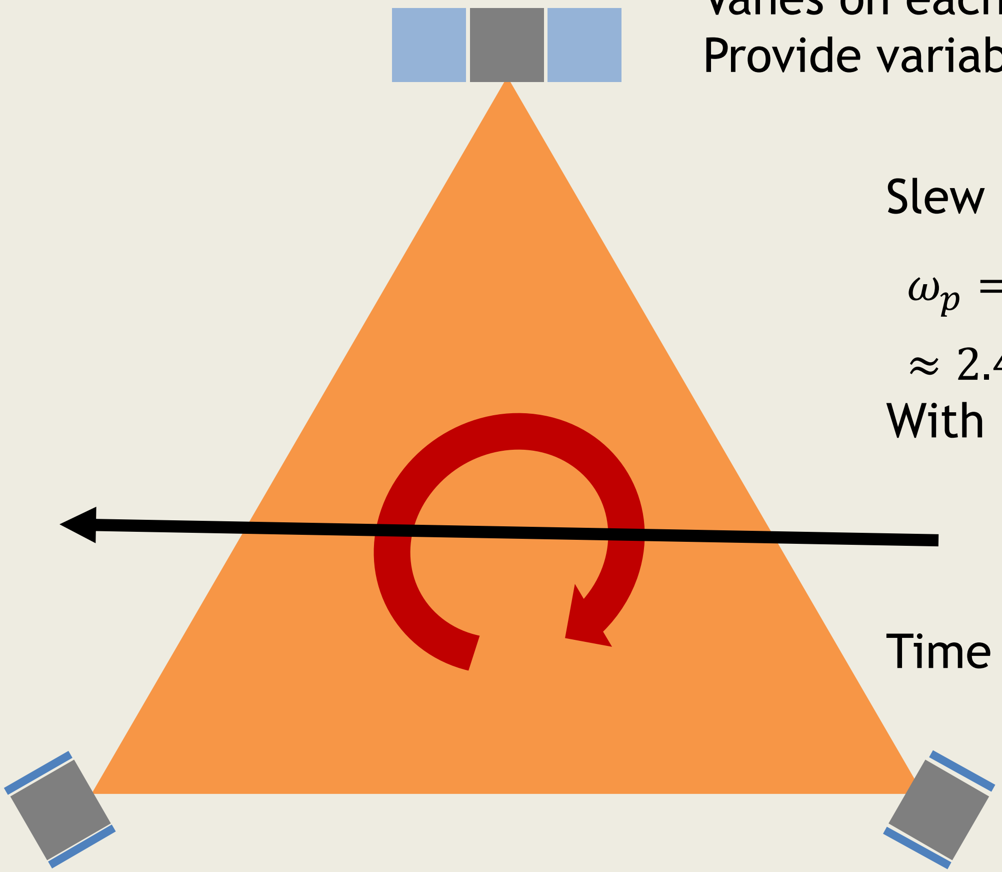
Spin Rate

Centripetal force on one tip CubeSat: $m_u \omega^2 r$
Force profile along diagonal: $\sqrt{3}Px$
P is the pre-load per unit length of membrane
Equating these forces at the tip:

$$\sqrt{3}Pr = m_u \omega^2 r$$
$$\Rightarrow \omega^2 = \sqrt{3}P/m_u$$
$$P \approx 0.05\ Nm^{-1}$$
$$m_u = 2\ kg$$
$$\omega = 0.2081\ s^{-1} \approx 2\ rpm$$

Maximum tension: $T_{max} = \sqrt{3}Pr \approx 4\ N$

Attitude Control



Vanes on each TipSat can be feathered
Provide variable SRP at each corner

Slew rate:

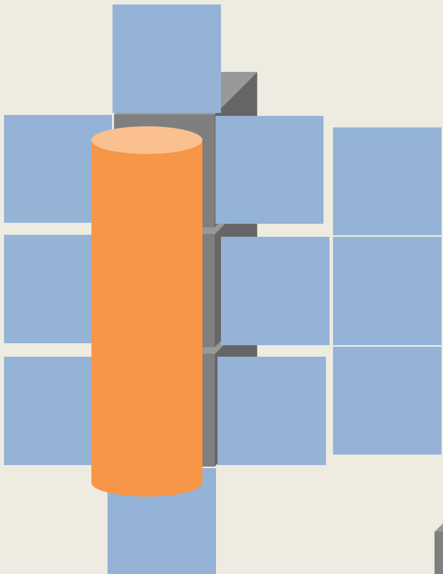
$$\omega_p = \frac{\tau}{I\omega} = \frac{A_{vane}P_{SRP}r}{I\omega}$$
$$\approx 2.46 \times 10^{-5} s^{-1}\ at\ 0.1\ AU$$

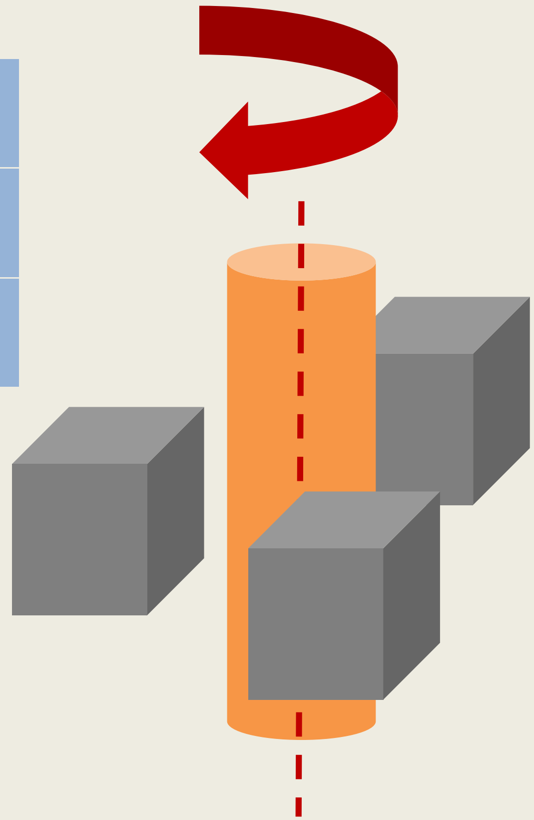
With

$$A_{vane} = 1\ m^2$$
$$r = 25\ m$$

Time for 90° slew: 18 hours

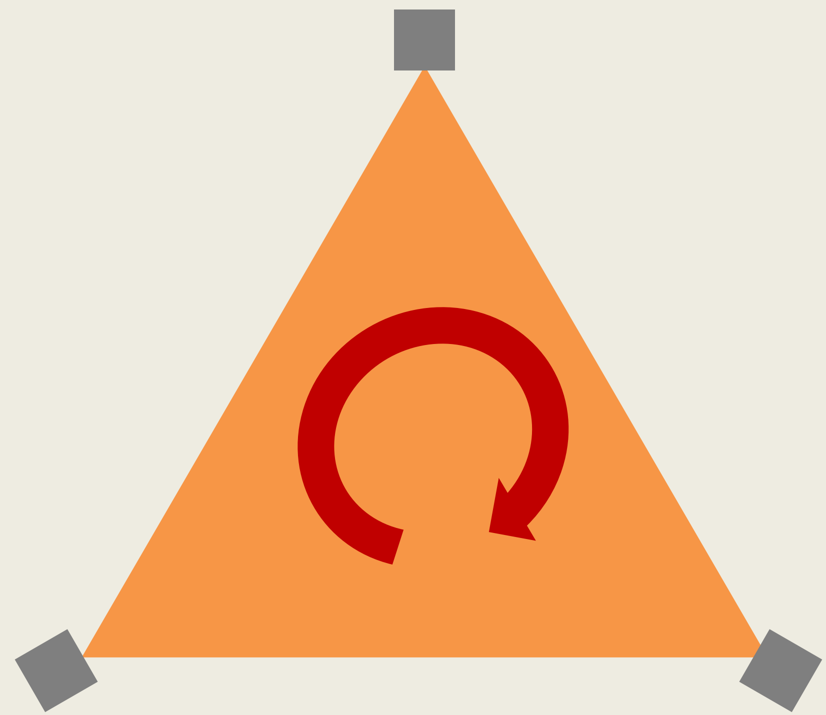
Deployment Concept





Deployment by spinning

Sail tensioned by centrifugal force, use the 3 1U CubeSats as end masses



Power

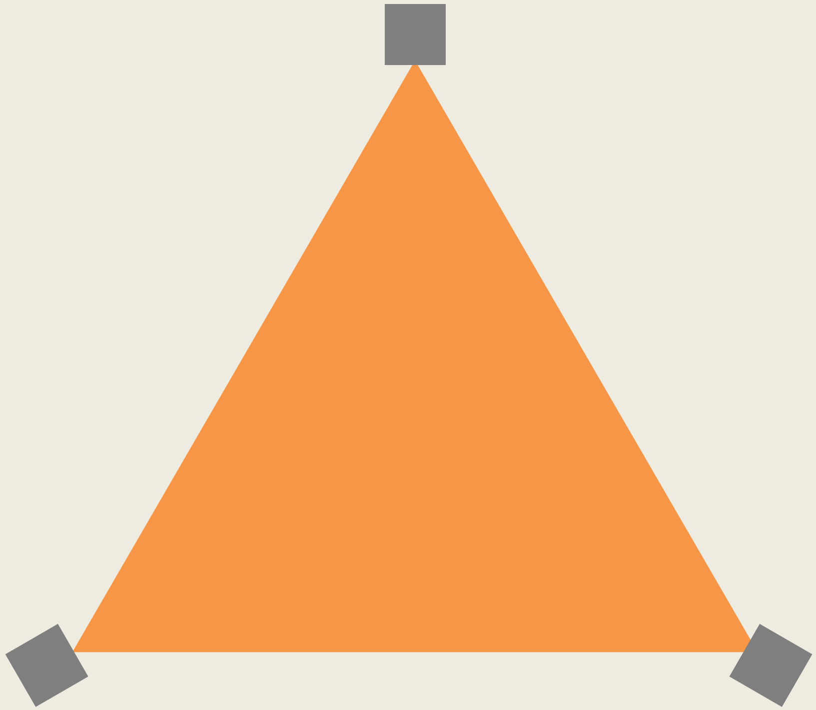
- Option 1: PV
  - 50 W array produces
    - 0.02 W at 50 AU
    - 0.005 W at 100 AU
  - Hibernation/Sleep/Short burst science + comm.
- Option 2: RHU + Thermoelectrics
- Option 3: Betavoltaics

Communication

- Option 1: X-Band/UHF down/uplink
- Option 2: Laser comm.
  - Synergy with imaging systems

System Architecture "Precursor"

- Tip 1 (Communication):
  - UHF, X-Band Radio (0.3 U)
- Tip 2 (Command):
  - Star Tracker (0.3 U)
  - CD&H (0.2 U)
  - Sail Monitor Camera (0.1 U)
- Tip 3 (Science):
  - Magnetometer / Imager (0.4 U)
- Common for each Tip:
  - EPS + Battery (0.2 U)
  - Deployable ACS tip vane (0.2 U)
  - Wireless comm. to other tips



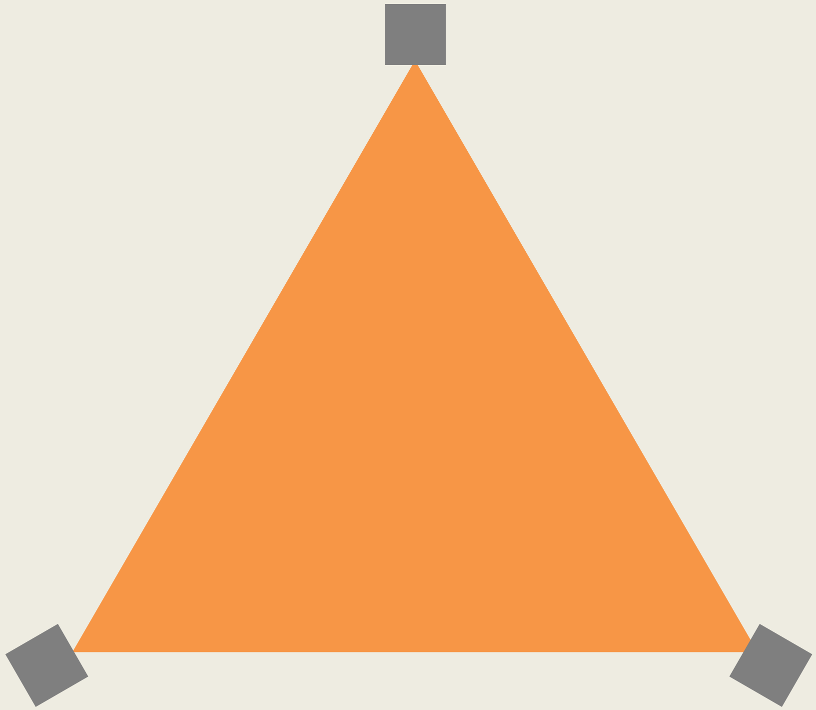
System Architecture “ISM Scout”

- Tip 1 (Communication):
  – Optical Comm./Camera (0.8 U)

- Tip 2 (Command):
  – Star Tracker (0.3 U)
  – CD&H MPU (0.2 U)
  – UHF/X-Band Radio (0.3 U)

- Tip 3 (Power):
  – Nuclear Magic Power (0.8 U)

- Common for each Tip:
  – ACS tip vane (0.1 U)
  – Deployable ACS tip vane (0.2 U)
  – Wireless comm. to other Tips



Take Aways

- Can make 0.60 mm/s^2, 14 g/m^2 sails now
- 200 AU in 35 years, 7 AU/year
  - Haumea/KBO in 10 years
- Can starting building and launching precursors now
- Low cost to develop, low cost to launch
- Multiple probes to spatially and temporally sample ISM/heliopause/KBOs

Questions, Risks, and Challenges

- Lifetime
  - Other deep space CubeSat missions will address this issue
    - INSPIRE, NEA Scout, Lunar Flashlight, MarCO, Europa CubeSats?
- Survival
  - CubeSat temperature at closest solar approach
- Deployment
- Communications
- Power