Ten Gram Interplanetary Spacecraft

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FISO seminar

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Outline

- NEOs and how few we've seen
- solar radiation pressure
- example solar sails and the need to get < 10 g/m^2
- design for BLISS
- trajectories with a_c=1 mm/s^2
- design for BEARS - so much more maneuverable!

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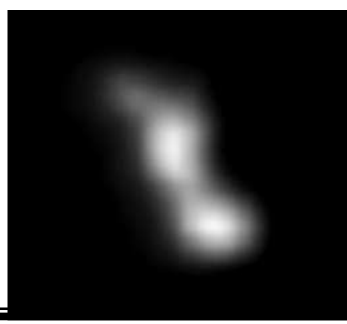
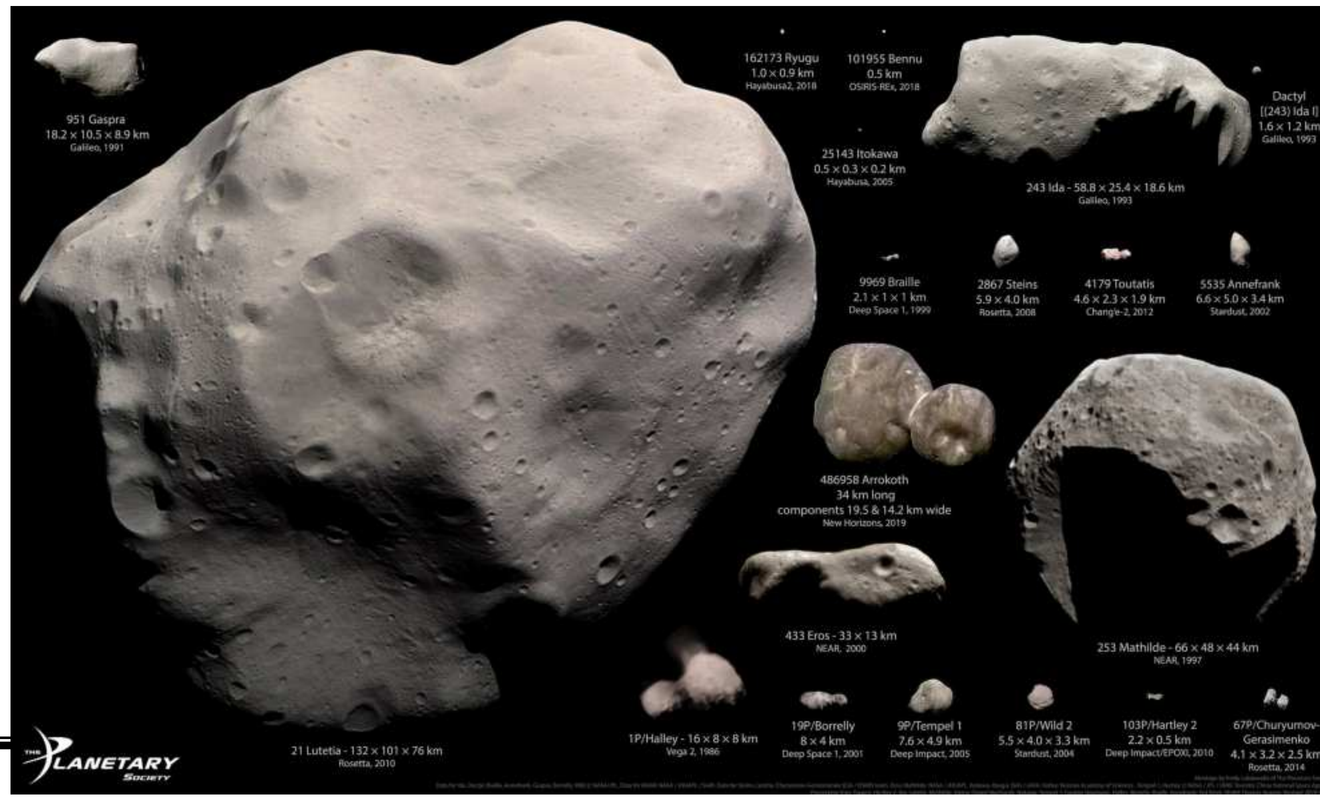
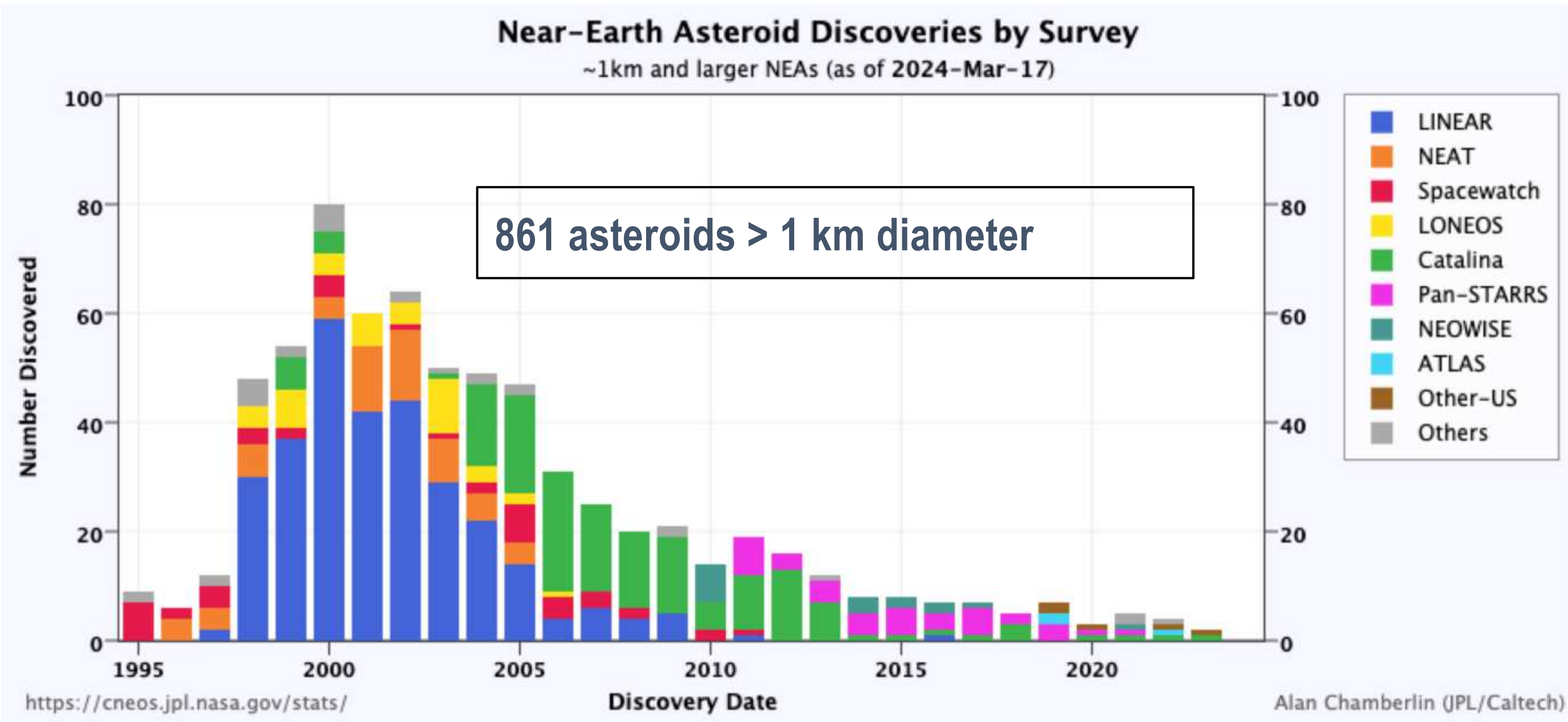
Visiting Asteroids

- 18 visited, 6 Near Earth
- 4 landings (1 impact), all Near Earth
- 16 planned in next decade





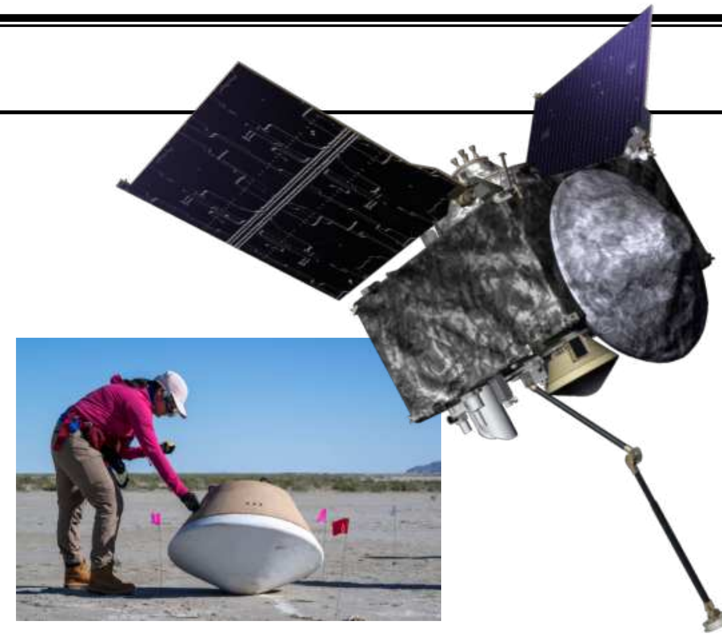
Target asteroids

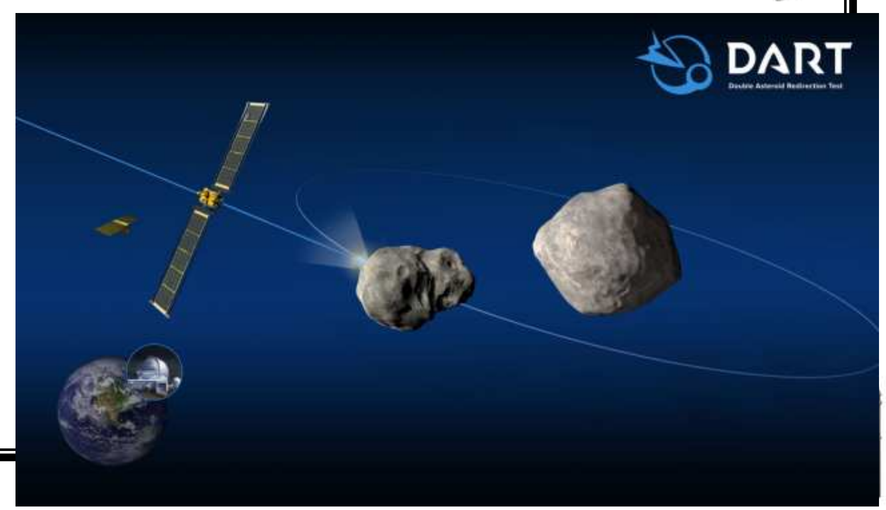


861 asteroids > 1 km diameter

Amazing science, but not cheap

- New Horizons (2006) - $700M
- OSIRIS-REx (2016) - $800M
- DART (2021) - $330M
- Lucy (2021) - $560M
- Psyche (2023) - $1B





Wouldn't we like to know more?

- Who knows what we will find?
- Our Mission:
  - bring a cell phone camera close to a NEO
  - take a few GB of pictures
  - come home
  - transmit the data
- Optimize: size and cost

BLISS: Berkeley Low-cost Interplanetary Solar Sail

- 1st mission: photograph 1,000 largest NEOs
- Science payload: 12 Mpixel cell phone camera
- Mission profile
  1) Deploy in GEO
  2) Spiral out from earth orbit
  3) Transit and match orbits with NEO
  4) Photograph from < 1km distance
  5) Return to earth
  6) Spiral in to GEO
  7) Transmit images
  8) Repeat

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Solar Radiation Pressure

Light has momentum

$$P\ [N/m^2] = S\ [W/m^2] / c$$

At 1 AU, for a perfectly reflective sail

$$P_0 = 2\ G_{SC}/c = 9\ \mu N/m^2$$

At 1 AU and an angle α (the cone angle)

$$P(\alpha) = P_0 \cos^2\alpha$$

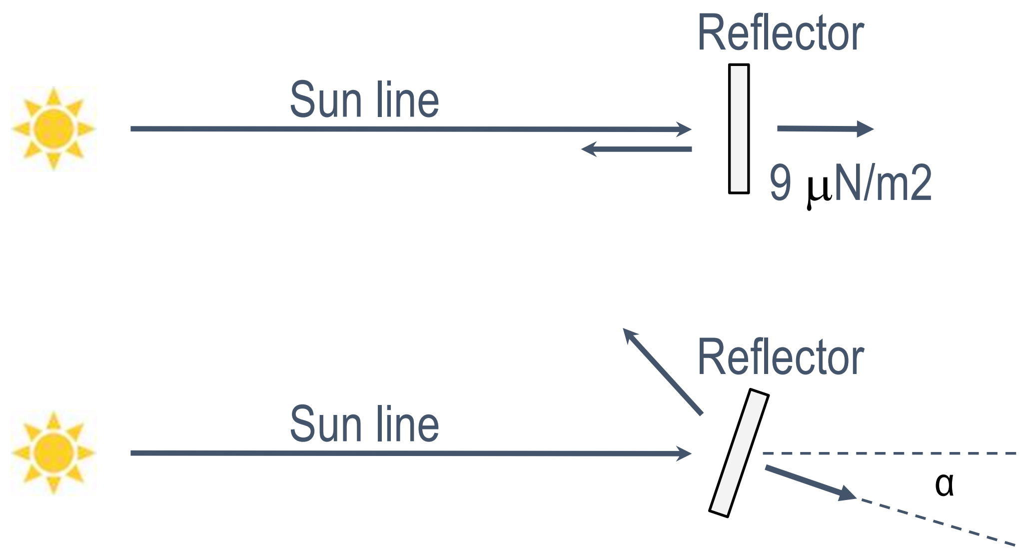
And a distance R

$$P(\alpha, R) = P_0 \cos^2\alpha\ \ (1\ AU/ R)^2$$

Acceleration

$$a_c = P_0\ A / m = P_0 / \sigma$$

σ = sail mass loading



Solar gravity

Earth gravity acceleration: 9.8 m/s^2 at the surface

Solar gravity acceleration:

6 mm/s^2 at 1 AU = 150,000,000 km

$a_{solar}(R) = (6 \text{ mm/s}^2)(1 \text{ AU}/R)^2$

Sail acceleration due to solar radiation pressure

$a(\alpha, R) = a_c \cos^2\alpha \; (1 \text{ AU}/R)^2$

Beta = (peak sail accel) / (solar gravity accel)

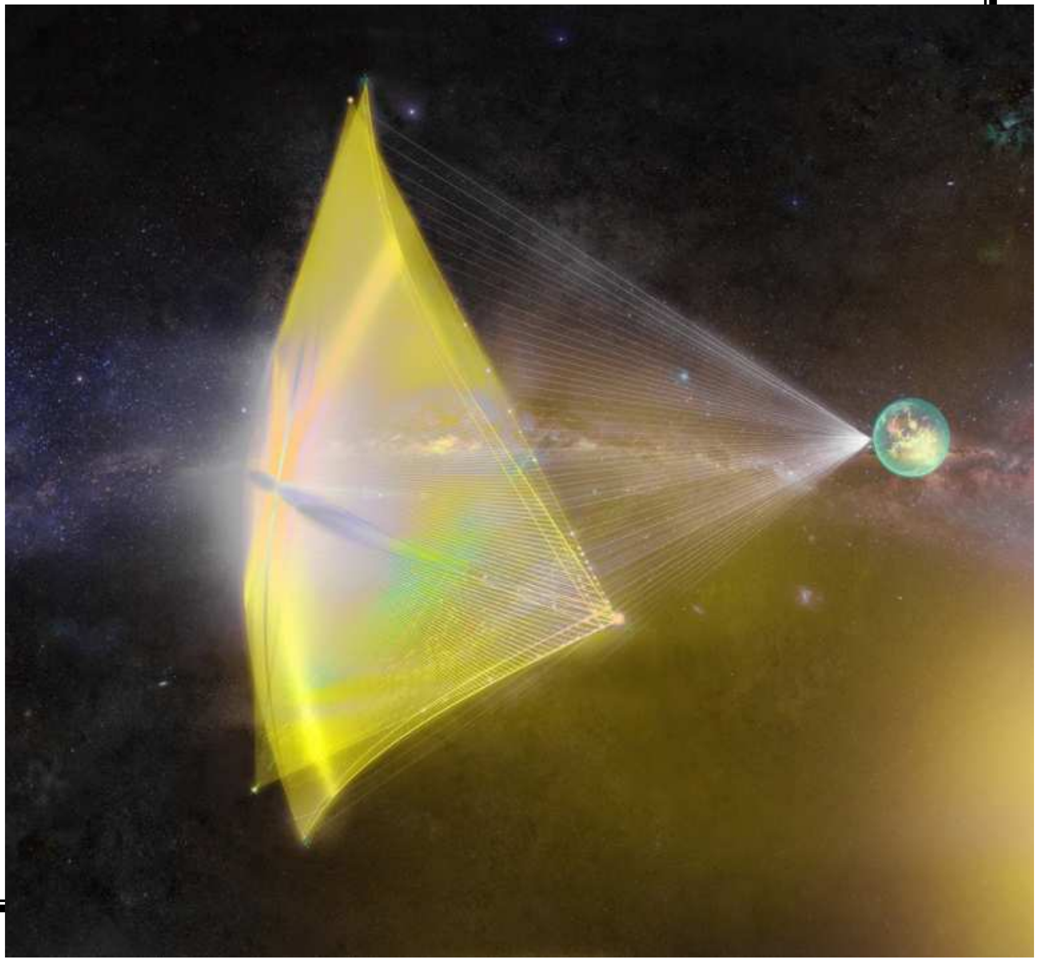
$\beta = a_c / (6 \text{ mm/s}^2)$

$= P_0 / (6 \text{ mm/s}^2) / \sigma$

$$\begin{cases} \dot{\boldsymbol{r}} = \boldsymbol{v} \\ \dot{\boldsymbol{v}} = -\dfrac{\mu}{r^3}\boldsymbol{r} + \beta\dfrac{\mu}{r^4}(\boldsymbol{r}\cdot\boldsymbol{n})^2\boldsymbol{n} \end{cases}$$

Breakthrough Starshot – a very different vision

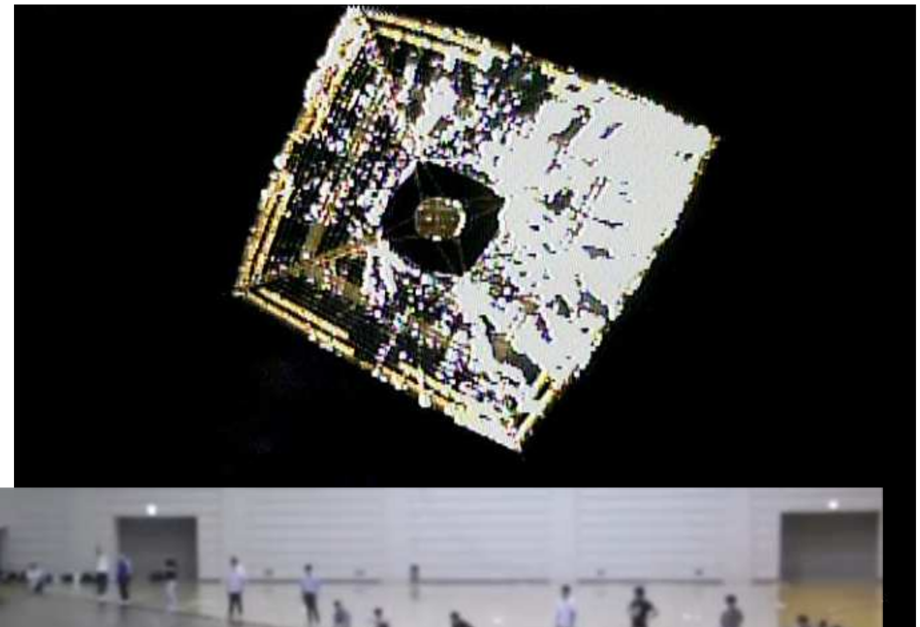
- Laser-powered sail to Alpha Centauri
- *Many* fundamental challenges



- What can we build with off-the-shelf tech?

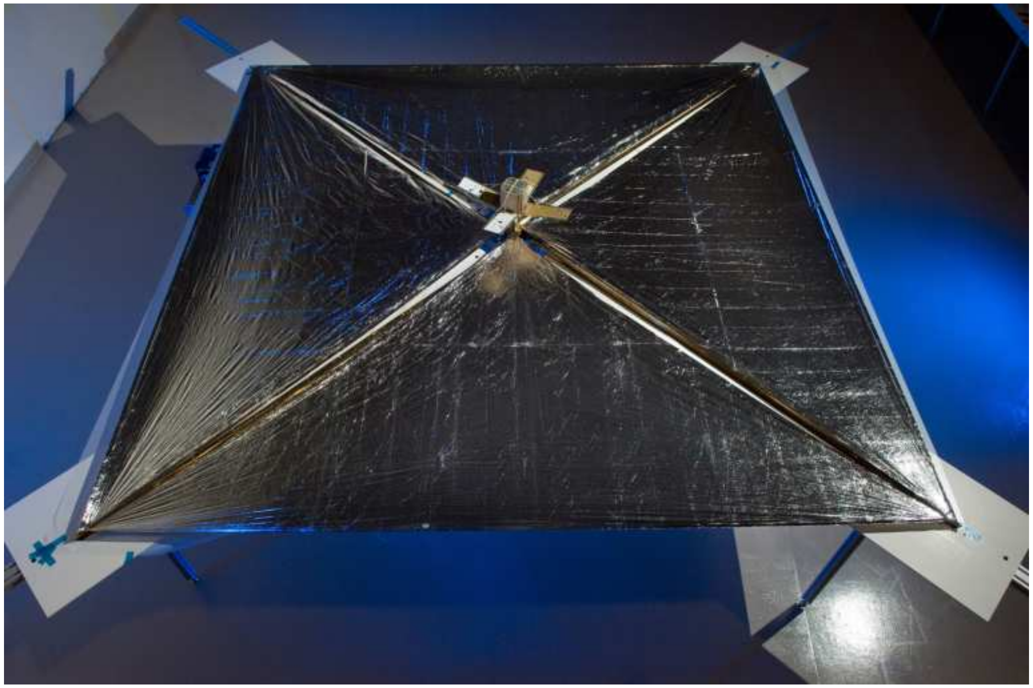
Solar Sail History – IKAROS (2010)

- Venus flyby
- 310 kg
- 200 m^2 sail, 7.5um polyimide
- σ = 1,500 g/m^2
- Sail had a measurable impact on velocity (m/s)
- Liquid crystals for attitude control (0.5 degree/day)



Nanosail-D (2010)

- Destroyed on launch (Falcon-1)
- 4.5 kg
- 9.3 m^2 sail
- σ = 500 g/m^2



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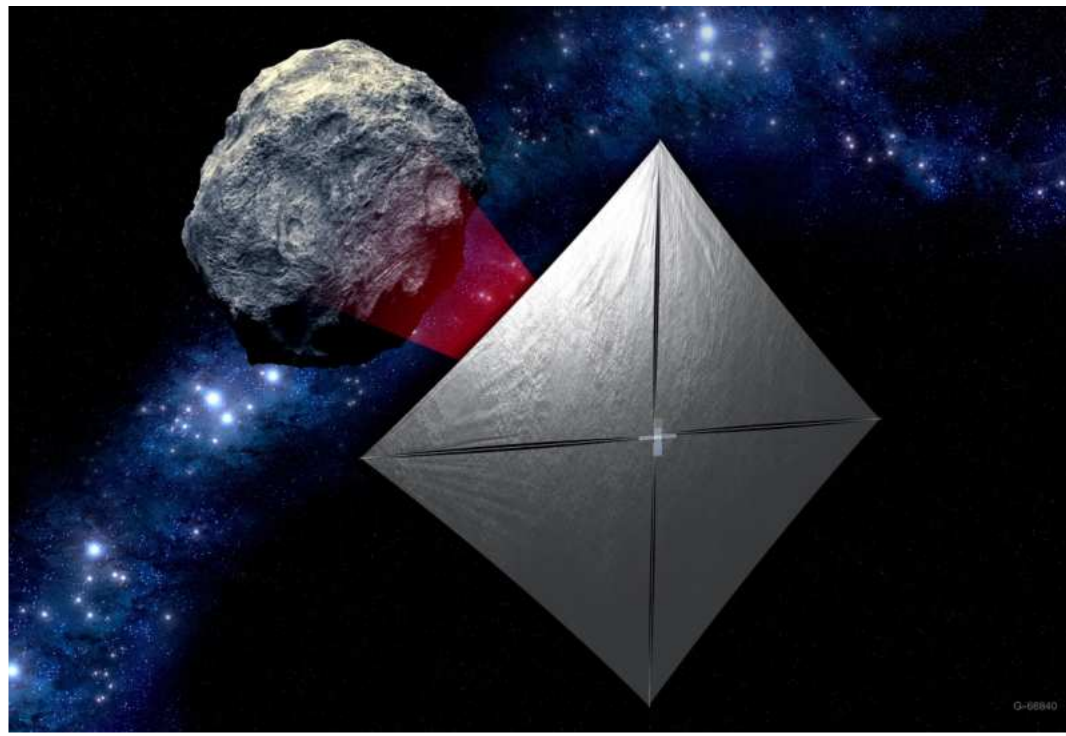
Lightsail-2 (2019)

- 3U cubesat
- 5 kg
- 32 m^2 sail
- σ = 160 g/m^2
- 720 km initial orbit
- Sail had a measurable impact on orbit

NEA-Scout (2022)

- Lunar flybys → asteroid
- Lost – no comms
- 6U cubesat
- 14 kg
- 85 m^2 sail, 2.5um thick
- σ = 165 g/m^2



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Effect of cone angle

- Maximize force along velocity
  - $\alpha = 0.6$
  - increase orbital energy
  - spiral out, slow down

- Oppose solar gravity
  - $\alpha = 0$
  - lower effective mu
  - step change in a, e

- Maximize force along velocity
  - $\alpha = -0.6$
  - decrease orbital energy
  - spiral in, speed down

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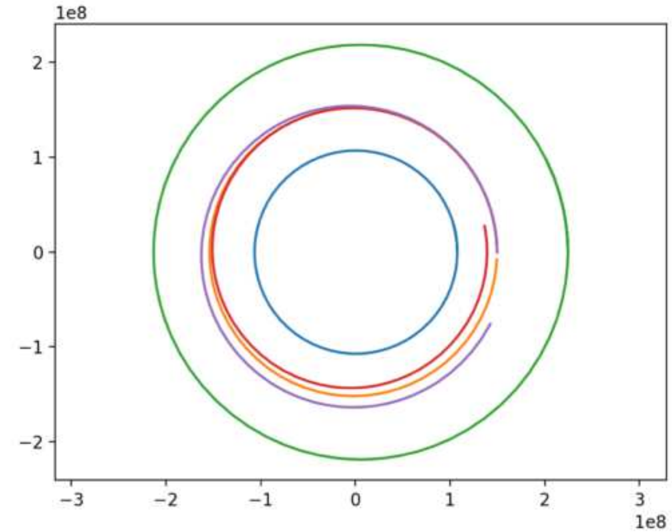
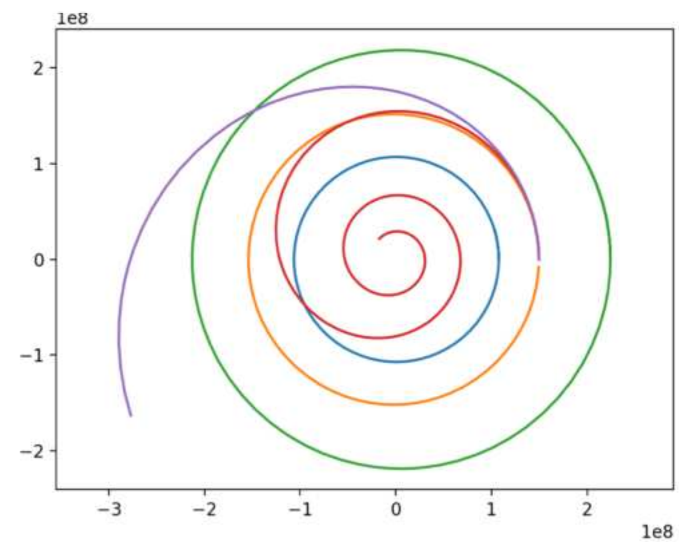
The effect of mass loading, σ

- 1 year sailing
  - One goes in, α = -0.6
  - One goes out α = 0.6
- Compare to Lightsail-2
  - 160 g/m^2 – best to date

80 g/m^2



8 g/m^2



How do we get to 8 g/m^2 ?

- The sail can be 1 um mylar (BoPET)
  - 50 nm aluminum frontside
  - 20 nm chromium backside (thermal radiation)
  - 1.5 g/m^2
- Deployment of large sails is hard
- Make the sail small!
  - Sail launches flat, 1to 5 meters in diameter
  - carbon fiber around circumference
  - carbon fiber control lines
- Can we make the rest weigh < 6 g?

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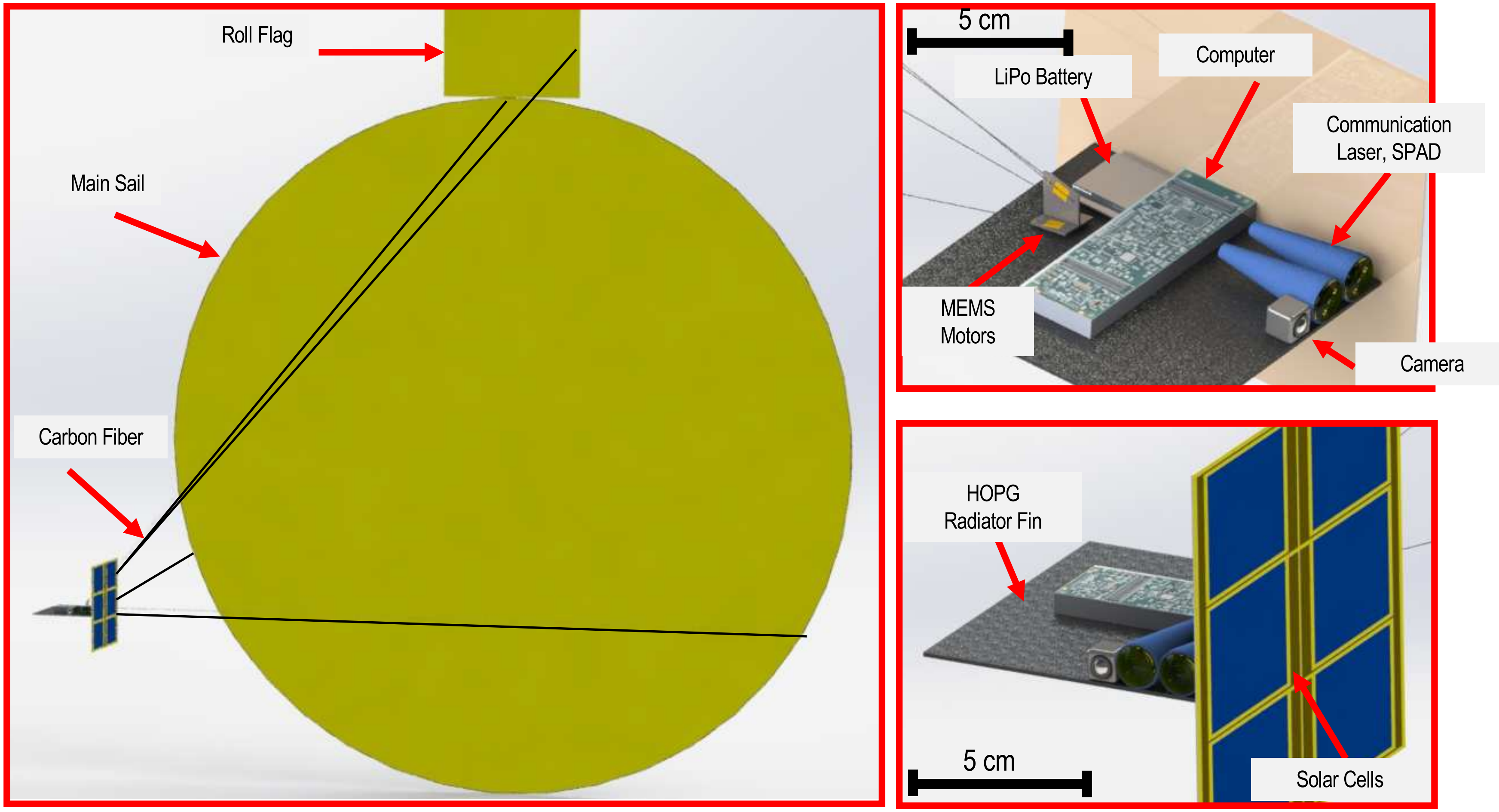
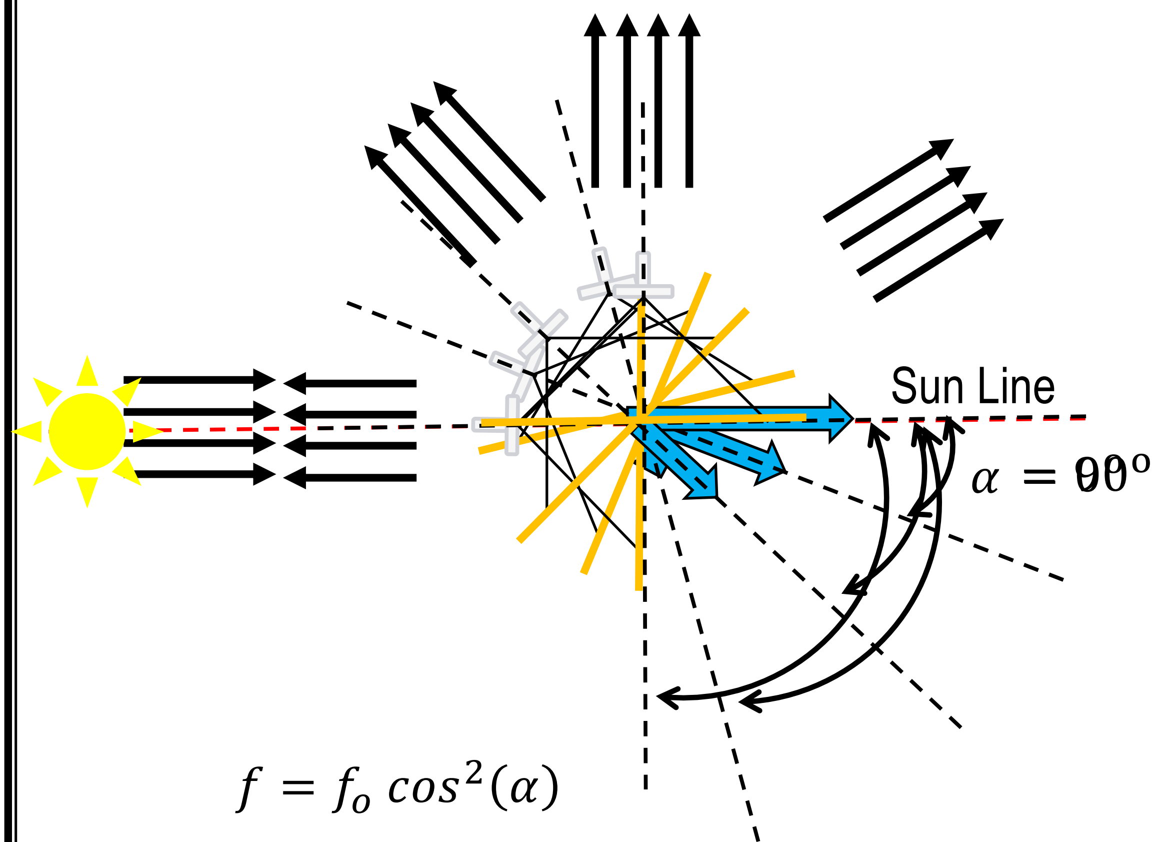
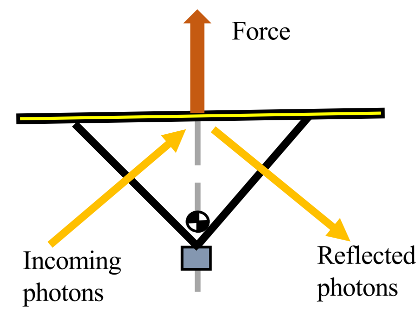
BLISS components

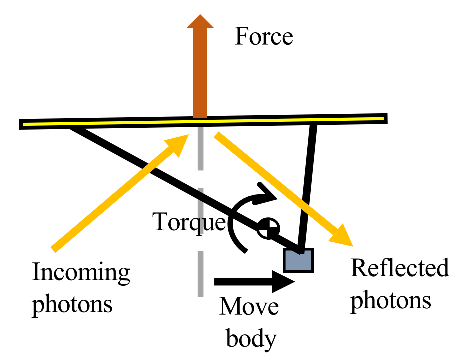


Force, yaw & pitch control



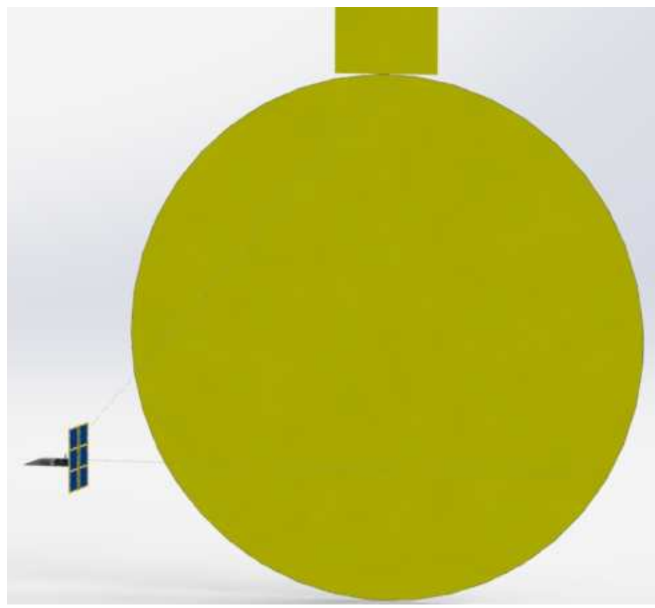
$$f = f_o \cos^2(\alpha)$$

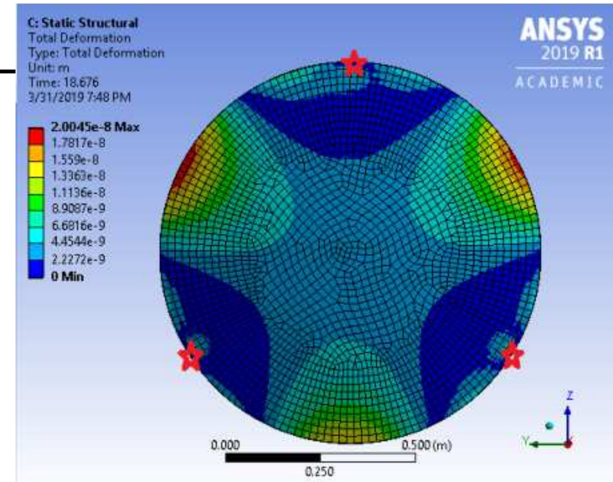


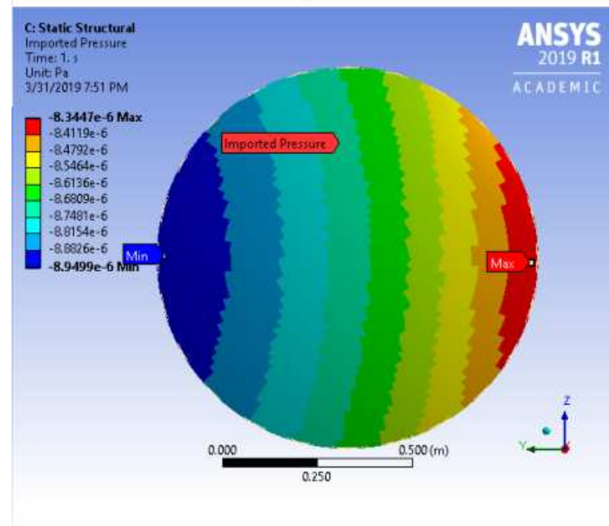


Sail deflection simulation

- 1 m diameter sail
  - 1 um BOPET, 50 nm Al
- 3 carbon fiber shroud lines
  - 280 um diameter, 2 m long (don't buckle?!)
- Carbon fiber support ring
  - 17 nm deflection







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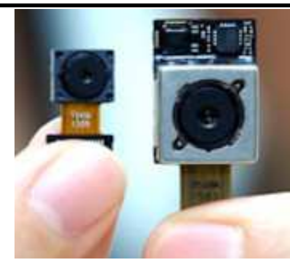
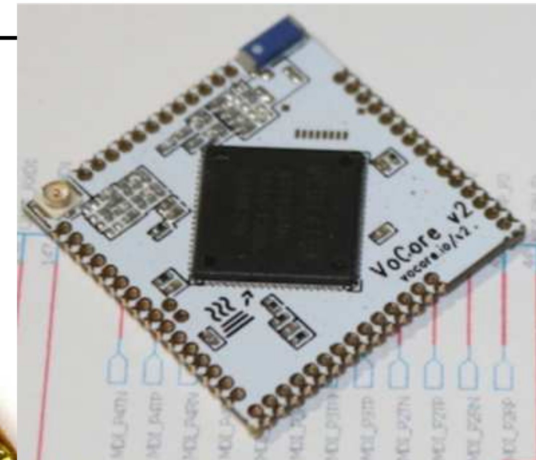
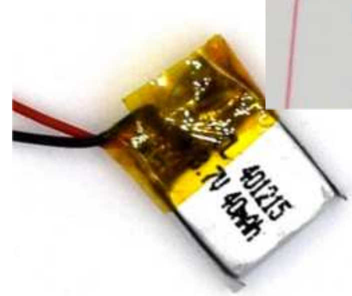
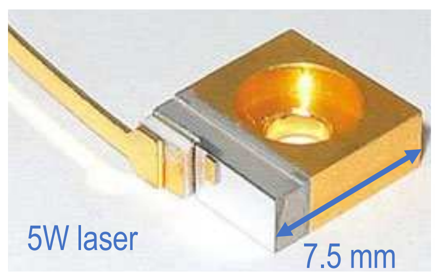
First Spacecraft (BLISS1) Components

- 12 Mpixel camera, < 1 g
- Vocore-2 single-board LINUX computer, 3 g
- Alta devices solar cells 10x10cm2, 2W, 2 g
- LiPo battery, 40 mAh, 1W, 0.3 g
- HOPG radiator fin, 5x10cm2, 1 g
- Optical transceiver, 2 g
- 1 m2 sail, 2 g





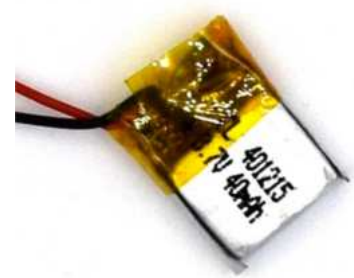




Power

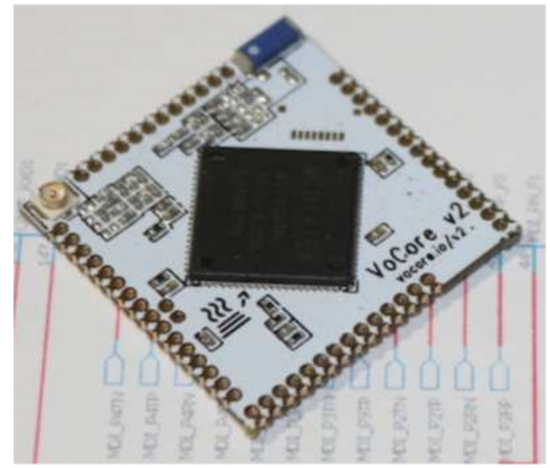
- Solar cells
  - 10x10 cm2
    - Alta devices? < 1 g/W
  - Several 2x2 cm2 to ensure some power at almost all orientations
- 3.7V, 40 mAh LiPo, 2W discharge

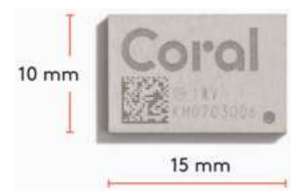
- Consumption
  - Camera: ~ mW
  - MEMS motors: ~mW
  - Processor: 1 W → 50 mW (> 2 hours on battery)
  - Communications: 2W



Computation

- Vocore 2 or equivalent
  - 580 MHz 32 bit LINUX
  - 128 MB RAM, 2TB microSD
  - Camera interface
  - graphics accelerator, DSP
  - Biggest mass item today (3 g)
    - Mostly PCB
- Coral TPU
  - 4 TOPS (tera-ops/sec)
  - 2W
- Custom CMOS version (future): < 1 g
  - Image processing
  - Rad hard





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Tapeout Class: EE194

- 1 semester
- 20 undergrads/chip
- Intel 16 – intrinsically rad-hard
- It works!
    - RISC-V processor(s)
    - analog
    - RF

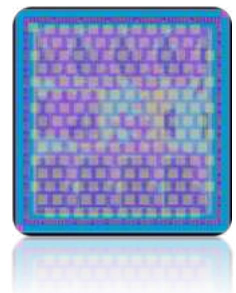
SOCMonkey

Spring 2017
ST 28 nm

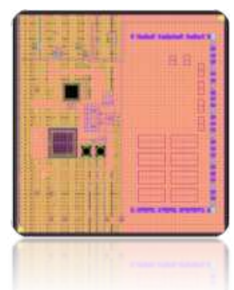
OSCIBear

Spring 2021
TSMC 28nm

BearlyML22

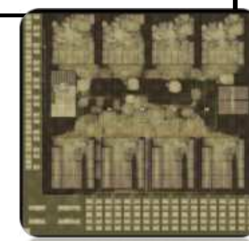


SCuM-V22

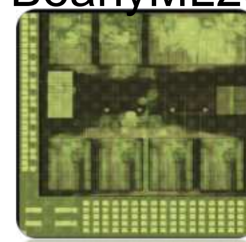


Spring 2022
Intel 16

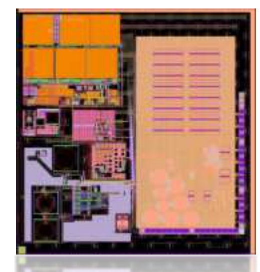
RoboChip



BearlyML23



SCuM-V23



Spring 2023
Intel 16

Radiation

- Failure rate of 0.1 per year would be fine
- Hopefully get a ride to GEO to avoid Van Allen belts
- No shielding (too much mass)
- Interplanetary space
  - 0.1 Gy/year?
  - ~5x worse than LEO? (different spectrum)
- Solar Proton Events – 50 Gy in a few hours?
- Electrostatic charging
- Gumstix computers survive 64 MeV, 200 MeV proton flux (Kathleen Morse)
  - Expect ~3 SEU/day
  - Rad-tolerant software

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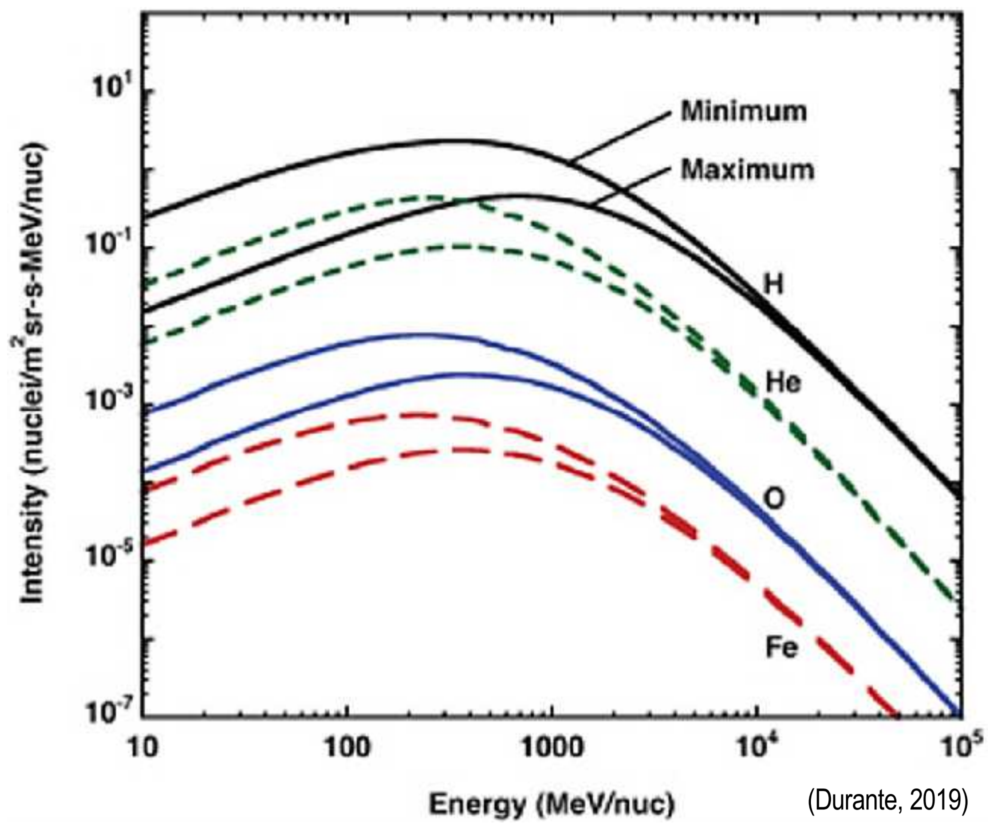
Radiation and Electronics

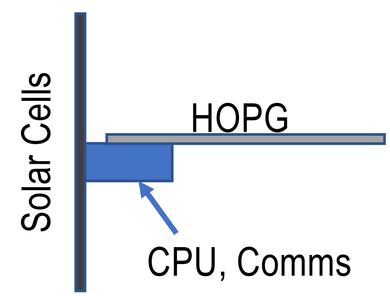
- Sources
  - Galactic Cosmic Rays
  - Solar Flares
  - Coronal Mass Ejections
  - Van Allen Belts
- Total Ionizing Dose
  - Fine-line CMOS *less* sensitive
- Single Event Effects
  - Rad-hard design
    - Redundancy
    - Error Correcting Codes
    - Watchdogs
    - Checkpointing (software)
- Planet, SpaceX examples



(Durante, 2019)

Temperature Control

- Battery (0…40?), laser (-10…60), electronics (-40…+85)
- HOPG Radiator fin
  - Panasonic PGS (Pyrolytic Graphite Sheet)
    - 50 um thick
    - 1300 W/mK conductivity in-plane
    - 1.7 g/cc
  - 10x10 cm^2 fin, 0.9 g
  - Radiate > 5 W w/ 10 C temperature difference
- HOPG heat spreader
- Solar cells
- Solar reflector
- Rotate spacecraft as necessary to shade/expose fin
- Run processor/comms to raise temp (if necessary)



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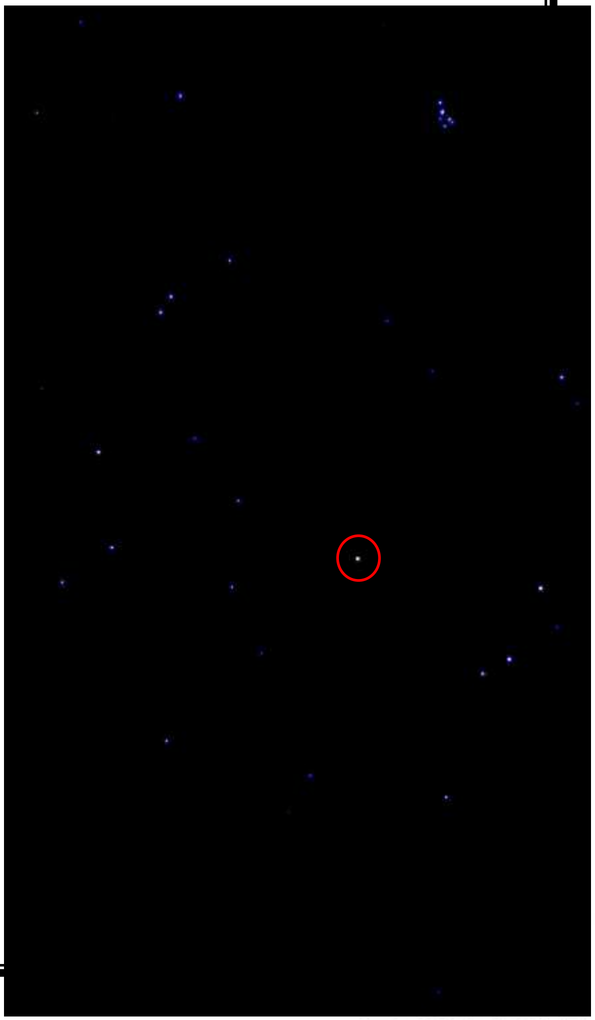
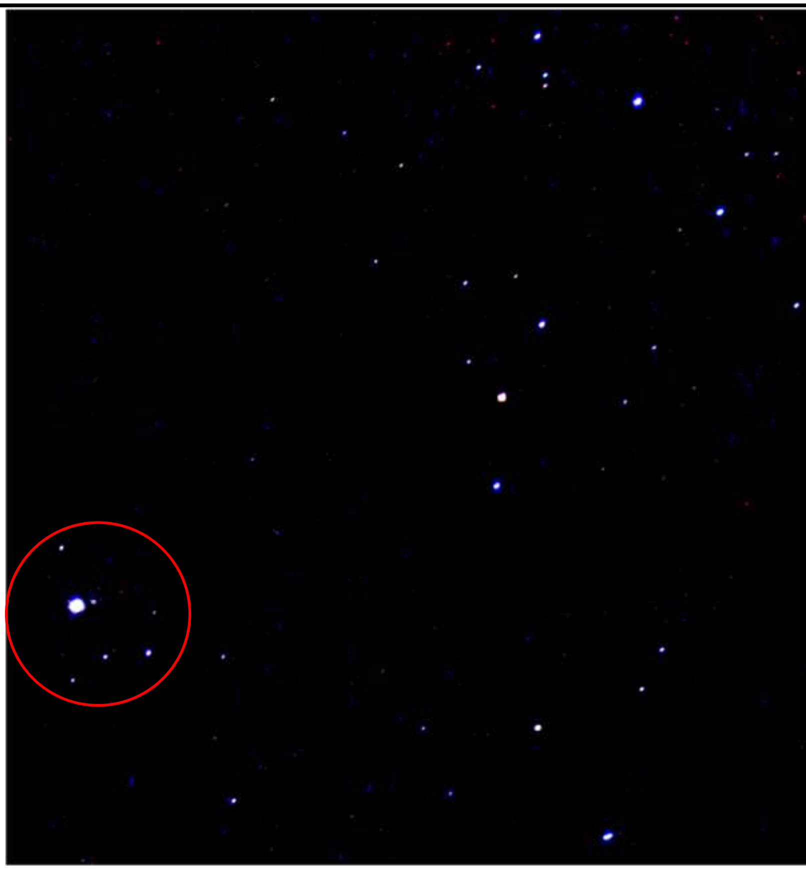
Cell Phone Camera

- Take pictures of NEOs
- Solve initial “Lost in Space” problem
- Determine location of inner six planets for rough localization
  - Pixel spacing ~ 0.1 mrad (20 seconds of arc)
  - Airy disk ~ 0.3 mrad (62”)
  - From literature, resolution ~10x better than pixel spacing → 0.01 mrad (2”)?
    - Existing cubesat star trackers claim to be around 2” to 10”
  - 10k to 100k km error from single planet

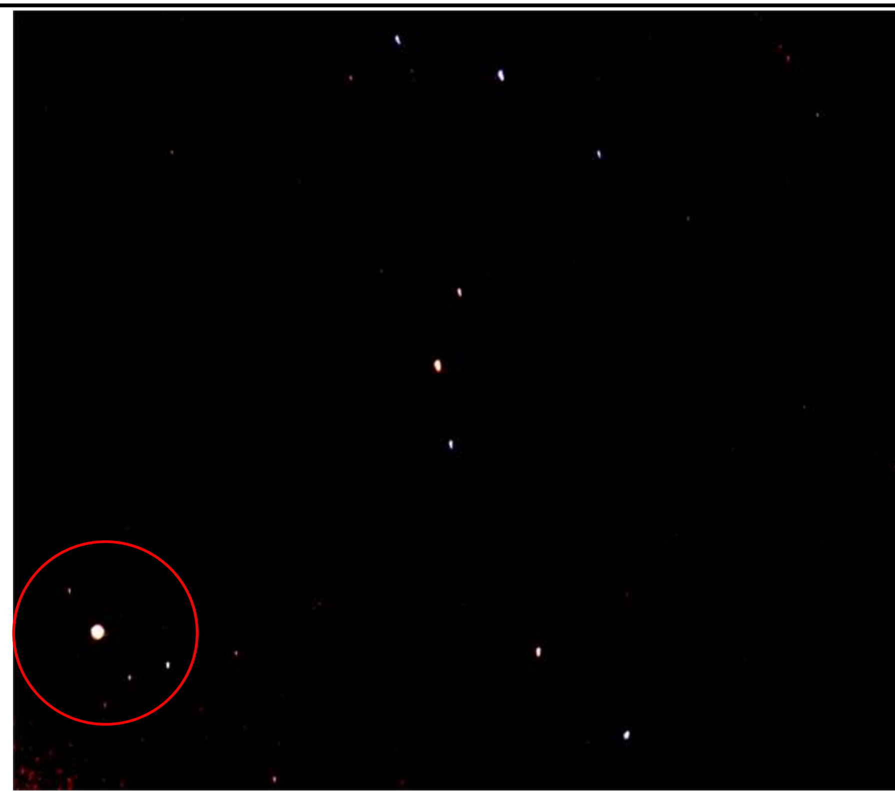
Venus, Saturn, Moon, Jupiter, Mercury, Mars (iphone SE, NightCap)



Jupiter, Poipu HI



3/2/19 5:13 AM



2/28/19 5:34 AM

I traveled ~5 million km between these two pictures
Jupiter has traveled ~2 million km

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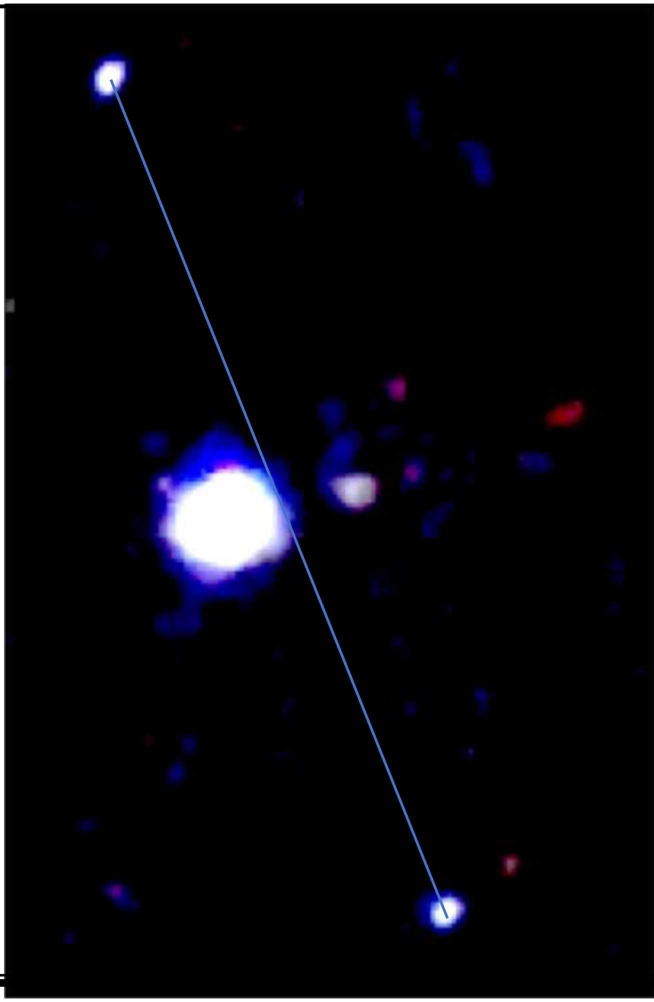
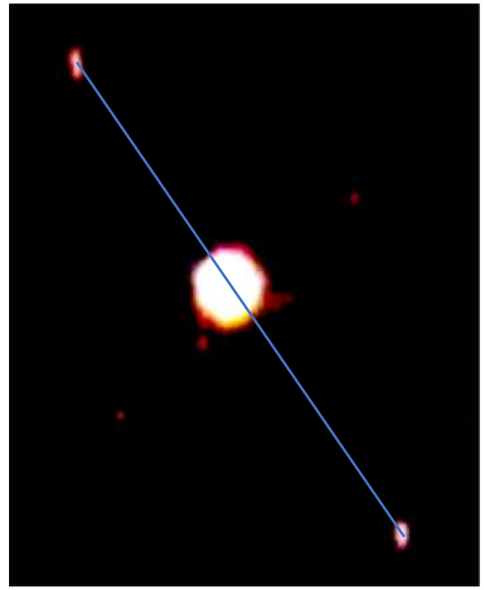
Jupiter, Poipu HI

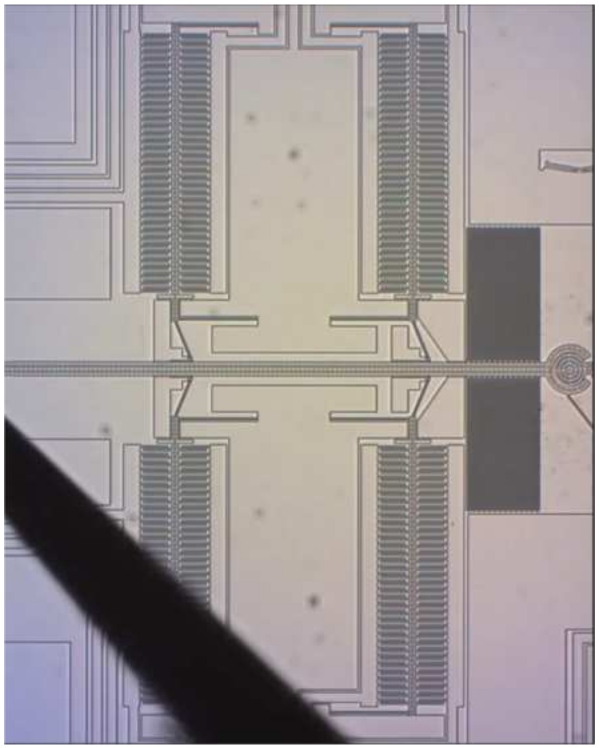


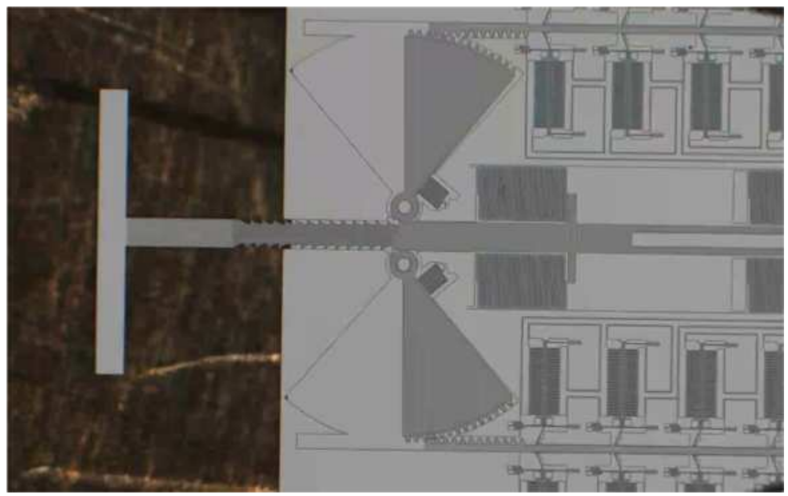


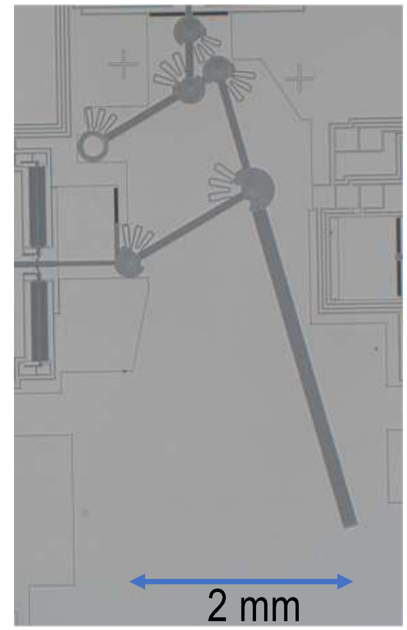
Jupiter ~24 pixels across, has moved ~1 radius?
12 pixels → 5 million km
500,000 km/pixel?

MEMS motors to pull shroud lines

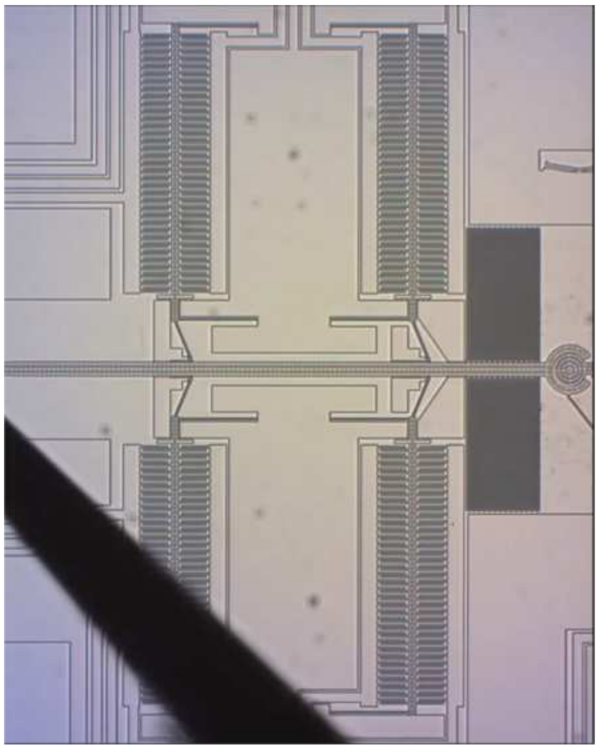
- Electrostatic inchworm motors
- 40 um thick silicon motors

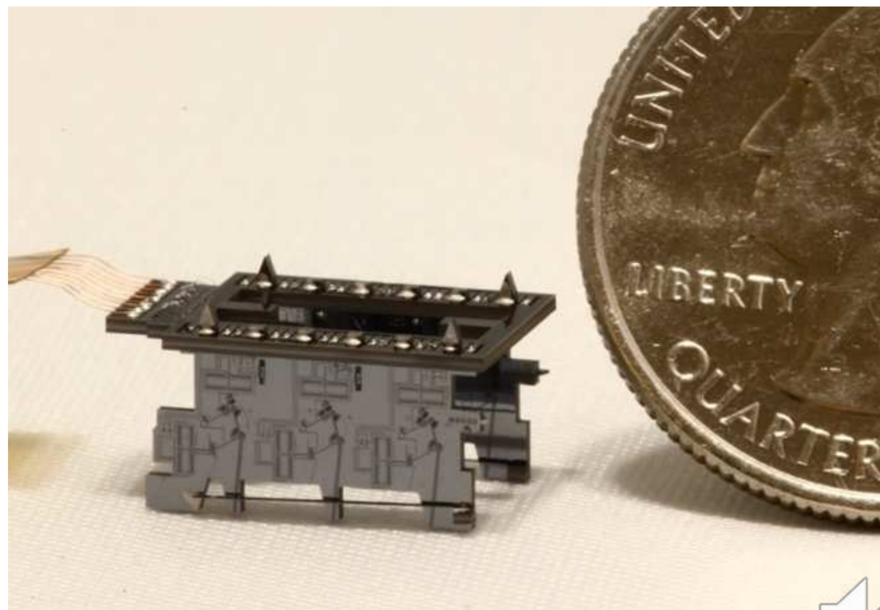






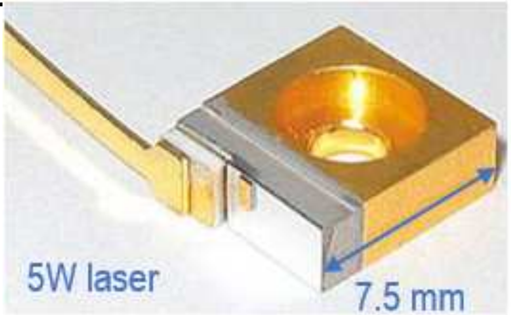
Silicon Motor, Silicon Hexapod

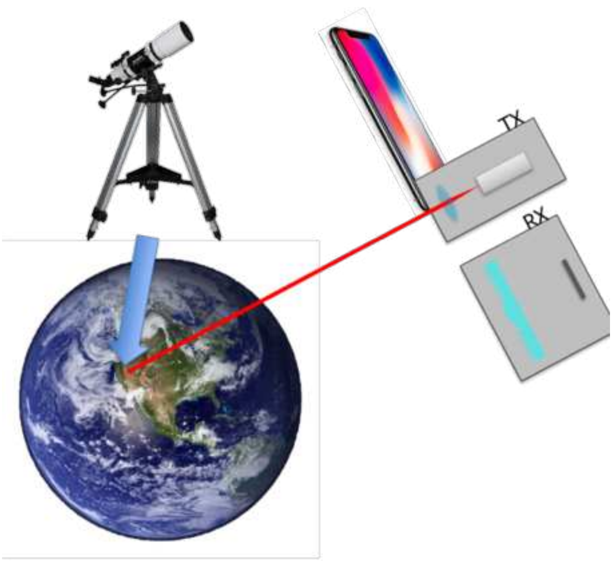




Communication

- Return to GEO
- Use camera to point at Berkeley
- Laser transmit ~1Mbps to small telescope
- RX is SPAD – single photon avalanche diode



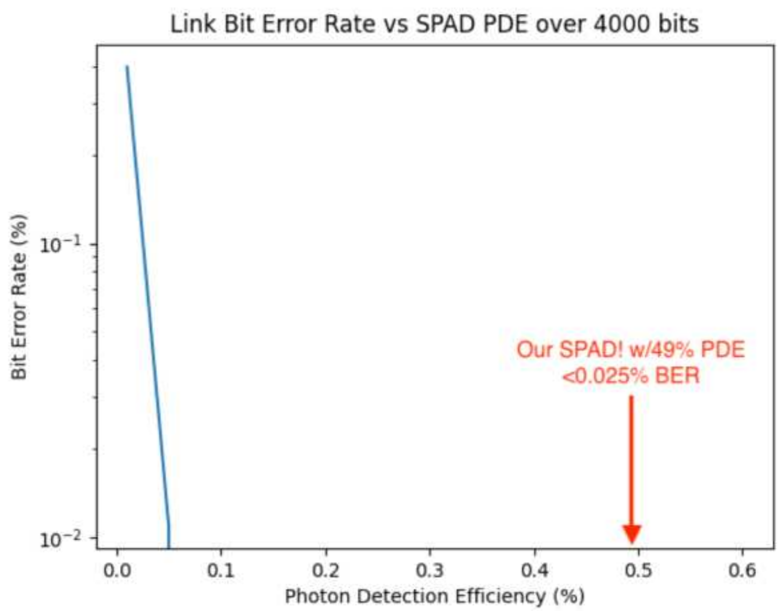


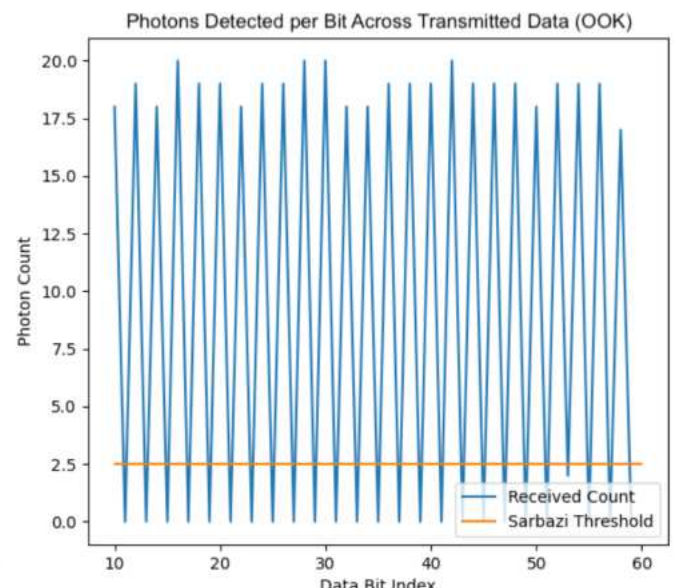
Dr. Lydia Lee

Laser comm, GEO → Berkeley

- 5W Transmit **35,680km**
  - 5W -> **64.9pW** received (180 photons/μs, dead time limited)
  - **1Mbps** (1us / bit) Link w/ **near zero bit error rate**

Bhuvan Belur

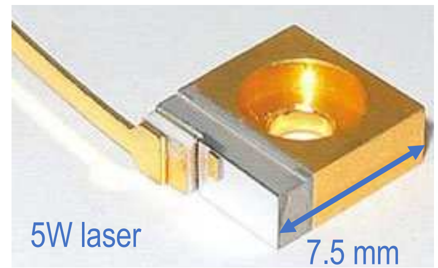




Transmitted data was a binary inverting series (101010...)

Laser Communication

- LASER
  - Wide range of laser wavelengths available
  - > 35% wall-plug efficiency
  - Peak power over 5W
- Detector
  - SPAD (single photon avalanche diode)
  - 50% quantum efficiency
  - Dark counts < 1000 c/s



- 1 cm apertures, 5W optical power, 10^6 km → > 1 photon/μs → ~ 1 Mbps
- Pulse-position modulation
  - Each symbol: 5W, 1 us, in one of 8 positions
  - 3 bits/symbol, 125 kS/s
  - < 2 W wallplug
- …but…need 0.1 mrad (20”) pointing accuracy at transmitter

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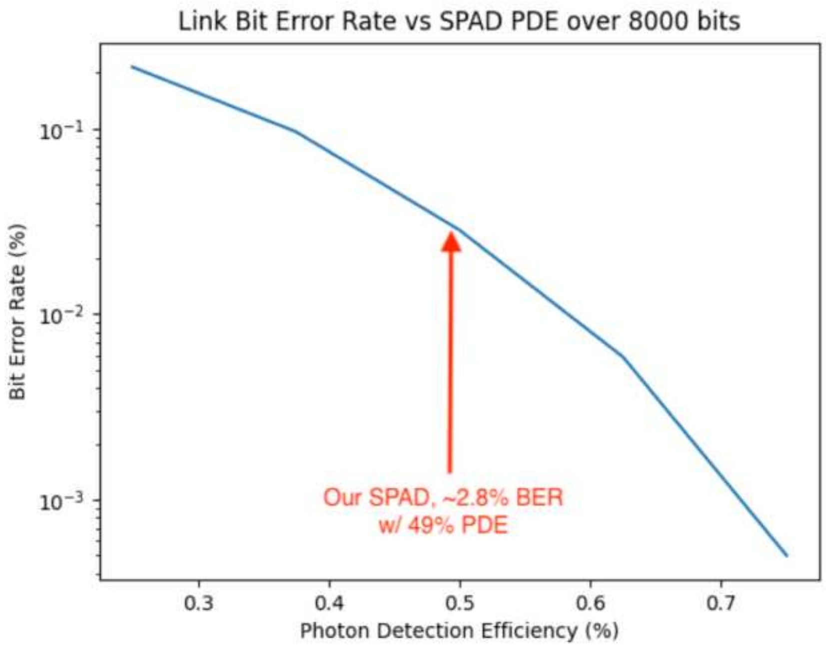
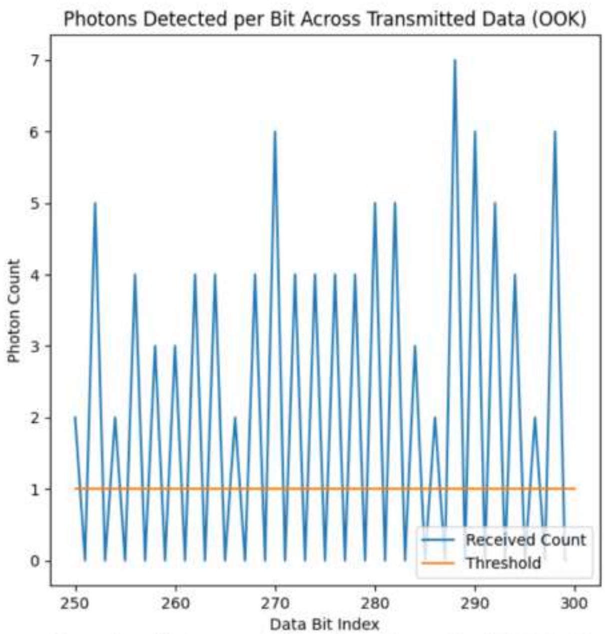
Scenario 2 : BLISS → BLISS

- 5W Transmit, **1,000,000km**
  - 5W -> **0.17pW** received (480 photons/ms, photon limited)
  - **50kbps** (20us / bit) Link w/ **2.8% BER**

$$A_T = 1cm^2$$
$$A_R = 1cm^2$$
$$\lambda = 550nm$$
$$R = 1,000,000km$$
$$\eta = 1$$
$$P_T = 5W$$
$$P_R = P_T \frac{A_T A_R}{\lambda^2 R^2} \eta = 0.17pW$$





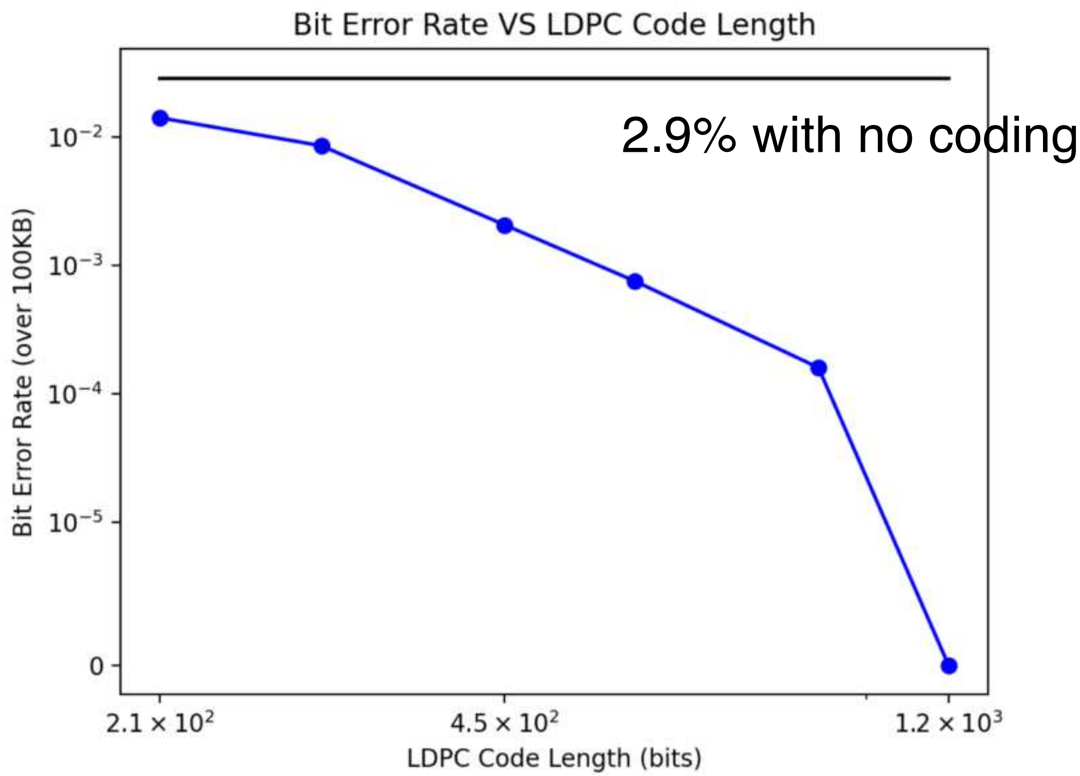
Transmitted data was a binary inverting series (101010...)

Bhuvan Belur

Error Correction Coding Results

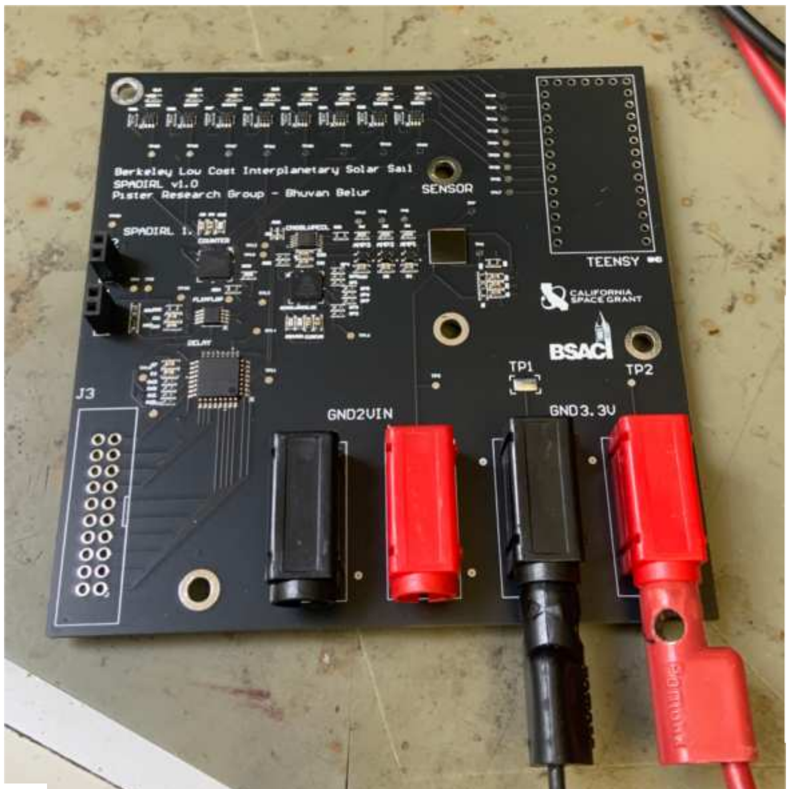
- Low density parity check code (LDPC)
- 12.5Kb packets
- 10% coding overhead → 100 kB w/ no errors

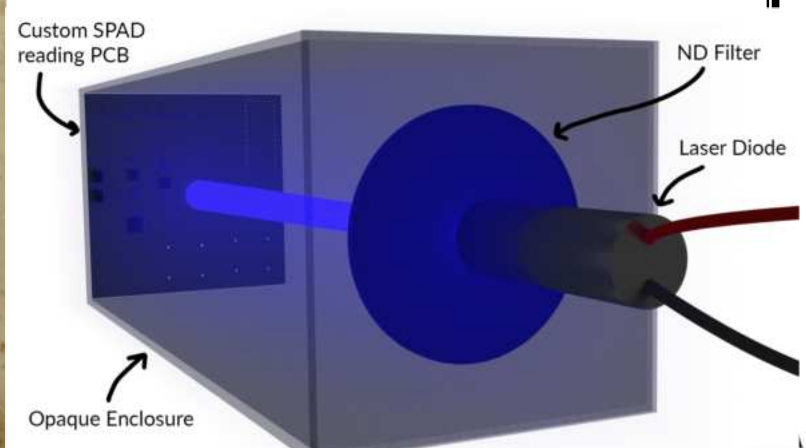
50 kbps between BLISS at 10^6 km!



Bhuvan Belur

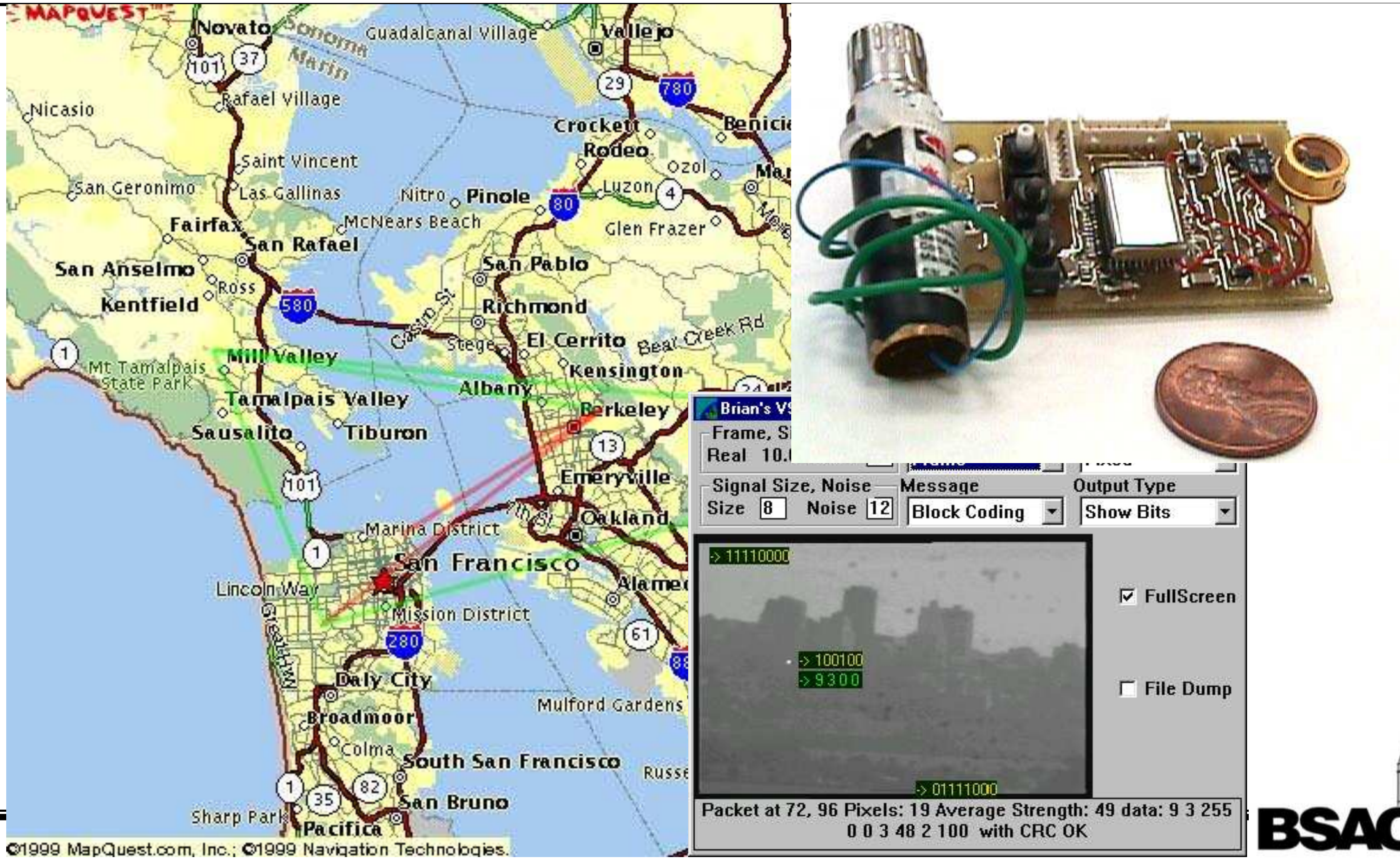
SPAD communication test board





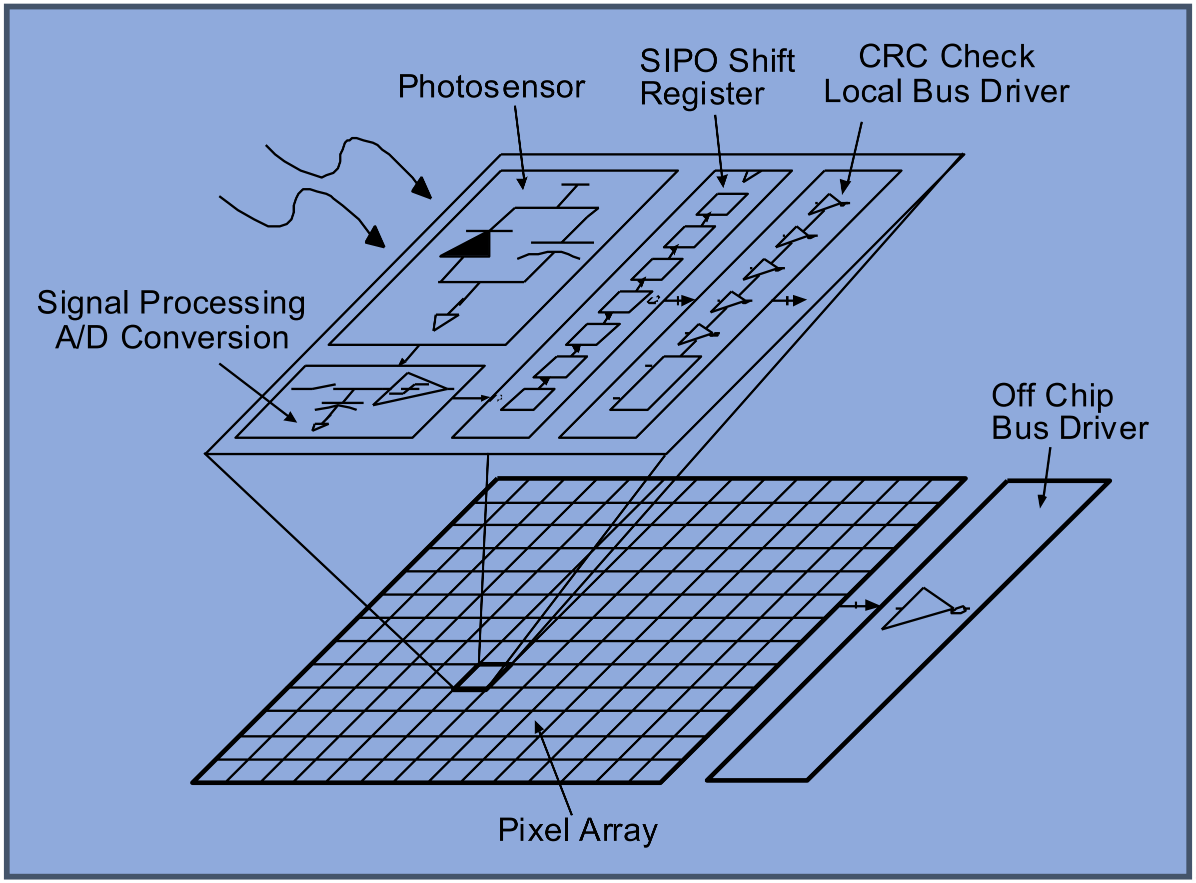
Bhuvan Belur

Video Semaphore Decoding - ~1999



CMOS Imaging Detector - 2004

- 8x8 array in 0.25um CMOS
  - 67 mW power consumption
- Orinda free-space link
  - 0.5 Mbps
  - 1 km range
  - 10 mW, 1 mrad laser div.
  - 1” collection aperture
  - 20 nW received
  - 12,000 photons/bit minimum



Leibowitz , Boser, Pister, “**A 256-Element CMOS Imaging Receiver for Free-Space Optical Communication”,** 2004

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BLISS: Berkeley Low-cost Interplanetary Solar Sail

- 1st mission: photograph 1,000 largest NEOs
- Science payload: 12 Mpixel cell phone camera
- Mission profile
  1) Deploy in GEO
  2) Spiral out from earth orbit
  3) Transit and match orbits with NEO
  4) Photograph from < 1km distance
  5) Return to earth
  6) Spiral in to GEO
  7) Transmit images
  8) Repeat

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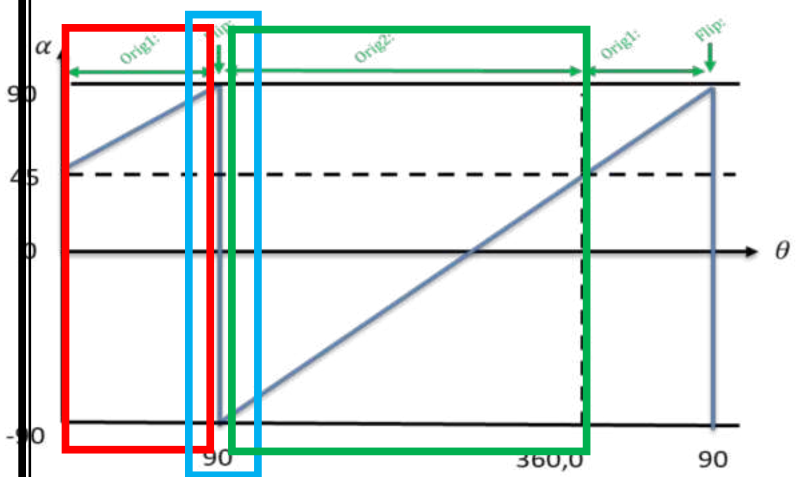
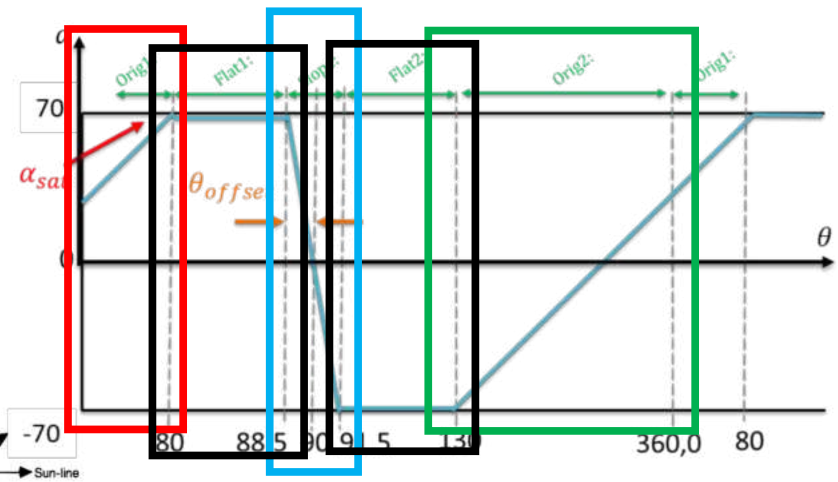
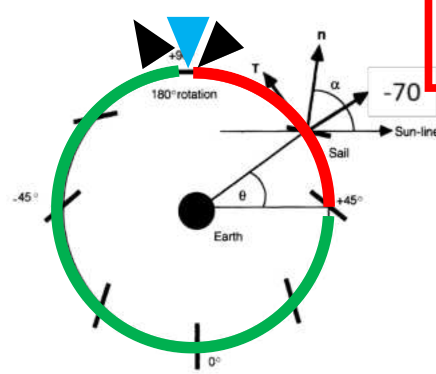
Escape from Earth!

McInnes' Orbit Rate Steering



Adjusted McInnes' Orbit Rate Steering using α_{sat} & θ_{offset}

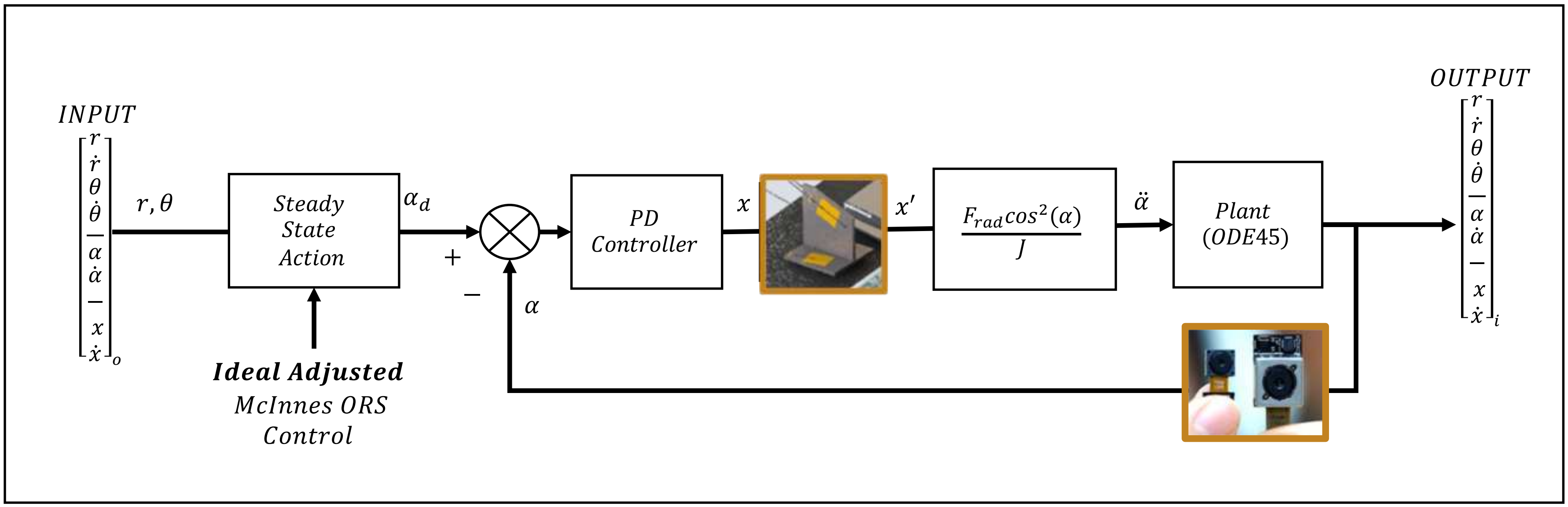




McInnes, Colin, *Solar Sailing: Technology, Dynamics and Mission Applications*, Springer, London, 2004

Matlab dynamics model for earth escape

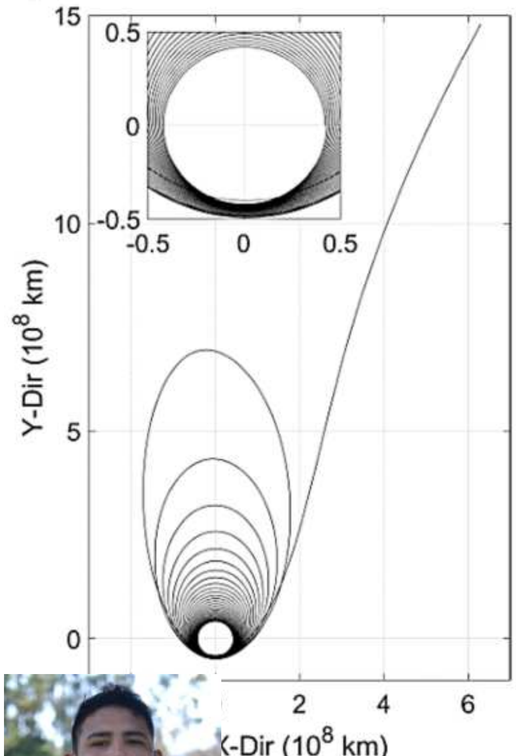
- Planar orbital dynamics
- Spacecraft rotational inertia
- MEMS actuator speed, displacement limits

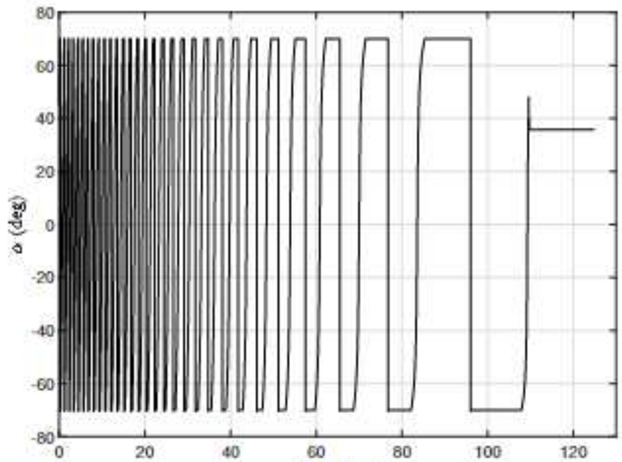


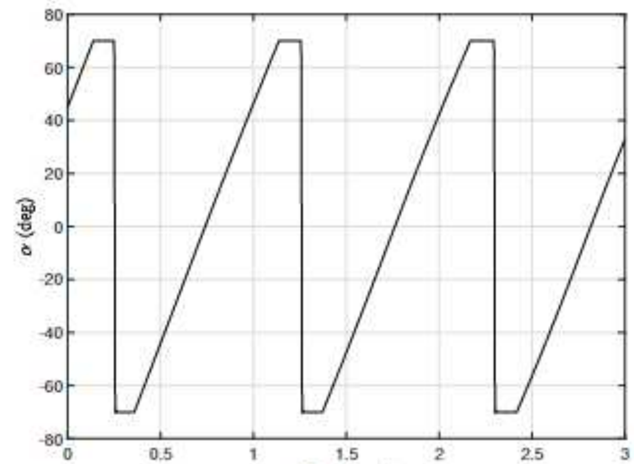
Alexander Alvara

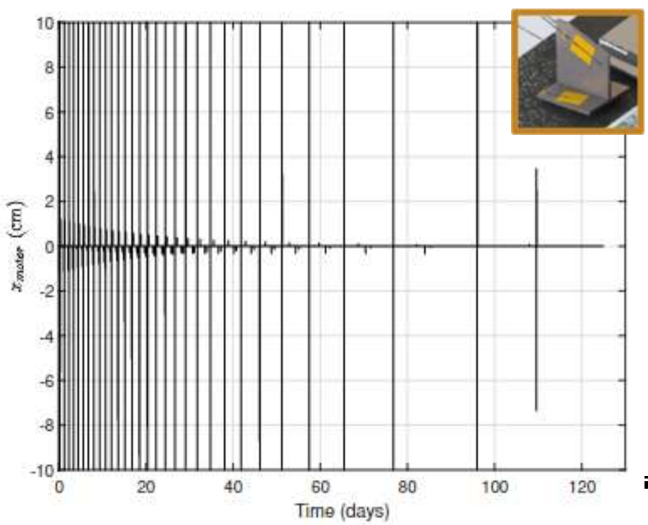
43

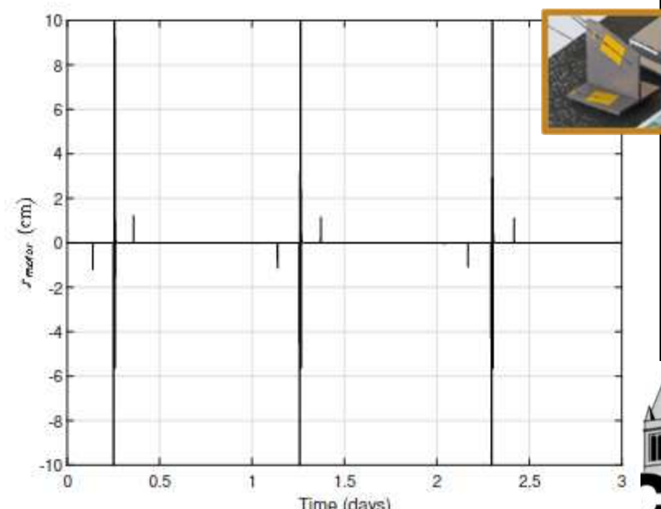
Escape from Earth! (in 4 months)



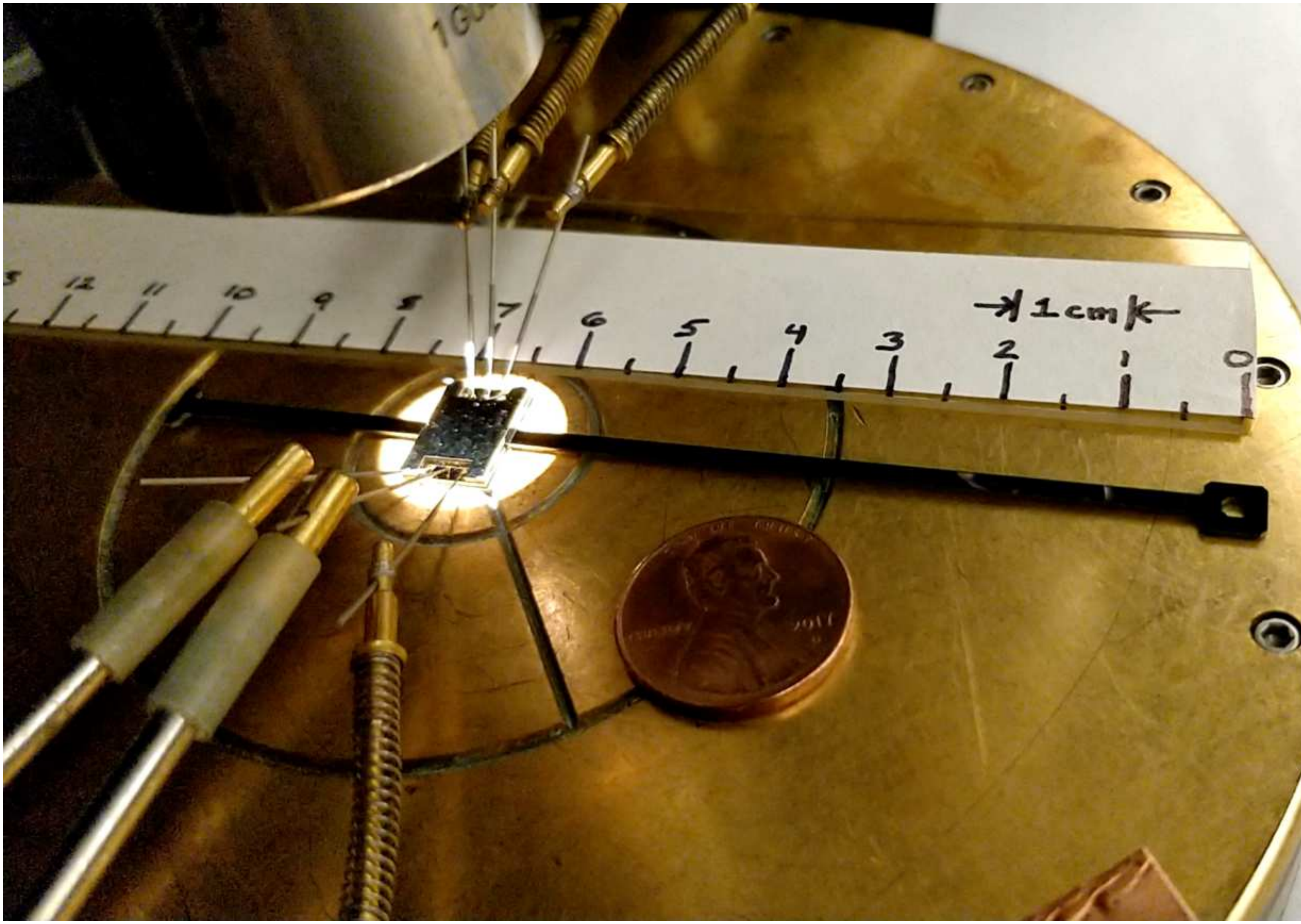


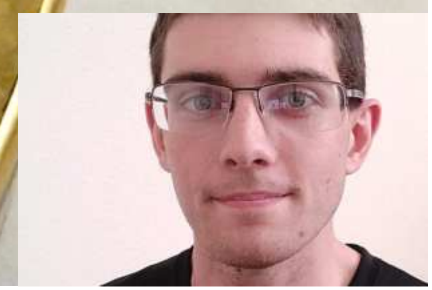






Alexander Alvara




Daniel Teal

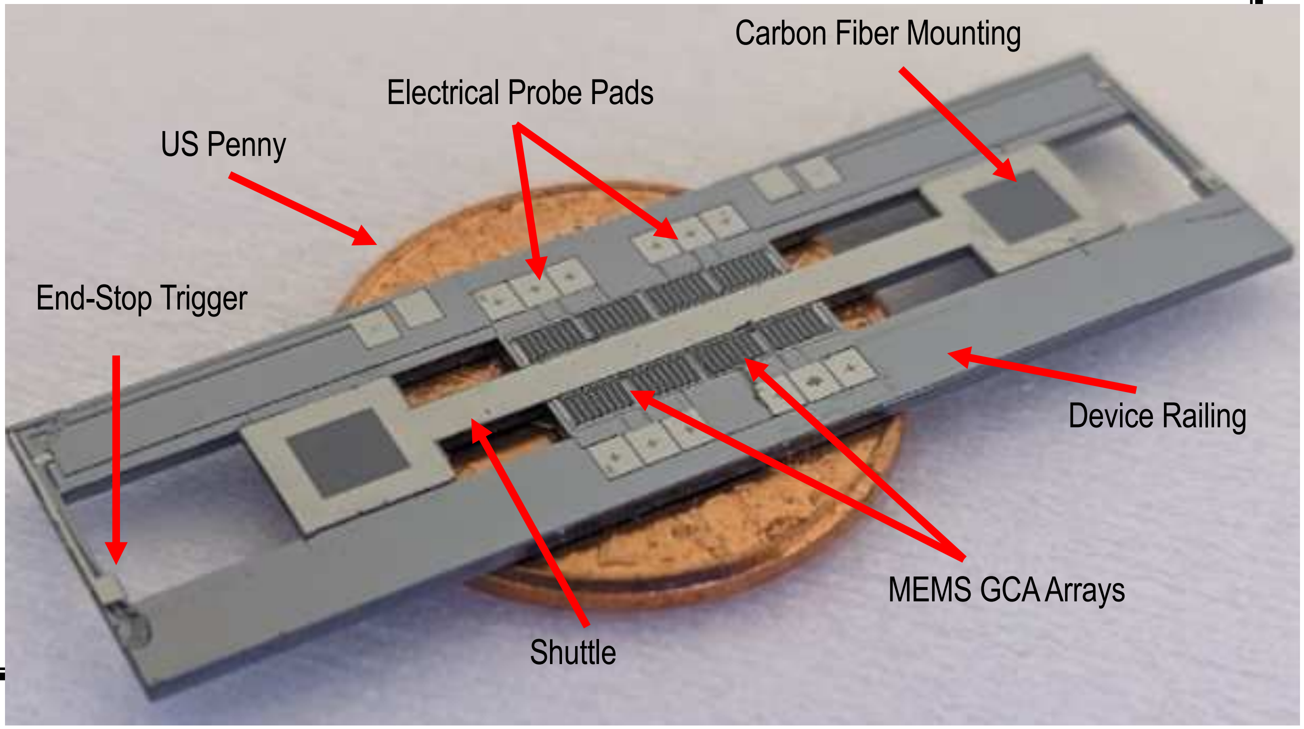
Bidirectional Electrostatic Inchworm Motors

Inchworms To Date

- Unidirectional
- Top speed: 400 mm/s
- Peak actuation force: 15 mN
- Max actuation distance: 8 cm

Need:

- Bidirectional
- Slower
- Lower force
- +/-10 cm



Alexander Alvara

BLISS: Berkeley Low-cost Interplanetary Solar Sail

- 1st mission: photograph 1,000 largest NEOs
- Science payload: 12 Mpixel cell phone camera
- Mission profile
  1) Deploy in GEO
  2) Spiral out from earth orbit
  3) Transit and match orbits with NEO
  4) Photograph from < 1km distance
  5) Return to earth
  6) Spiral in to GEO
  7) Transmit images
  8) Repeat

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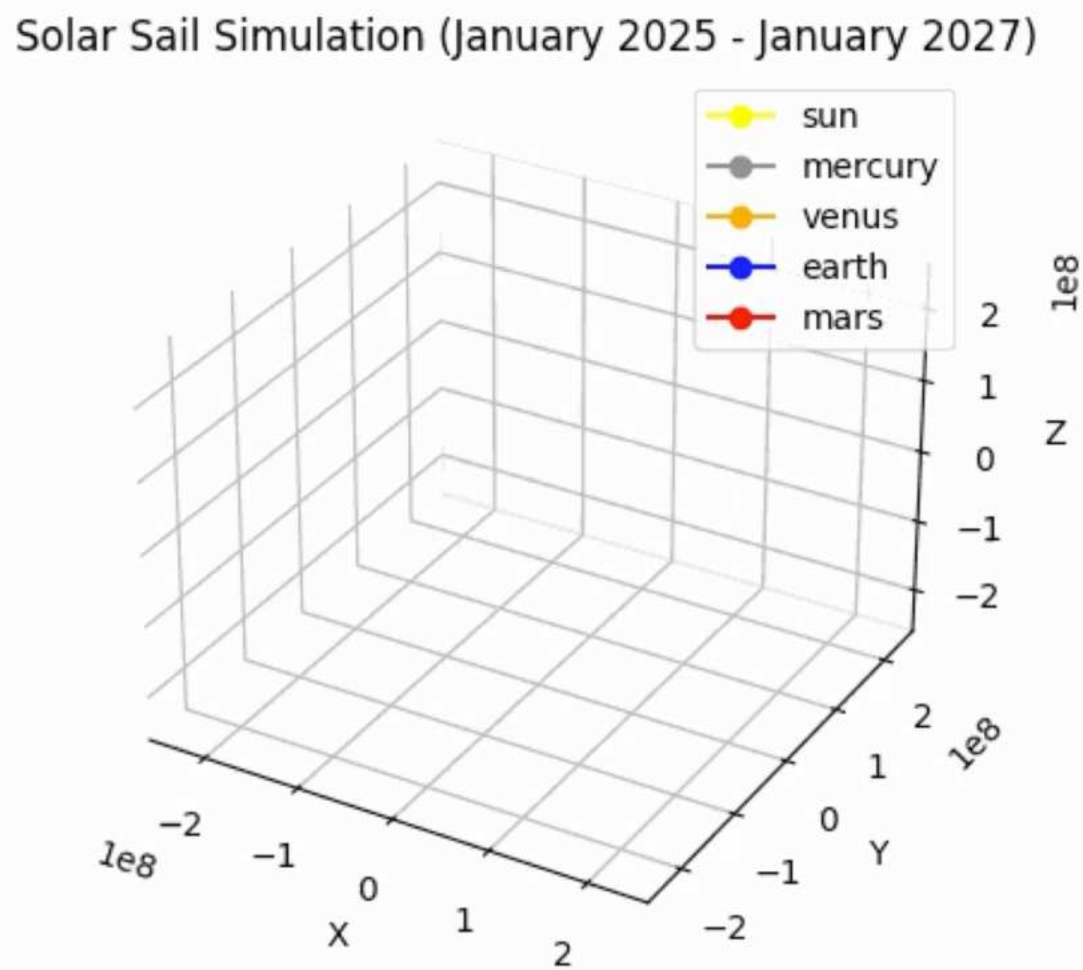
Trajectories

729 sails for 2 years

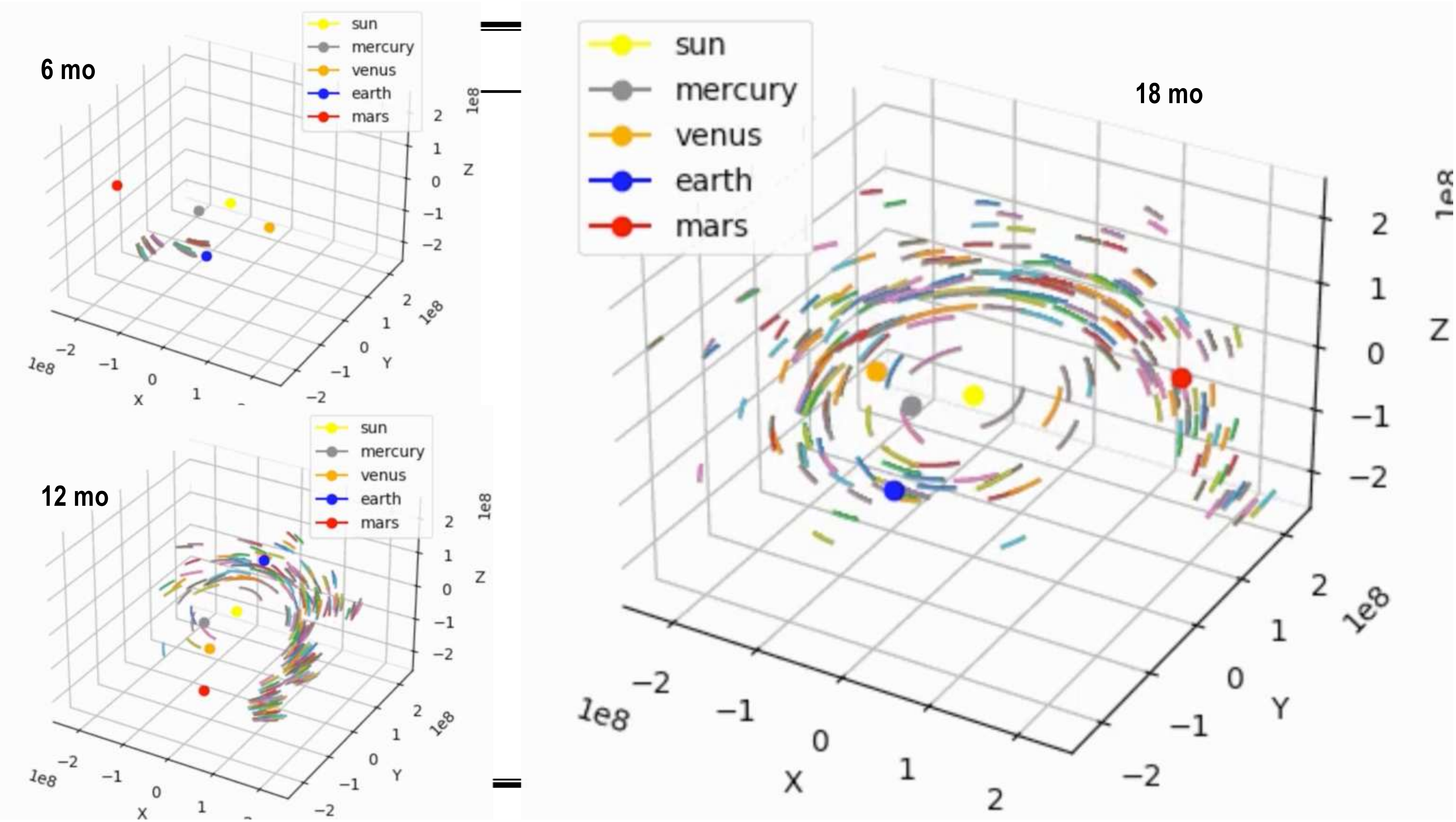
{-0.6, 0, 0.6} rad cone angle

switch every 2 mo. for 12 mo.

0 cone angle thereafter

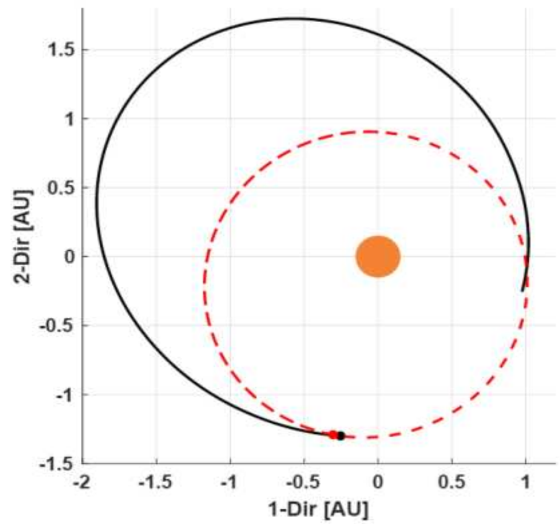


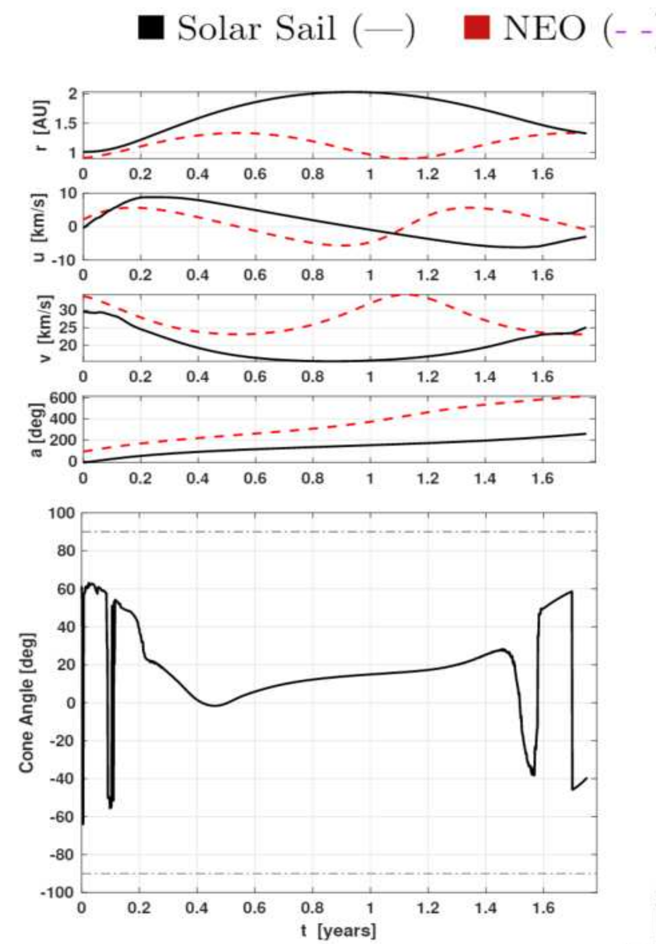
Andrew Ji, Marvin Lin, Shazaib Lalani,
Luke Harris, Matthew Cranny


6 mo
12 mo
18 mo
sun
mercury
venus
earth
mars
X
Y
Z
1e8

Optimizing interplanetary trajectories

- Impulsive (chemical) thrust is “easy”
  - Hohmann, slingshots, etc.
- Low thrust (ion) is harder
  - Optimal solutions published
- Solar sail: general solution remains unsolved
  - Mission to Bennu shown



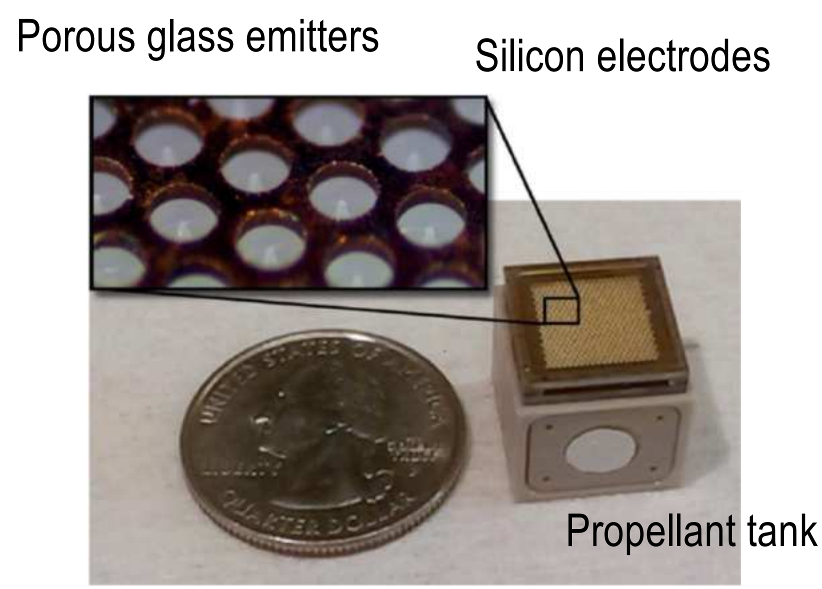


Dr. Emmanuel Sin

Ion thrusters are so much easier!

Electrospray thrusters

- Paulo Lozano, MIT
- Krejci2017 “Emission characteristics of passively fed electrospray microthrusters with propellant reservoir”
- EMI-BF4: 1-Ethyl-3-methylimidazolium tetrafluoroborate ionic liquid
- Isp ~760s
- Many thrusters run 60-90 hours w/o change. Max 172 hours (0.6g fuel) with increased potential
- Switch between positive and negative potential every 30 s.
- 35-40% efficient electrical→kinetic



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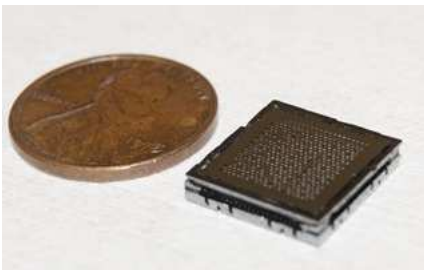
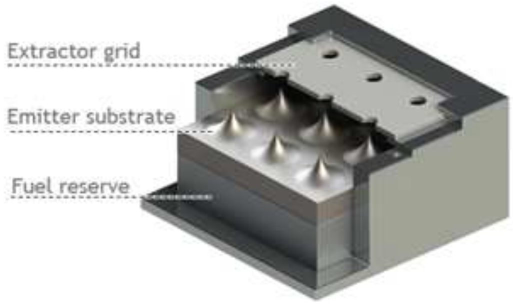
Accion (Natalya Bailey) Tile Electrospray Thruster





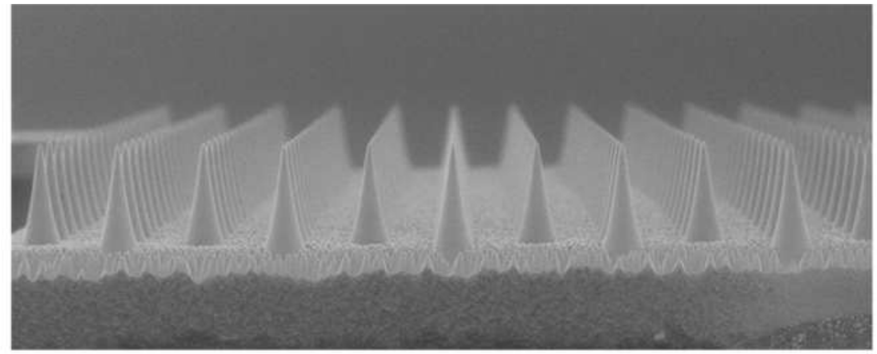
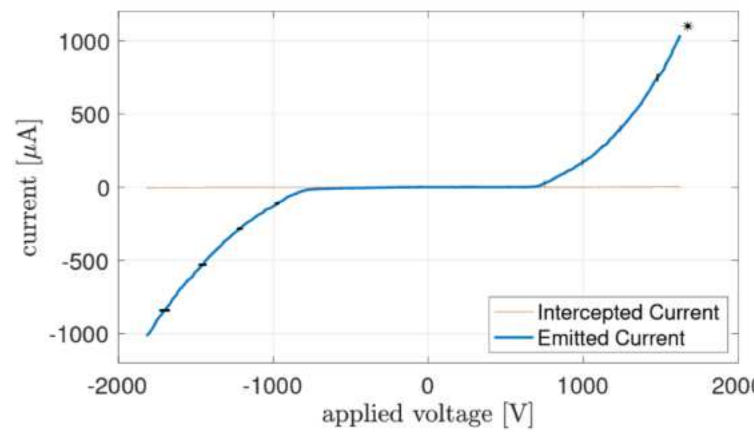


Fig. 3 **SEM image of a section of an Accion Systems TILE emitter array. The extractor electrode has not yet been mounted.**

Table 5 **Thrust and specific impulse estimates**

Current (µA)	Voltage (V)	Thrust (µN)	$\dot{m}$ (µg/s)	$I_{sp,ion}$ (s)
50	800	3.2	0.19	1653
150	1050	9.8	0.39	2573
250	1180	17.7	0.60	3003



Petro et al., "Characterization of the Accion Tile Electrospray Thruster", AIAA P&E, 2020

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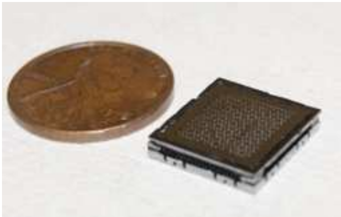
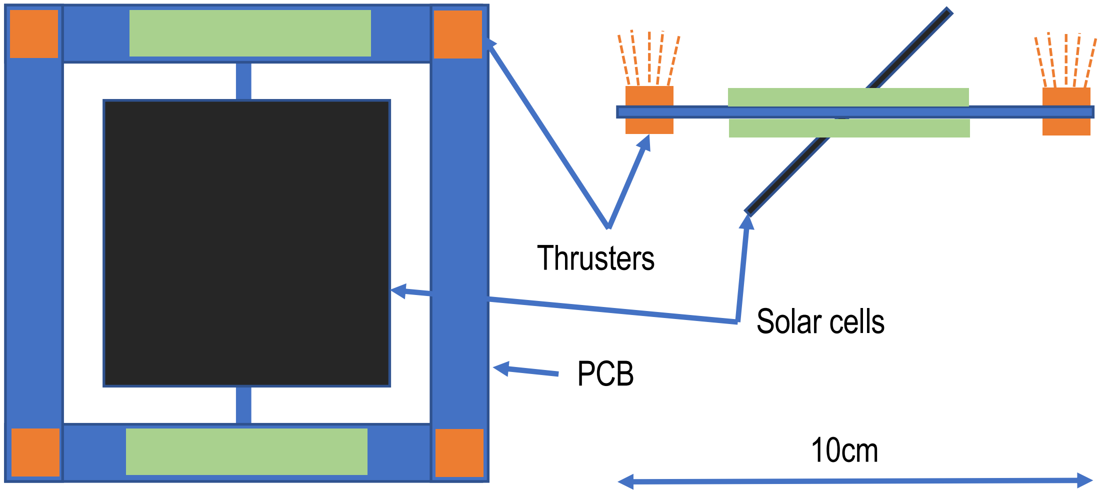
Very Small maneuverable spacecraft

- Electric propulsion
  - 8-axis thrusters (overkill)
- Solar+battery
- Iphone cameras (several)
  - Navigation
- Iphone-level processor
  - CPUs, GPUs
  - Radiation-aware software
- 10 cm scale – COTS?
  - 100 grams
  - a=1 mm/s^2; ΔV=3 km/s
- 5 cm scale – flying credit card
  - 10 grams
  - a=10 mm/s^2; ΔV=5-10 km/s
  - *Land* on NEO!



Accion electrospray thruster.
18 uN; I_{sp}=3,000s



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Testing

- Vibration
- Vacuum
- Thermal
- Radiation

- Trip to LEO

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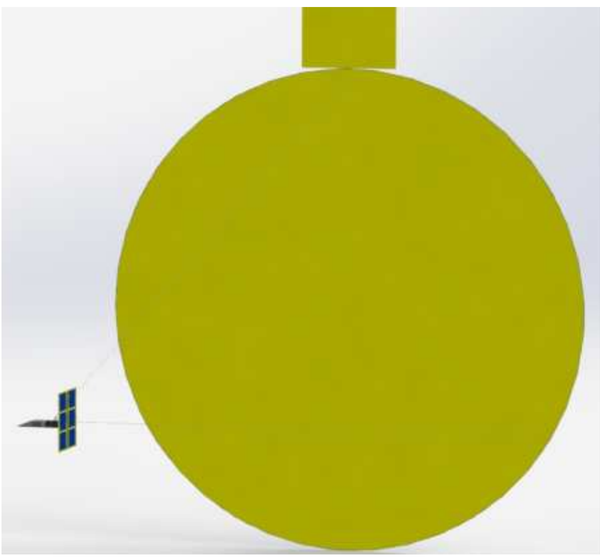
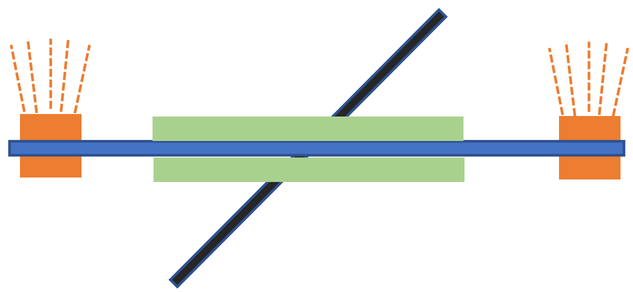
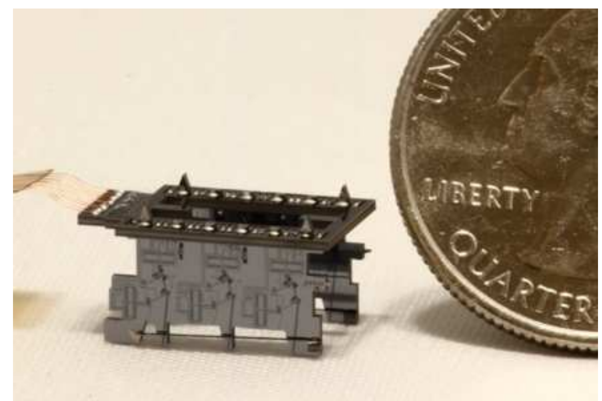
Conclusion

- Off-the-shelf technologies should be able to make 10 gram interplanetary spacecraft
- They should be cheap
- Build and launch 1,000 for…$5M?
- Need a sponsor!







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Shaula & Lesath

~(24,30) pixel x,y separation, 38 pixel diagonal
3.4 mrad known separation between Shaula and Lesath
→ Estimate pixels are ~0.1mrad

Jupiter diameter: 143 thousand km
Jupiter distance from earth: 802 million km
Jupiter angular span: 143/802 mrad = 0.18mrad

So Jupiter should be about 2 pixels wide, not 24.
The difference is due to: diffraction limit of lens, atmospheric blurring, vibration of camera, etc.

BSAC