SmallSats Beyond Saturn Without Radioisotopes: A Preliminary Assessment

Interplanetary Small Satellite Conference, *Web-hosted from Pasadena, California*

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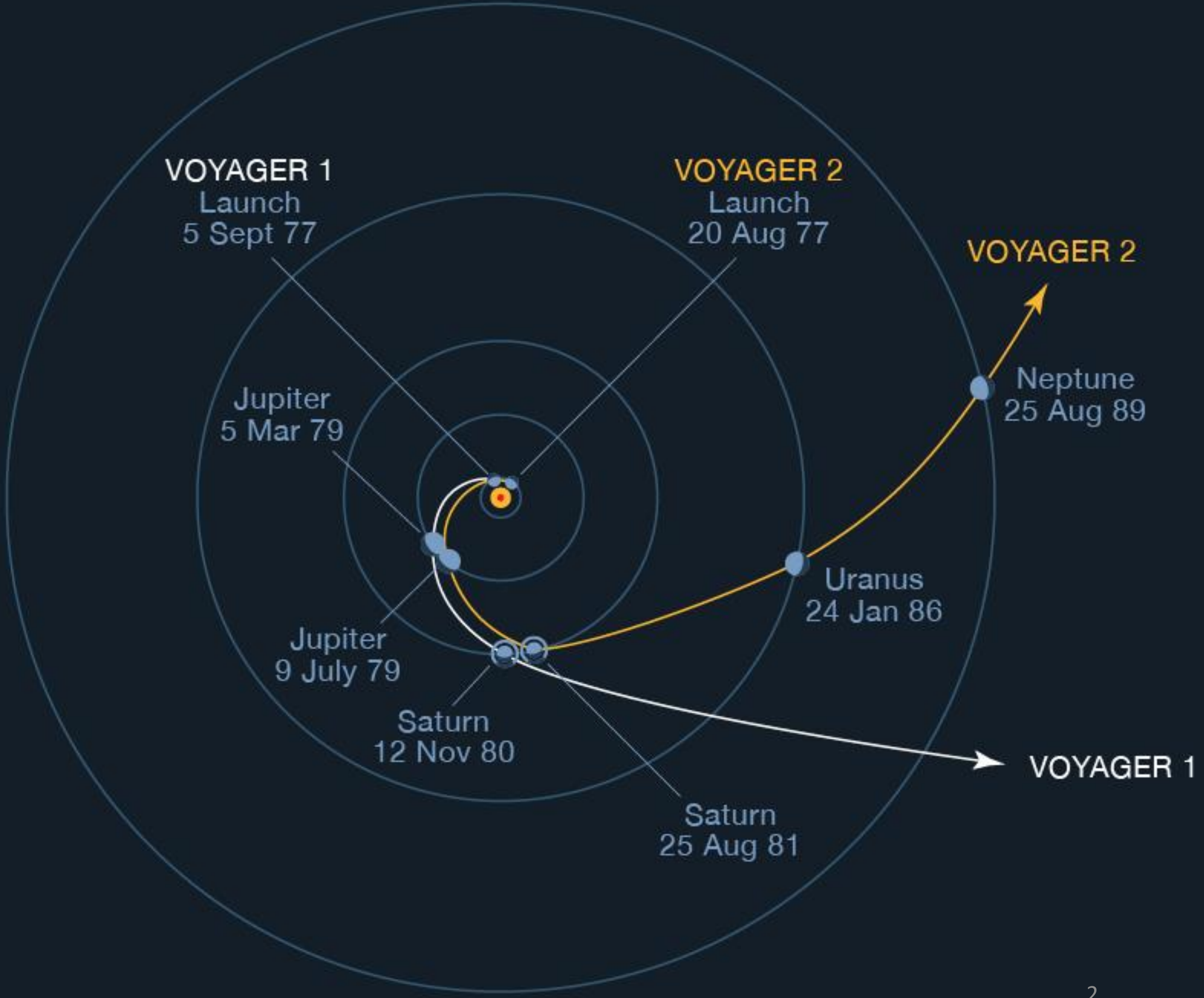
Visits beyond Saturn are rare.

The vast majority of the volume of the Solar System lies beyond Saturn’s orbit, and outside the Ecliptic plane.



How might we learn more, affordably?

Classical approach, with very sophisticated, high-yield missions with broad objectives

- *New Horizons*, *Voyager 1 & 2*, and *Pioneer 10 & 11* are the only spacecraft to venture beyond Saturn's orbit.
- Each weighed >250 kg (some >>250 kg).
- Cost >FY19$300 M (most >>$300 M).
- Operations teams with 10s of people.
- Radioisotope power.

Focused SmallSat approach, very specific objectives

- Inspired by the CubeSat/SmallSat revolution in small, low power electronics and miniature instruments.
- 1/10th the cost* and mass, and
- 1% of the equivalent continuous power level, and
- 1% operations staffing of such missions today.
- Launched as secondary payloads ridesharing with primary missions to the Outer Solar System.
- Use Jupiter swingbys to different targets beyond Saturn's orbit.

Innovation: Outer Solar System SmallSats (**OS4**)

- Small solar-powered outer Solar System (OSS) spacecraft could be capable of operating to ~~just beyond the heliopause~~ past Neptune's orbit.
- Could use inflatable UV-rigidized solar collector for power, thermal and RF; low data rate telecom.
- Make use of low duty cycle/low-power avionics derived from high-end consumer electronics.
- Employ miniaturized magnetic field, plasma, and dust instruments with modest power and data needs.
- May enable affordable access to ~~edge of~~ Outer Solar System
  - Explore Heliosphere, including high inclinations
  - Opportunistic small body flybys
  - Focused measurements during Saturn, Uranus, or Neptune flybys *might* be possible with different instruments.
  - Minimal-staff operations thru autonomy.

Magnetometer & Plasma Sensors

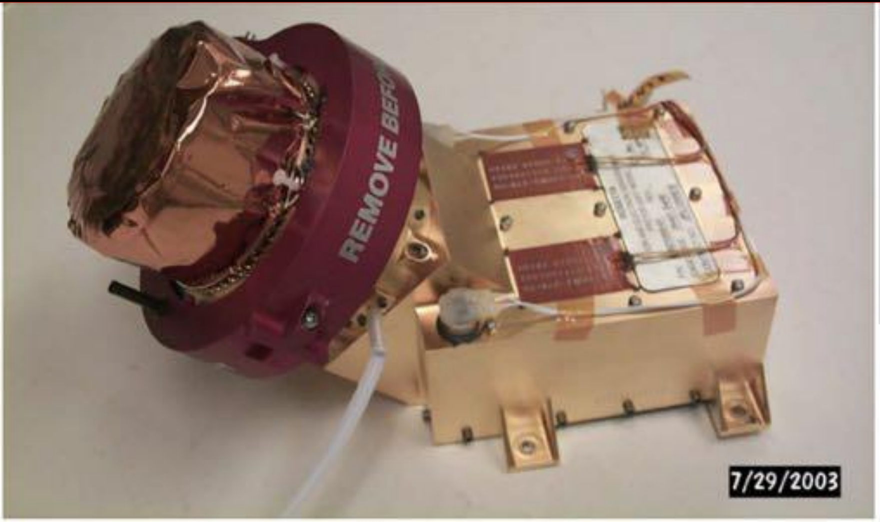
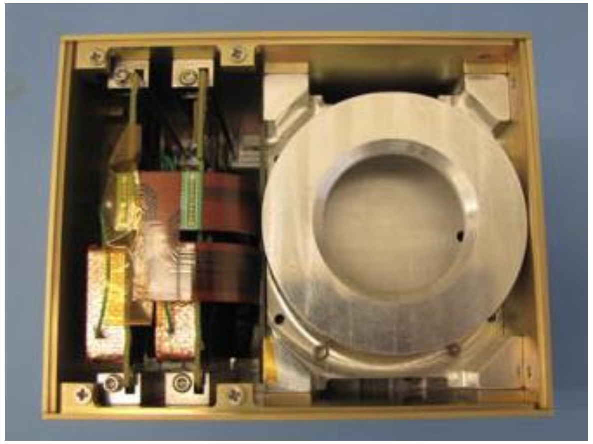
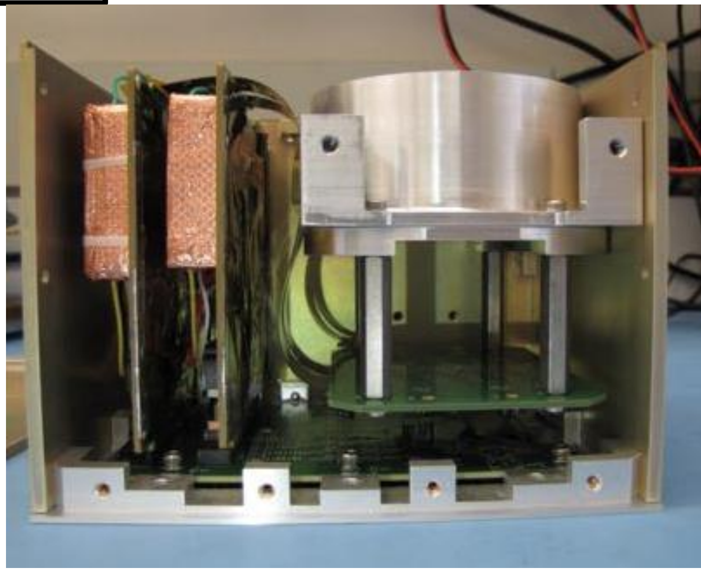


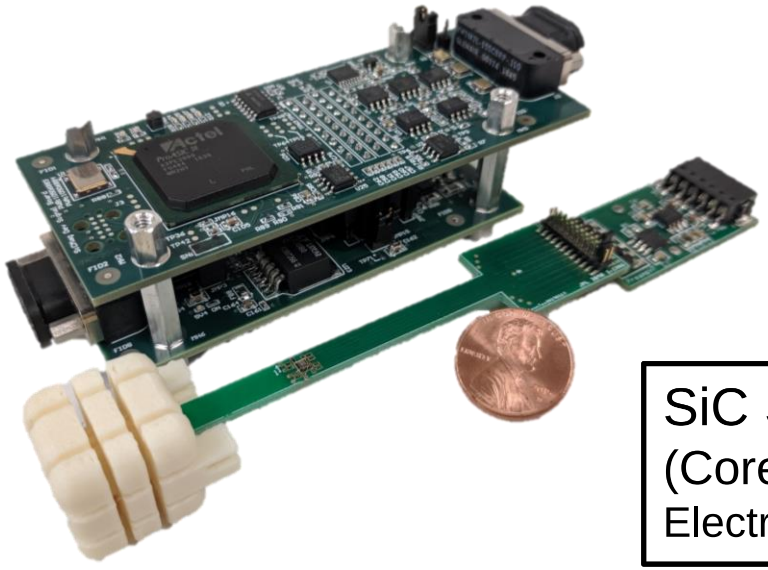
Figure 4. Photograph of completed IES instrument shortly before the integration with the Rosetta spacecraft. The red "Remove before Flight" cover is seen protecting the entrance grid A thermal blanket cap covers the upper portion of the detector assembly.

SwRI Solar Wind Ion & Electron Sensor (IES)
(Mihir Desai, et al./SwRI)
(Rosetta heritage sensor, re-done electronics w/ modern components) [see next slide for placement]



Miniaturized Electron and Ion Telescope (MeRIT)
(Mihir Desai, et al./SwRI)
(CuSP & CeRES heritage)

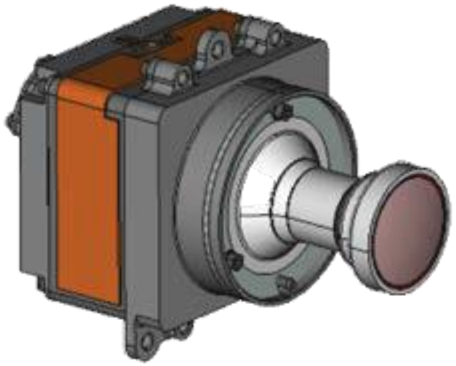




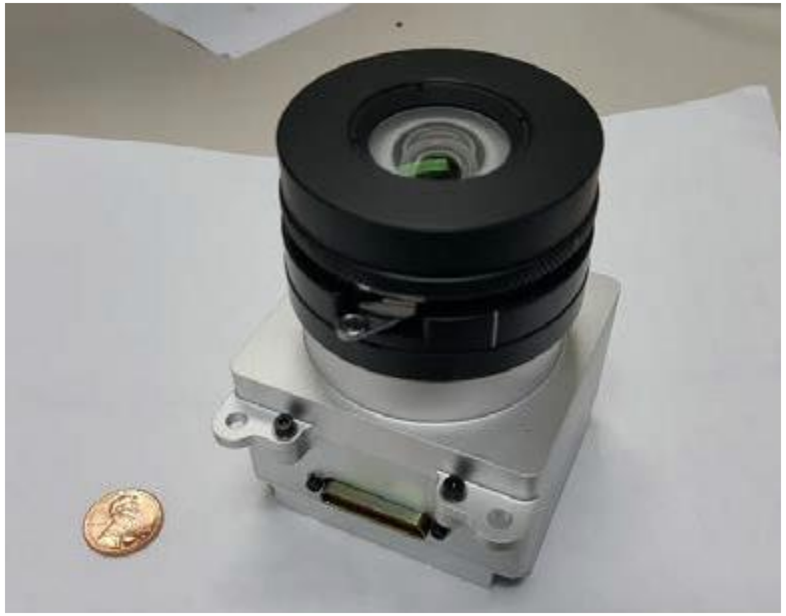
SiC Solid-State Quantum Magnetometer
(Corey Cochrane/JPL)
Electronics to be miniaturized to ASIC/SoC

Cameras for Measuring Holes in Reflector Created by Dust and Taking Periodic Portraits of the Solar System

Mars2020 NavCam



65 x 74 mm at base x 90 mm along optical axis. 700 g

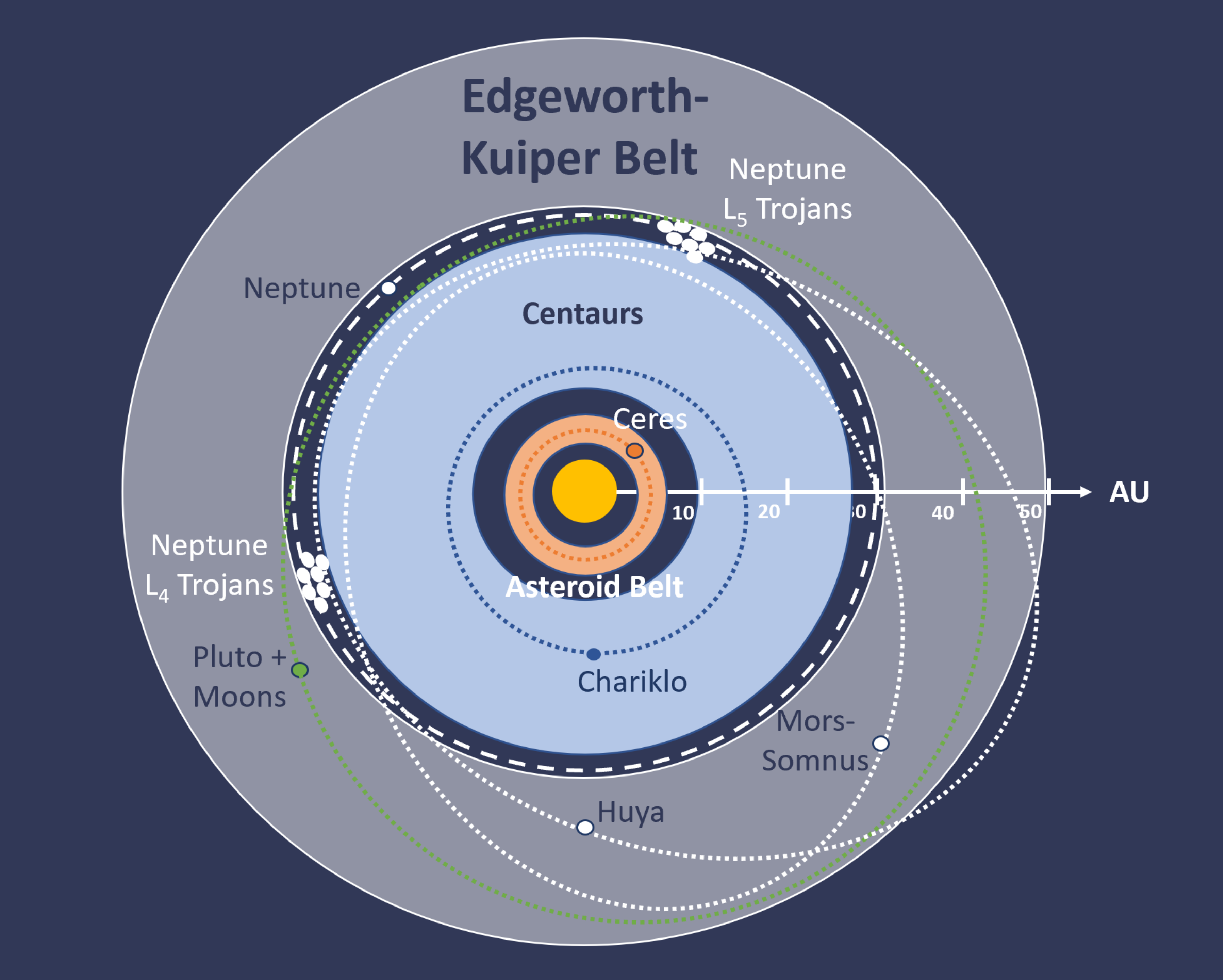


Mars2020 EECAM Camera Specifications	
Sensor Capabilities	
Type	20M Pixel CMOS Image Sensor
Array Size	5120 x 3840
Pixel Size and Pitch	6.4um2 on 6.4um Pitch
Full well charge	15ke-
Pixel Dark Noise	8e- RMS
Windowing	Yes
Shutter	Global
Color	Bayer RGB Color
Pixel Quantization	12bit
Electrical Interface	
Commanding & Data	LVDS
Protocol	MER/MSL/Mars2020 NVMCAM
Power Input	+5.5V (+/- 0.4V)
Power	< 3 W
Memory	1Gbit SDRAM
FPGA	MicroSemi Rad-Tolerant ProASIC3
Camera Specifications	
Mass (CBE, no optics)	< 425g
Volume (CBE, no optics)	65 mm x 75 mm x 55 mm
Operating Temperature Range	-55C to +50C
Survival Temperature Range	-135C to +70C
Optics Configurations	
Navigation Camera	95° X 71° (H x V), f/12, iFOV < 0.32 mrad/pix
Hazard Camera	134° X 110° (H x V), f/12, iFOV < 0.46 mrad/pix
Sample Caching System Camera	0.49 magnification, 130mm stop to plane-of-focus, +/- 5mm Depth of Field

Christophe Basset, Colin McKinney, Mark Schwochert, Justin Boland/JPL, 2017

Big challenges

- Getting to the ~~edge of interstellar space~~ inner Edgeworth-Kuiper Belt without radioisotopes for power or heat today is impossible (at least if you want to do anything useful and send a signal back…)
- At ~~125~~ 30 AU, sunlight's power density per unit area is 1/~~15,625~~ 900th of the level at Earth.
- It may be impossible for at least the next ten years, but we have an approach that *might* work
  - For spacecraft maybe <~~100~~ 250 kg
  - With simple, pre-programmed measurements
  - Very limited maneuvers beyond Jupiter
  - Capture and store energy from ambient sunlight
  - Almost everything "off" almost all the time
  - All equipment able to run cold, e.g., -40 C (-40 F), or possibly colder



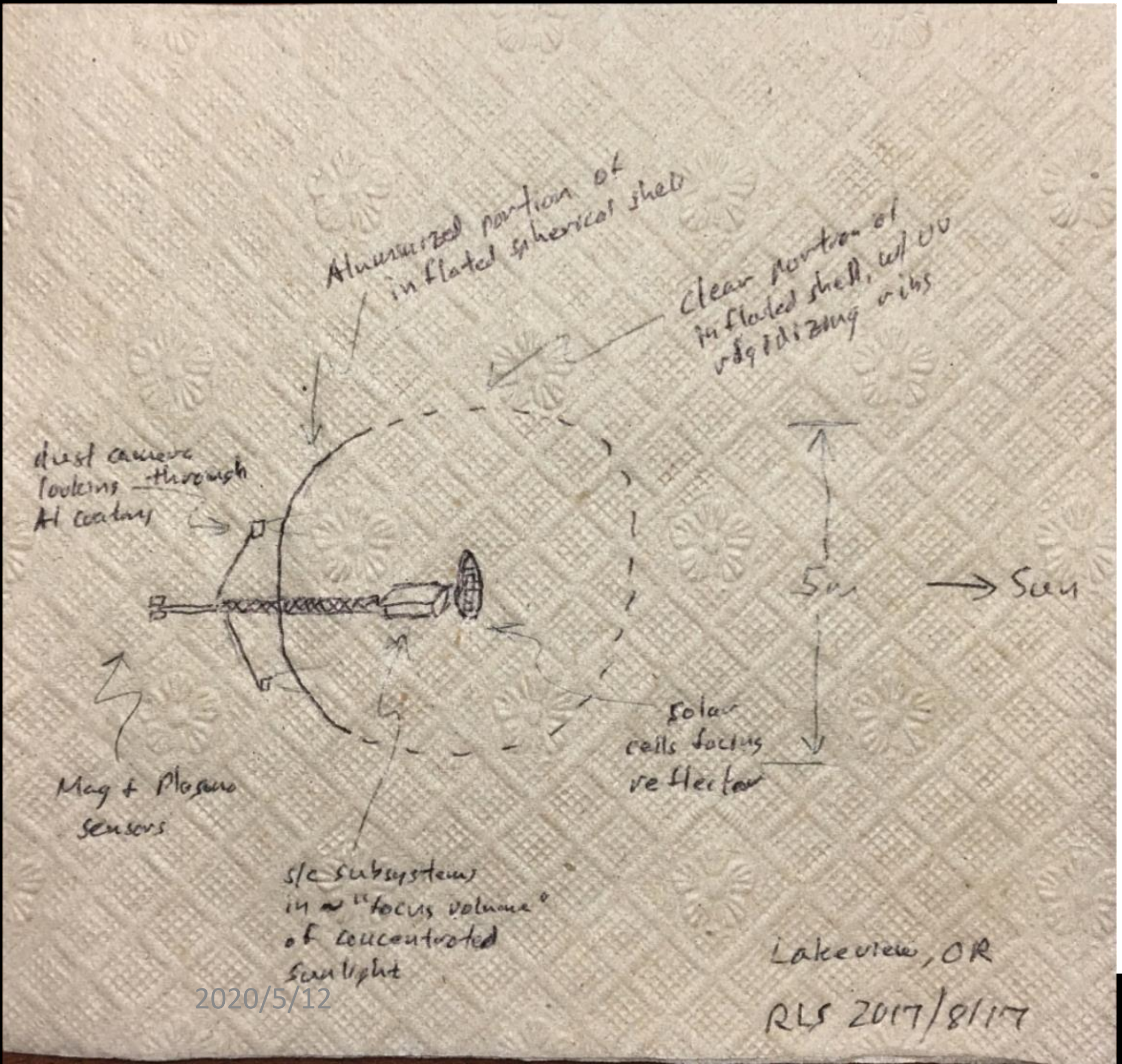
Many Interesting Objects within 30 AU of the Sun...

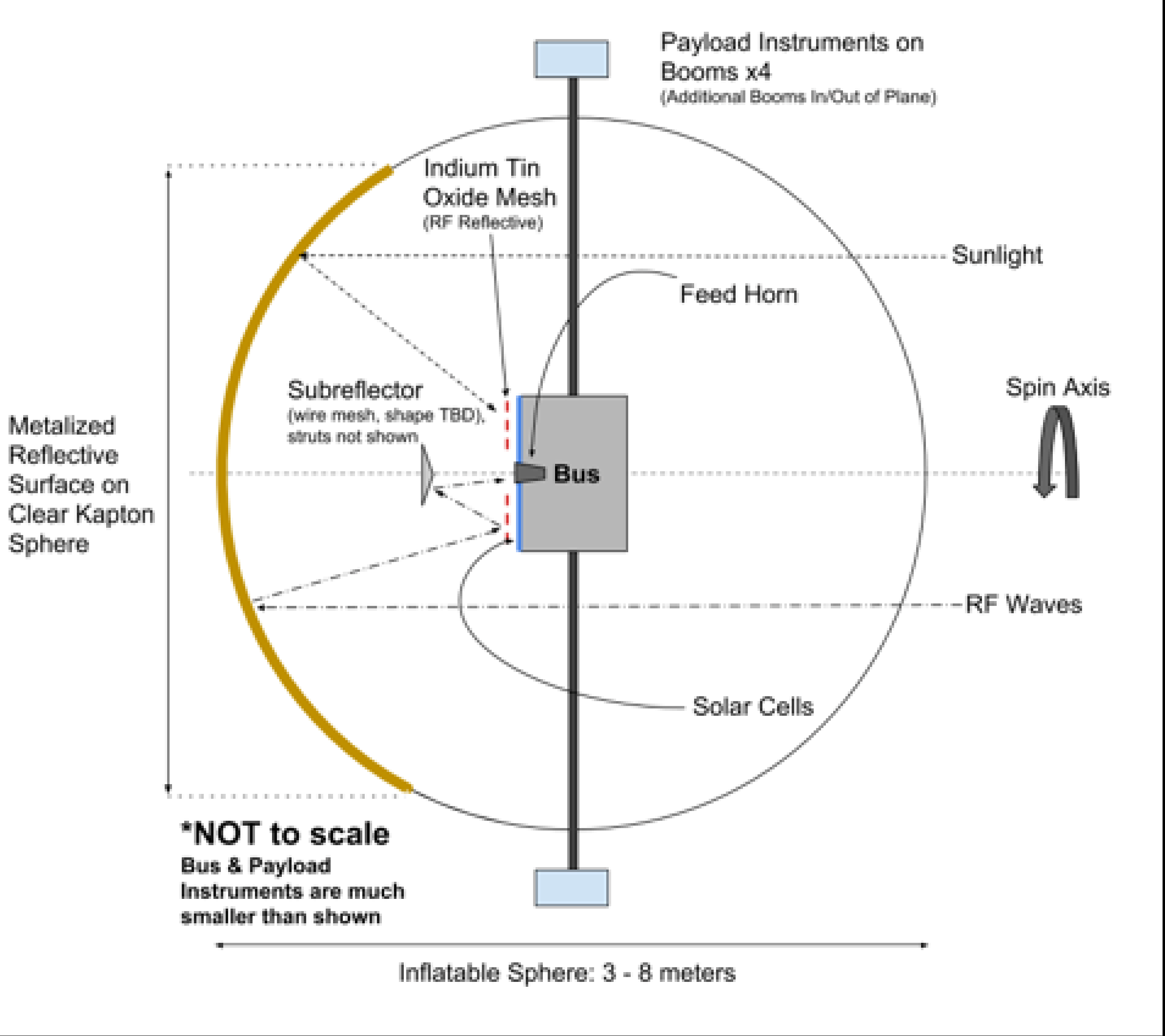
(orbits of
Jupiter @5 AU,
Saturn @ 10 AU, and
Uranus @19 AU not shown,
for graphic clarity)

Note: arguments of perihelion for example Edgeworth-Kuiper Belt objects are notional for graphic clarity.

Cole Gillespie/CalPoly-SLO, 2020/5/6

What are napkins for?





Pre-Decisional Information -- For Planning and Discussion Purposes Only

Sebastian Lee Gnagy/CalPoly-SLO, 2018/11

Big inflatable spheres have been in space before:

Echo 1A, 1961
30.5 m diameter
0.2 um (0.5 mil) thick Mylar
71 kg, incl inflation gas

Static Inflation Test of 135 Ft Satellite In Weeksville, NC
NASA Langley Research Center 6/28/1961 Image # EL–1996–00052

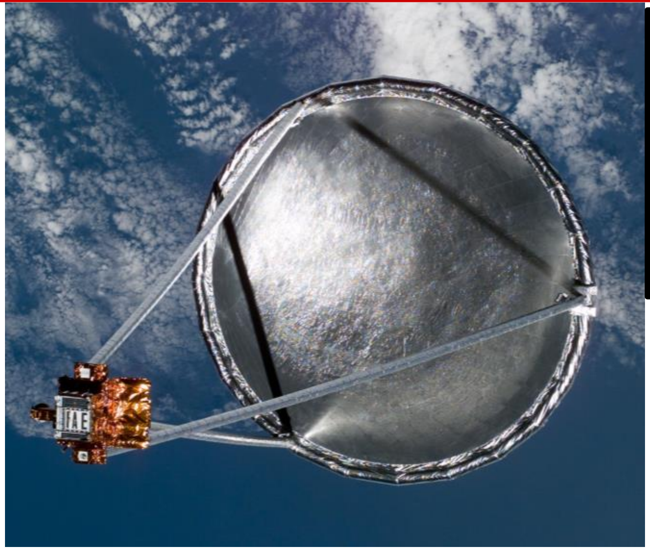
Inflatable Sphere antenna (X-Band design)

- A prototype for an inflatable antenna has been developed at JPL
- The antenna is a 1m sphere, functional for the X-Band , producing an approximate gain of 31 dB (experimentally measured) for a reflective surface of 70 cm in diameter
- Inflation is achieved with sublimating powder (benzoic acid) which allows for a very compact design with no pressure tank and only few grams of powder (approximately 1 gram per year of mission life)
- To counteract deflation due to thermal fluctuation and/or micrometeoroid puncturing, a system of rigidization is under development using UV pockets which rigidize with sunlight. An experiment in vacuum chamber is shown in the video
- This work was supported by JPL R&D and NASA Center Innovation Fund grants

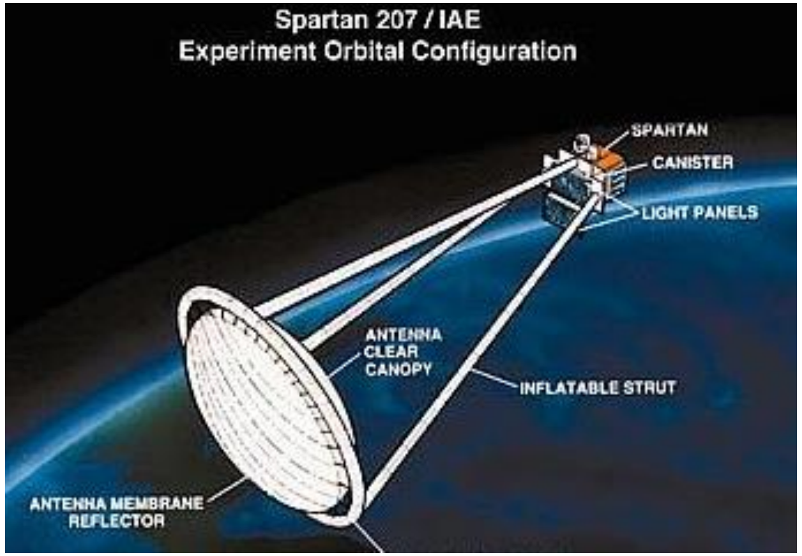
Rigidization experiment

Babuscia, Sauder, Bienert, Chandra, Thangavelautham, Feruglio," Inflatable Antenna for CubeSats: A New Spherical Design for Increased X-Band Gain", IEEE Aerospace Conference, Big Sky (MT), 2017.

Combined Solar Reflector/High Gain Antenna Configuration is Based on a 1997 Tech Demo



1997 Spartan 207 tech demo to deploy a large reflector with high enough surface accuracy for RF use. L'Garde developed and implemented a capability to mathematically calculate gore shapes, bond segments together, and inflate.



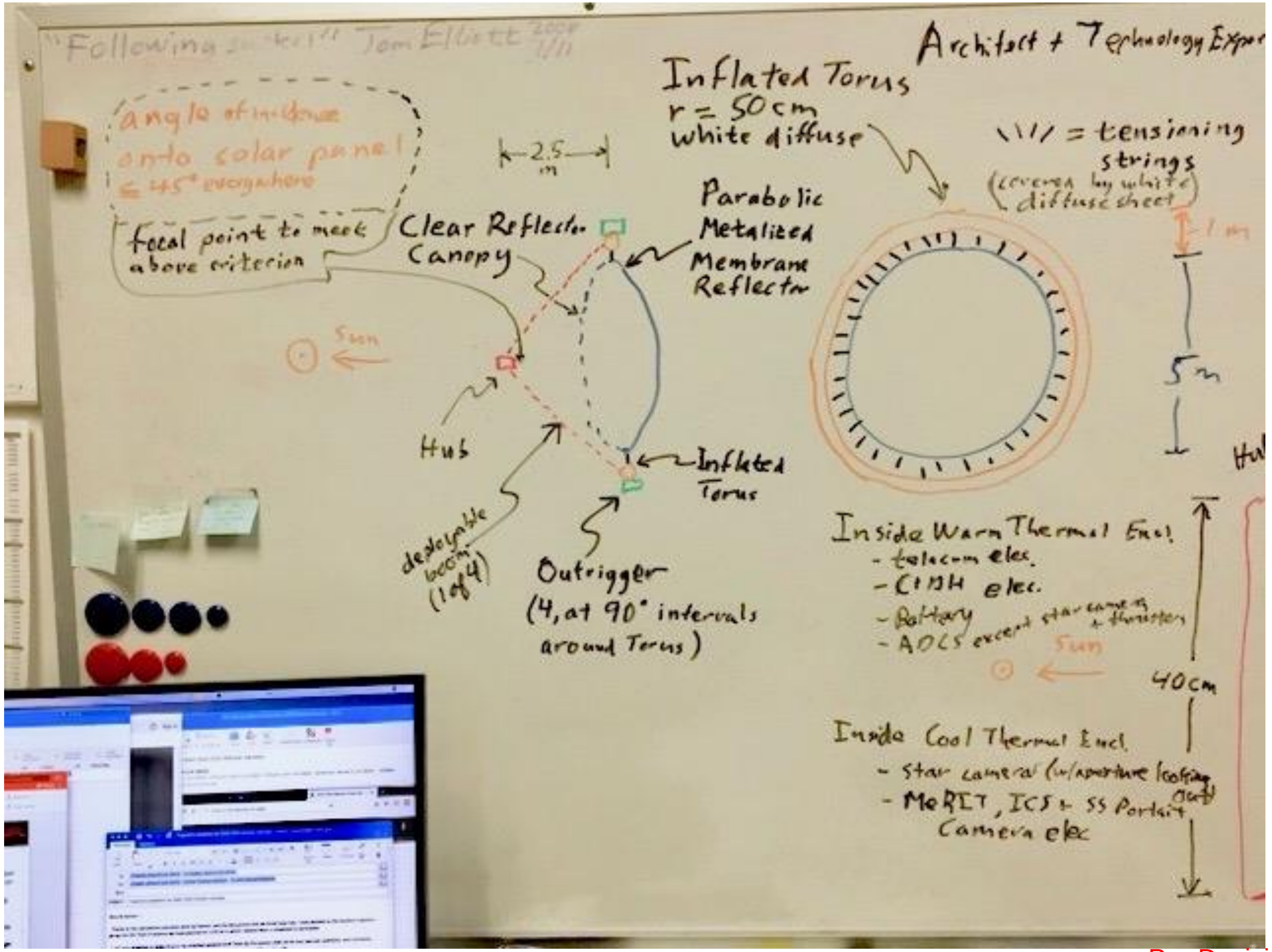
"All the experiment objectives were met with the exception of the inflation of the lenticular reflector structure." This lenticular construction was to create the surface shape of the aluminized *antenna membrane reflector* surface, opposed by the *antenna clear canopy* that together were to enclose the inflated volume.
Thus, no measurement was made in space of the surface accuracy.

Ground testing led to "expected to be on the order of 1 mm rms…"

~5 m

Robert Staehle. 2020/1/22

From real Tech Demo to conjecture for a different application...

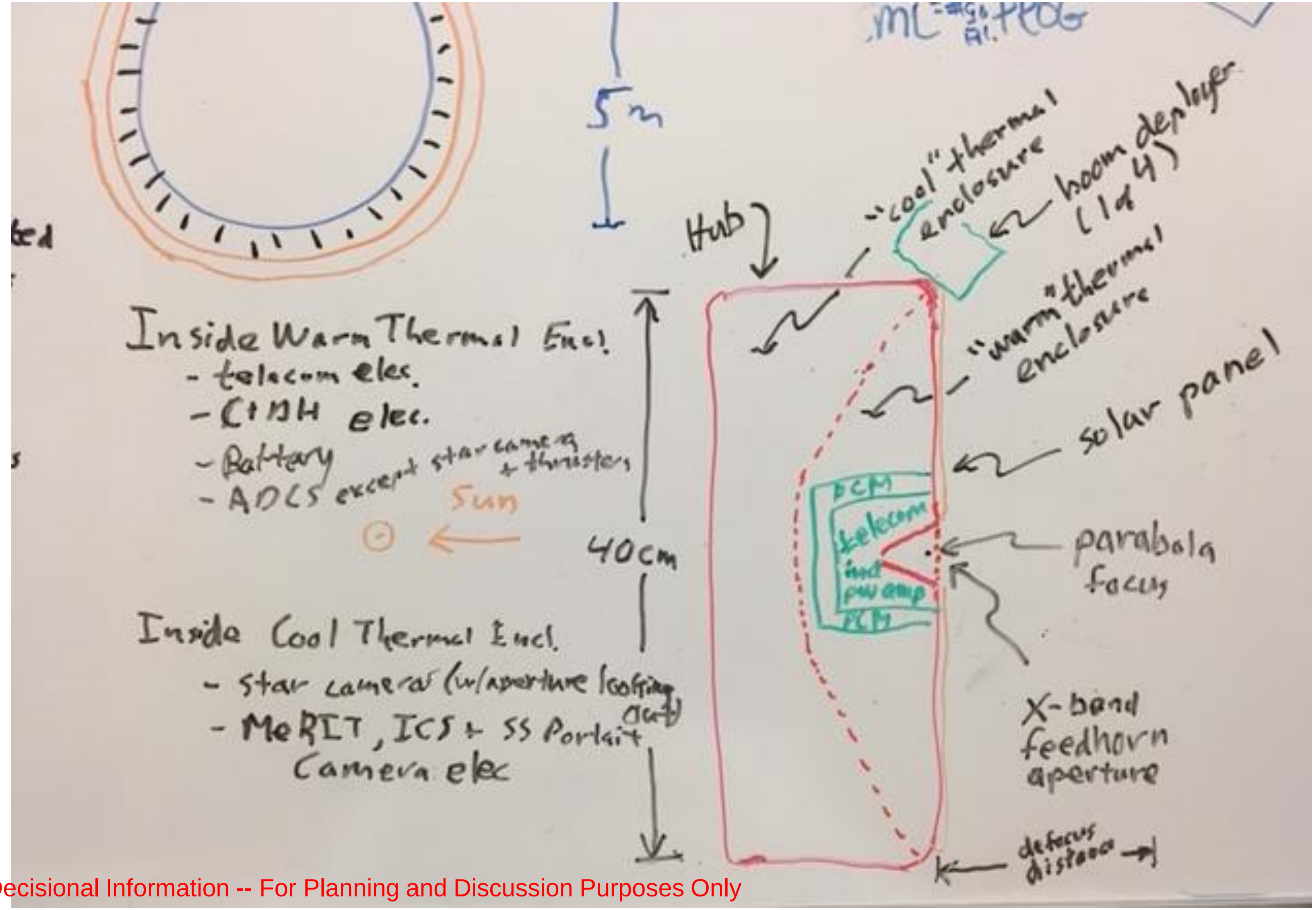


- Orientation shown for outer Solar System cruise.
- S/C spins 1-2 rpm (guessing) around axis linking Hub and center of Parabolic Metalized Membrane Reflector.
- For telecom passes (weekly to monthly), spin axis is precessed from Sun-point to Earth-point, then back after pass.

Robert Staehle. 2020/1/8

Pre-Decisional Information -- For Planning and Discussion Purposes Only

The "Hub" is where most of the operating equipment lives, in relative warmth...

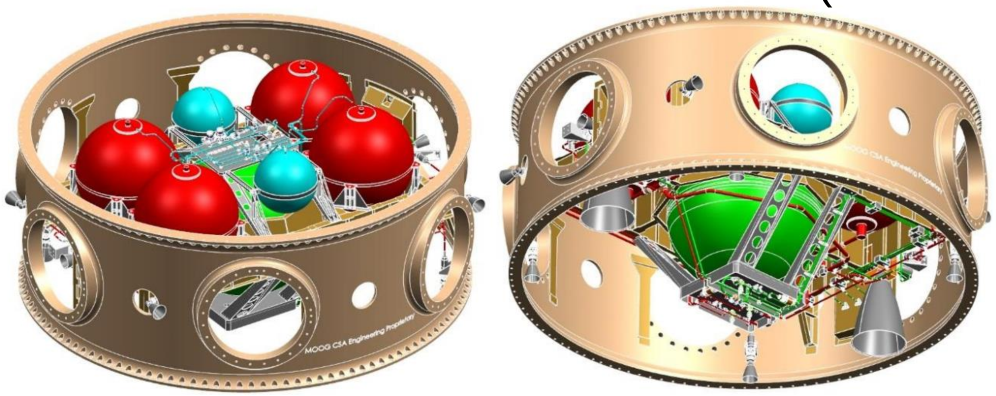


Pre-Decisional Information -- For Planning and Discussion Purposes Only

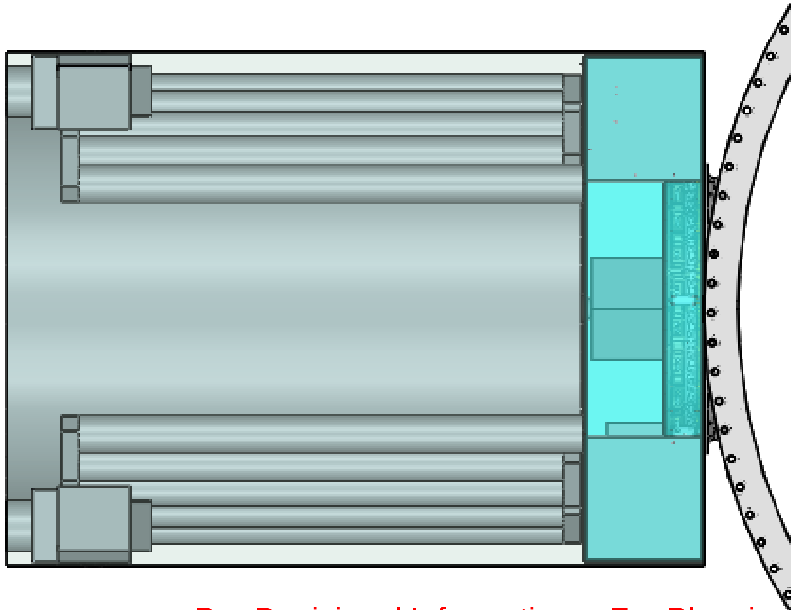
Robert Staehle. 2020/1/8

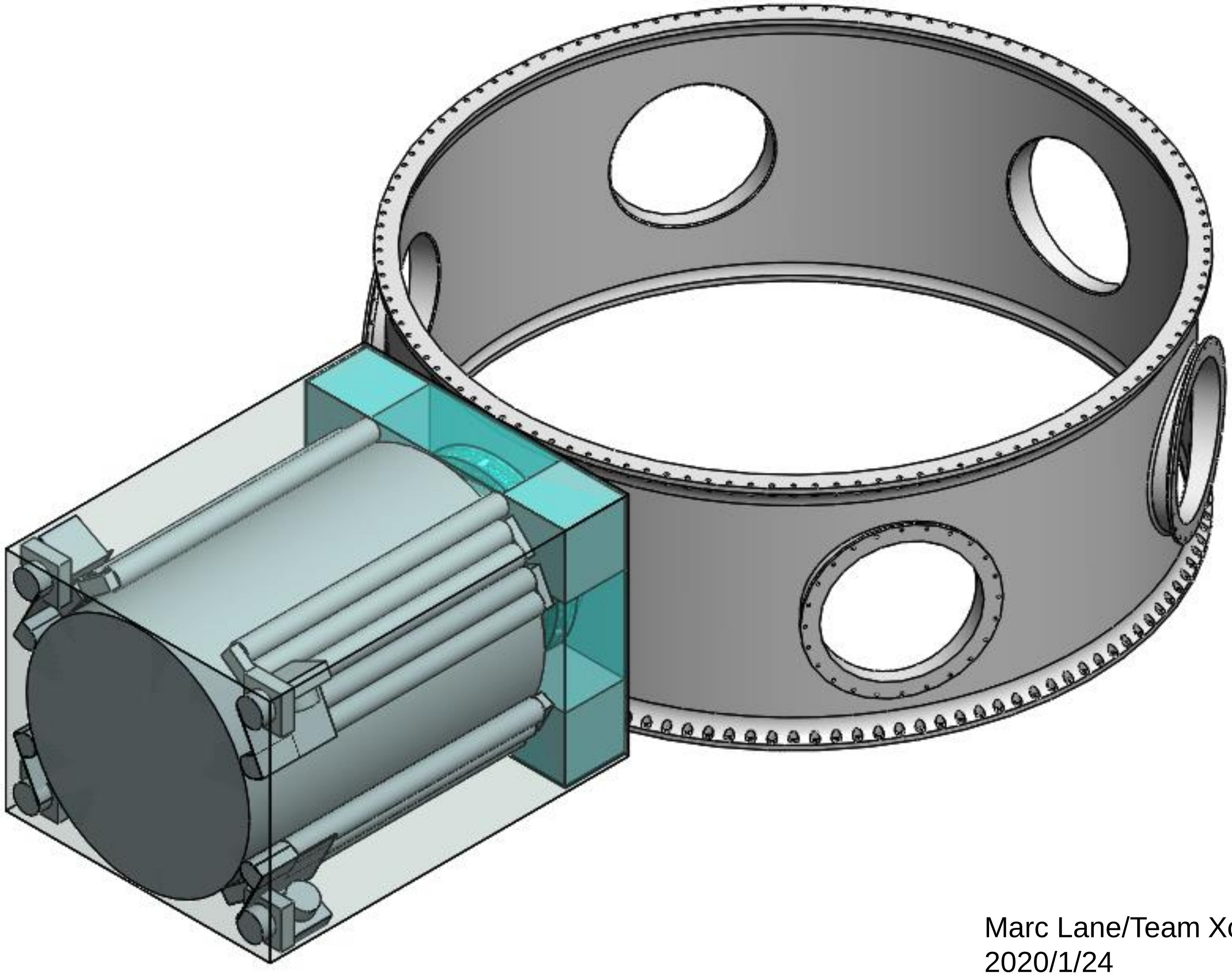
OS4 Hub, *Stowed* Parabolic Metalized Membrane Reflector, and ESPA Ring

(Inner Solar System Solar Panels not shown)



Moog: used with permission





Marc Lane/Team Xc
2020/1/24

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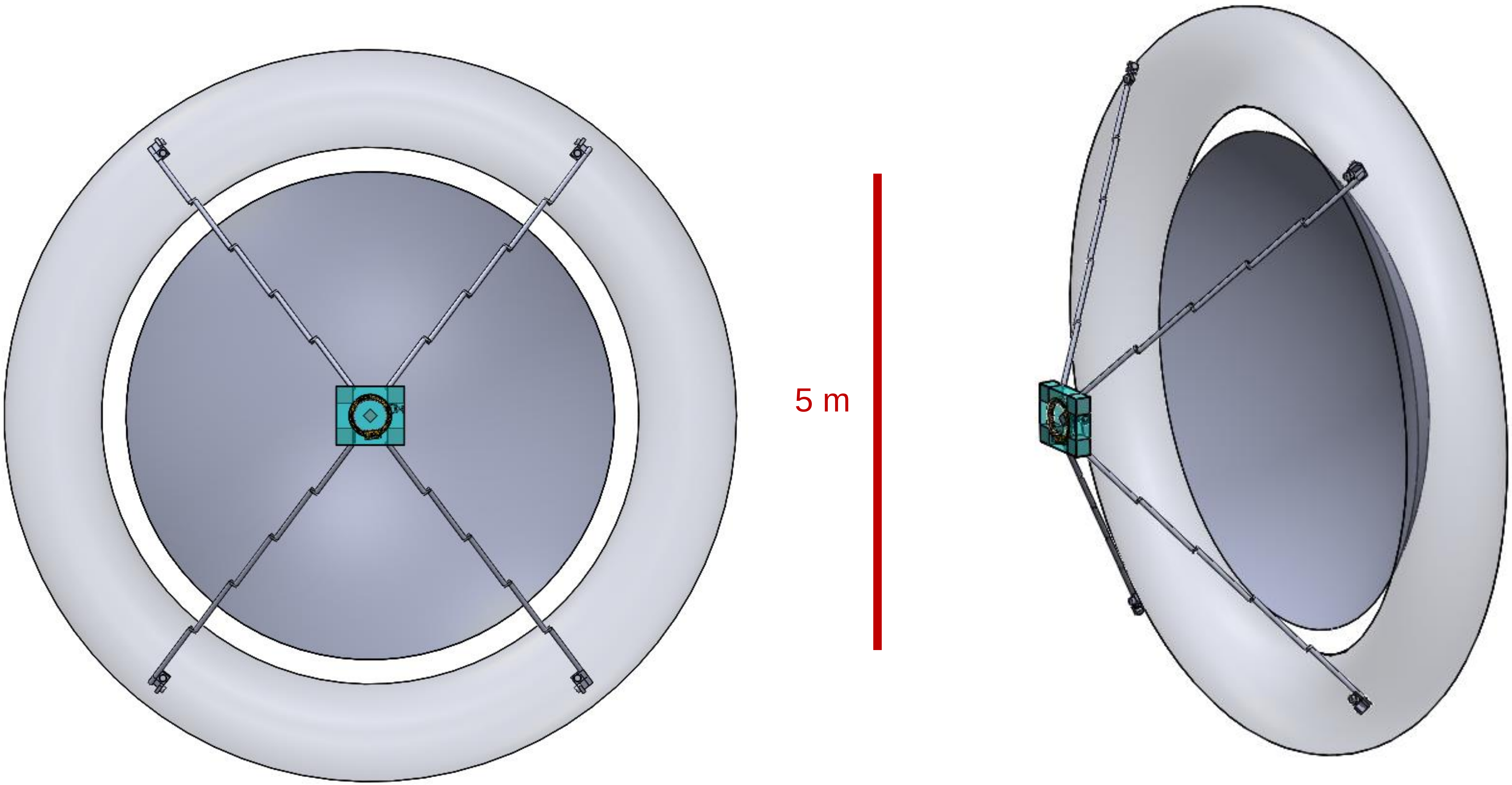
Deployed Parabolic Metalized Membrane Reflector, Torus, and OS4 Hub



Pre-Decisional Information -- For Planning and Discussion Purposes Only

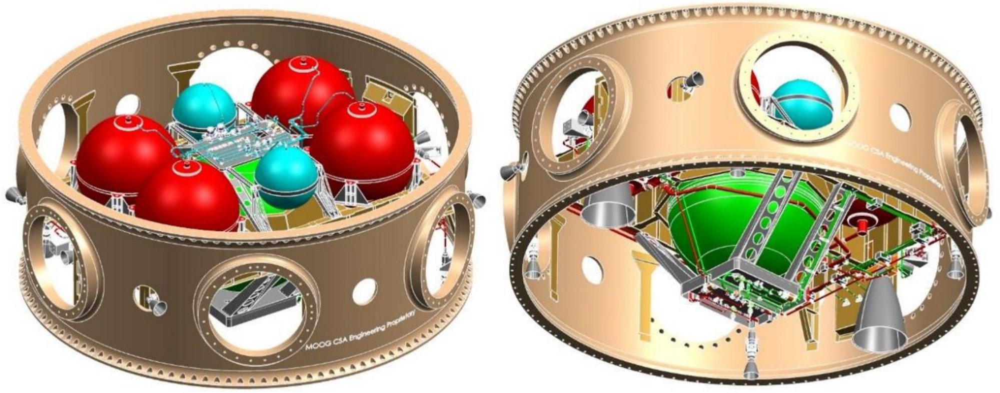
Nicholas Bonafede/CalPoly-SLO, 2020/1

OS4 configuration

- The 5-meter diameter inflatable would be composed of a Parabolic Metalized Membrane Reflector, Clear Canopy, diffuse Torus support, and tensioning straps.
  - UV-rigidized after inflation with sublimate.
- Extendable booms would provide support and facilitate deployment.
- Small pulsed plasma thrusters (PPT) for attitude control would be mounted on four thruster modules at the end of the booms on the Torus.
- Hub would contain avionics as well as providing support for the 60-cm diameter concentrated solar array/high gain antenna feed, optical diffuser, and radiator.
  - Hub is well insulated with multiple MLI blankets and thermal switches.

Rideshare and deployment

- Propulsive ESPA Ring could perform the 200-1000 m/s trajectory correction burn in the first 30 days of the mission.
- Propulsive ESPA would be more than capable of providing the necessary delta-V for OS4 (estimated at 217kg).
- OS4 would separate from Propulsive ESPA after final Jupiter targeting maneuver.



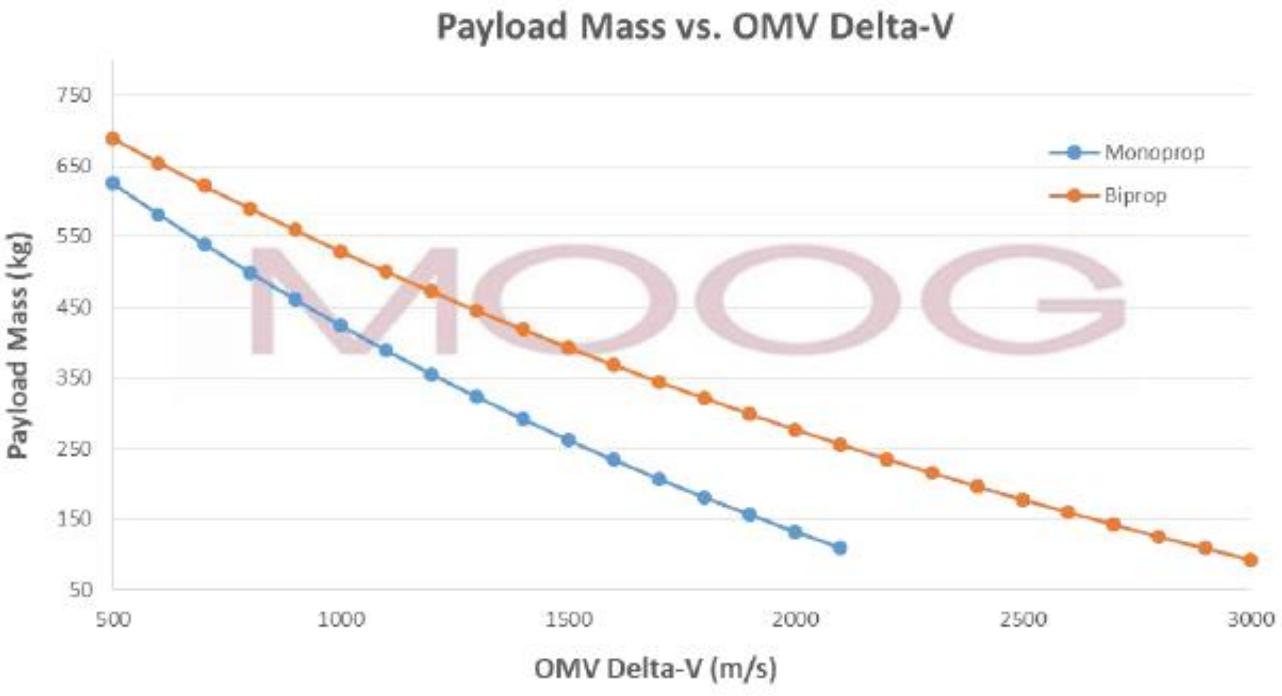


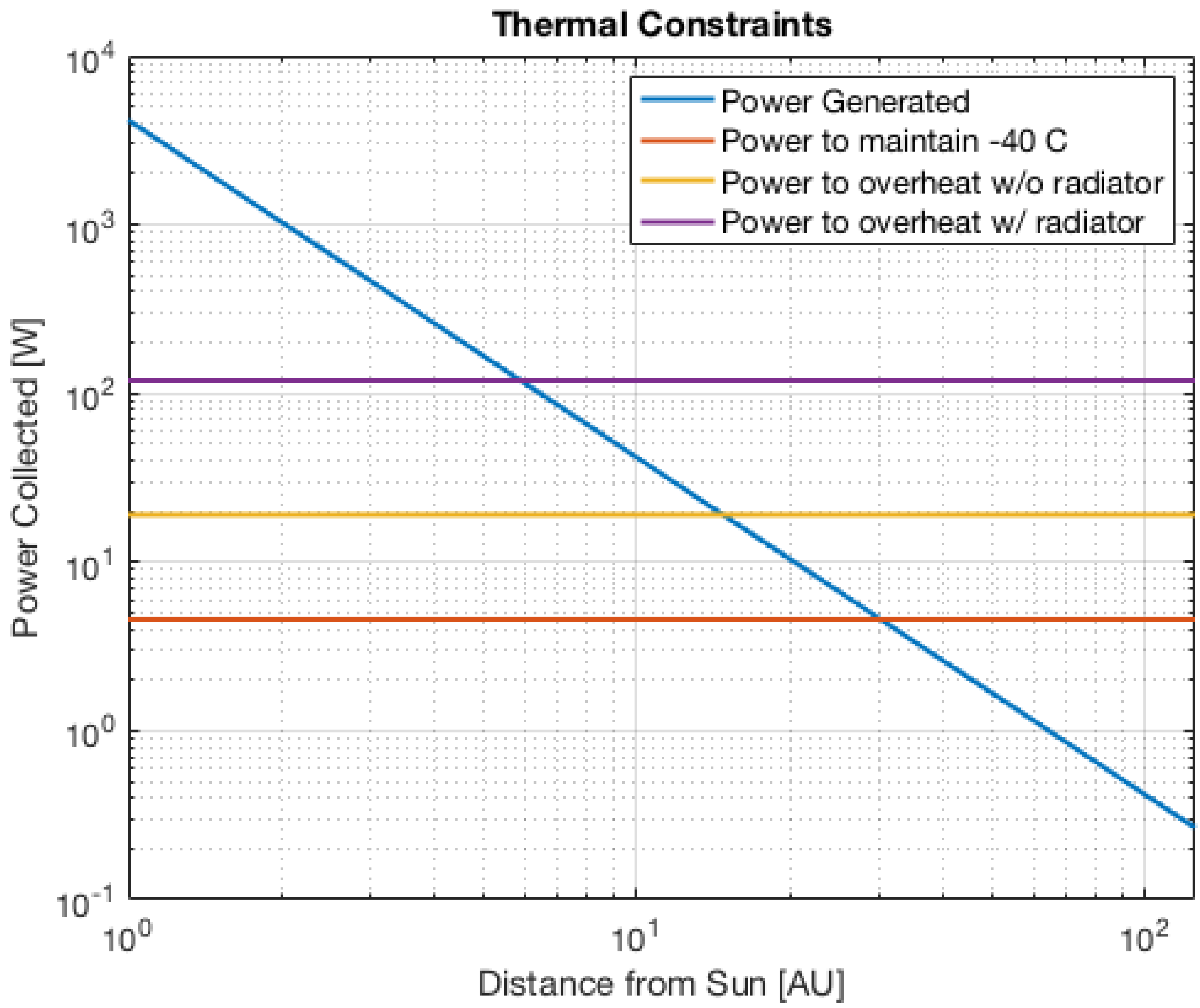
Figure 8: Typical OMV Performance Curve

Images from "Extending Rideshare: Mission Case Studies Using Propulsive ESPA" By Marissa Stender, Chris Loghry, Chris Pearson, Eric Anderson, and Joseph Maly of MOOG, April 12, 2015
https://www.spacesymposium.org/wp-content/uploads/2017/10/C.Pearson_31st_Space_Symposium_Tech_Track_paper.pdf

Proposed Operations Concept

- OS4 would rideshare as an ESPA ring secondary payload on a primary mission trajectory to Jupiter.
- Within the first 30 days, a maneuver would be performed by the propulsive ESPA ring to target the OS4 flyby timing to optimize "slingshot" momentum exchange for faster trajectory to 30+ AU.
- (Primary mission's launch assumed optimized for Jupiter orbit insertion.)
- OS4 would inflate the Parabolic Metalized Membrane Reflector and Torus, extending the booms, and then spin stabilize.
- After the flyby, OS4 would enter a monthly data collection and communications cycle.
  - Charging mode
  - Magnetometers and Plasma Sensor readings for 15 minutes, 12x/month
  - Dust cameras 15 minutes, 3x/month
  - One 8-hour telecom pass
    - 2 hour slew from Sun-pointing to Earth-pointing before pass and vise-versa after pass
- The mission would last 12 years to Neptune's orbit.

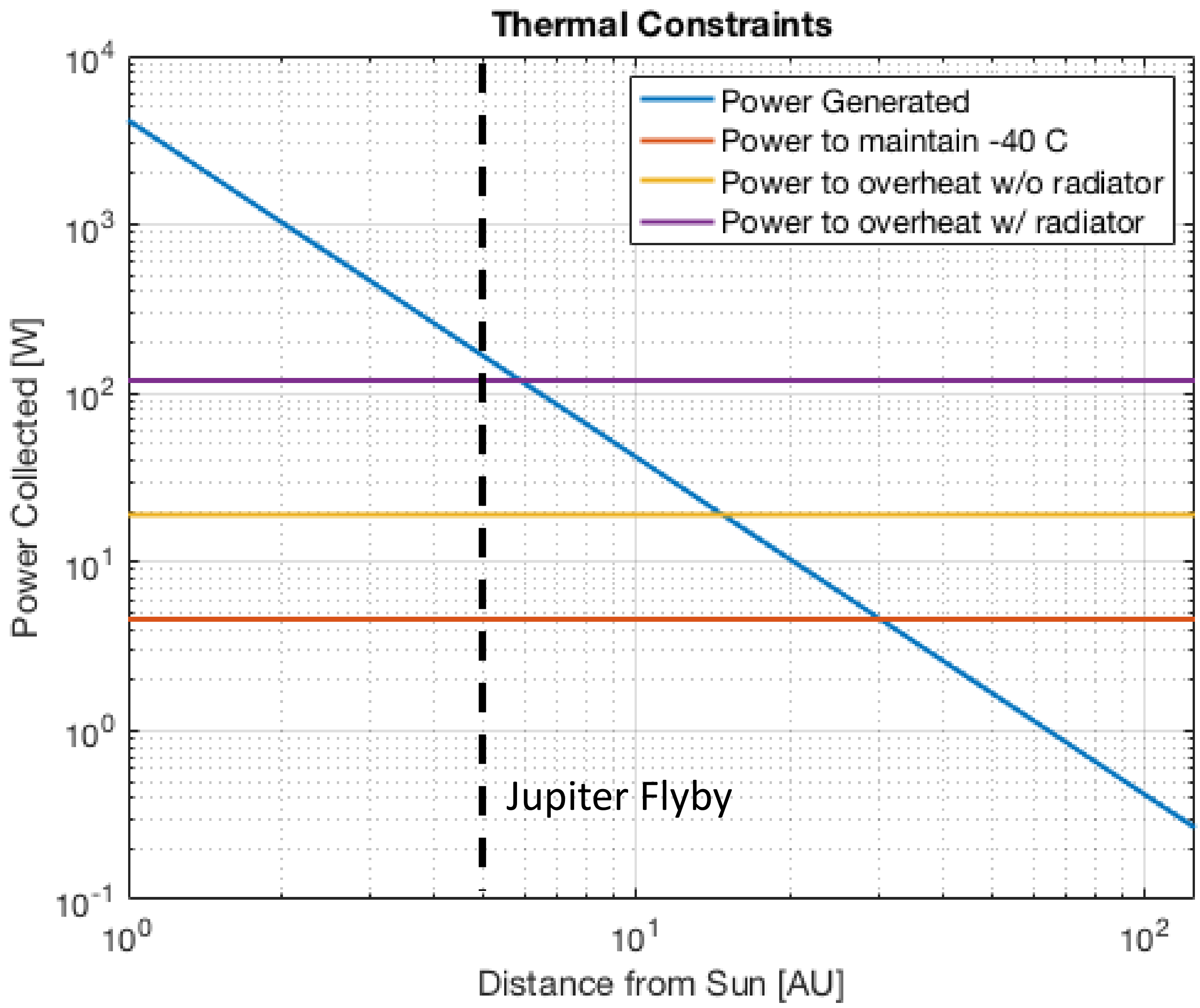
"Cold Case"



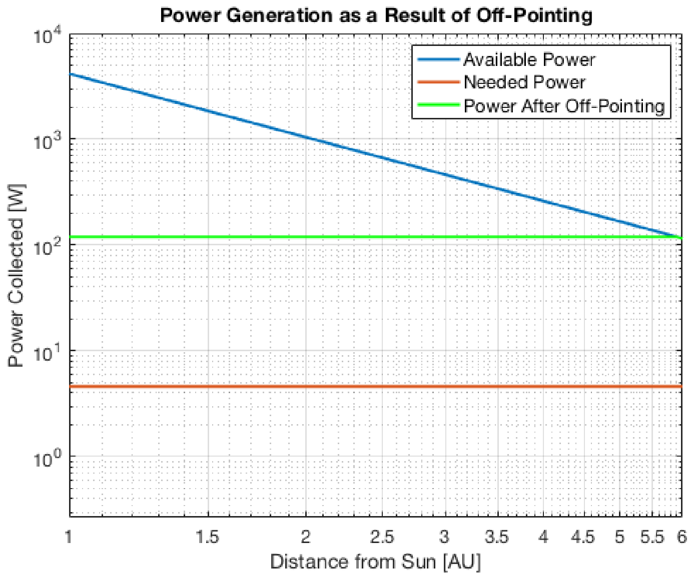
- Without radioisotope power, the spacecraft would get very cold in the Outer Solar System.
- With technological advancements, -40° C is assumed the lower bound for batteries and other avionics. (Might be improved to <~-60 C)
- With Double Stack MLI, 4.6 W of continuous power would be needed.
- Phase change material would capture waste heat from the transmitter and redistribute it evenly over the duty cycle of the spacecraft between telecom passes.
- Power generated by the solar panels as the blue line decreasing over distance. The orange line shows the 3.6W of continuous thermal power lost. The intersection of the lines shows the maximum range.

Nicholas Bonafede & Sydney Retzlaff/CalPoly-SLO, 2020/1

"Hot Case"



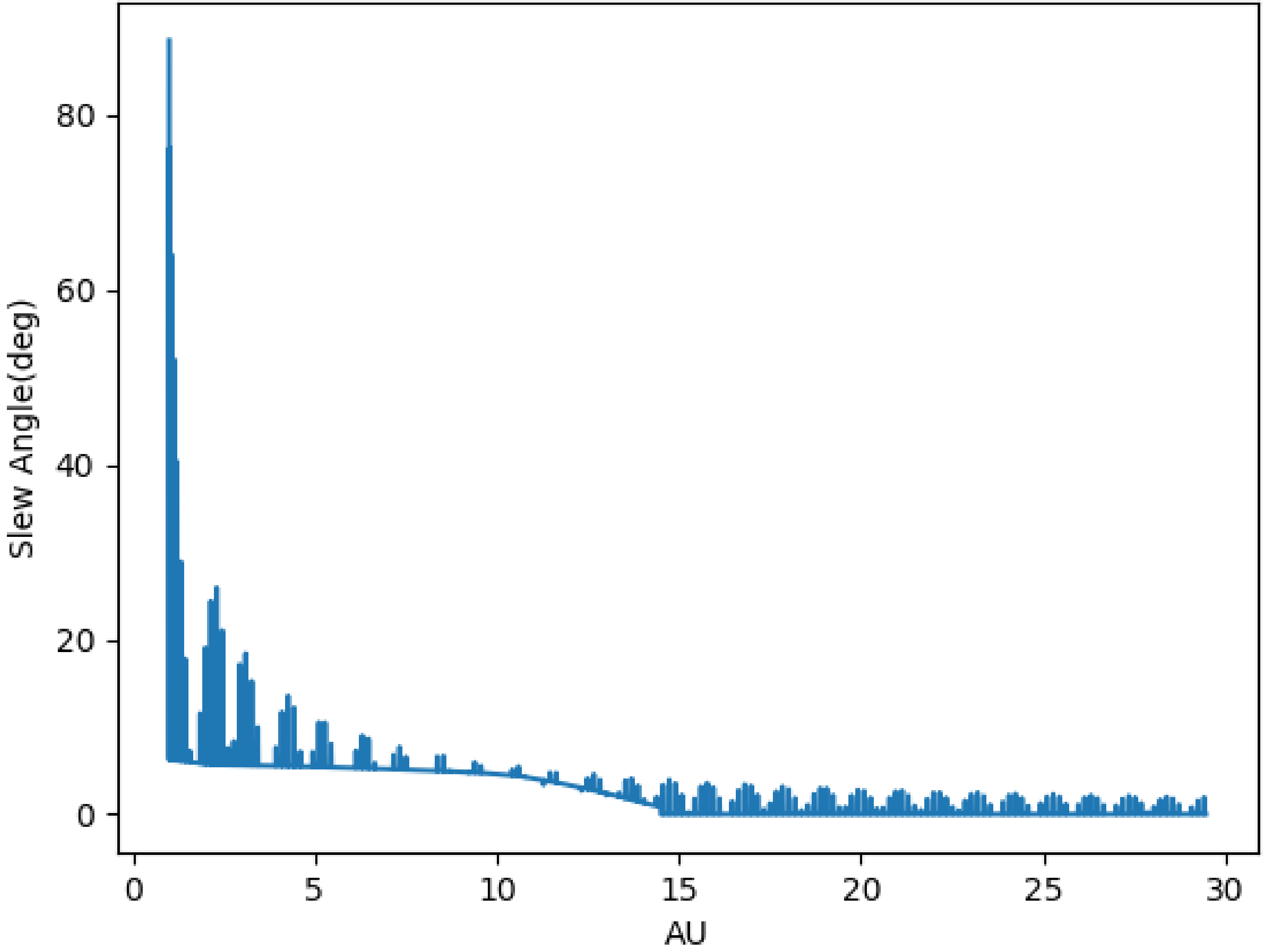
- During the Inner Solar System Cruise phase, the spacecraft would risk overheating from the solar energy concentrated by the inflatable.
- In order to avoid this, the spacecraft must not point directly at the Sun until 16 AU (yellow line in the graph), but a 100 W radiator (purple line) brings this down to ~6AU.
- Thermal switches would be used to thermally isolate the radiator for the cold case.



Nicholas Bonafede & Sydney Retzlaff/CalPoly-SLO, 2020/1; Maya Gordon/CalPoly-SLO, 2020/5

Attitude Pointing On- and Off-Sun (ROM illustration)

- Slew angles to track the sun throughout the mission (including keep-out zone).
  - This assumes a straight, constant velocity trajectory.
- This would total 450 hours of slew time (after 1.25 AU).



Liam Mages/CalPoly-SLO, 2020/1

Extending operational distance:

A balance between thermal regulation, power draw, and configuration

- Team Xc study concluded that a goal of 30 AU could be achievable, but it may be possible to extend the maximum distance.
- Preliminary calculations show that replacing the MLI with a more insulated system such as a dewar could get OS4 to 44AU.
  - This would increase mass
- At that point, power is the limiting factor. If power draw can be cut down, the spacecraft could theoretically reach 60 AU.
  - Must assume that the thrusters require no heating power in addition to other power cuts
- To get to the heliopause at 125 AU, in addition to the above assumptions, the dish would have to be 10.5 m in diameter.
  - No longer a SmallSat, reducing ride-share opportunities

?*Affordably* start on a path to explore the outer Solar System with SmallSats a decade from now?

Questions…

Thank you!

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Backup Material

Some modern low-power electronics

Ultra Low Power IoT Microcontroller Families							
Series	Vendor	Grade	Architecture	Sleep Power (mW)	Active Power (mW)	min temp active ºC	max temp active ºC
PIC32MX2	Microchip Technologies	Commerical	RISC_V-32	0.297	165	-40	85
AtmegaS128	Atmel	Space Grade	AV-RISC-32	0.0825	36.3	-55	125
SAM L11	Microchip Technologies	Commerical	ARM/Cortex	0.00165	2.64	-40	125
Atmega328P	Atmel	Automotive	AV-RISC-32	0.00495	6.6	-55	125
SAM D	Microchip Technologies	Commerical	ARM/Cortex	0.14256	14.19	-40	125