SmallSat 2016 CubeSat Pre-Conference Workshop:

Near Earth Asteroid (NEA) Scout Solar Sail Implementation

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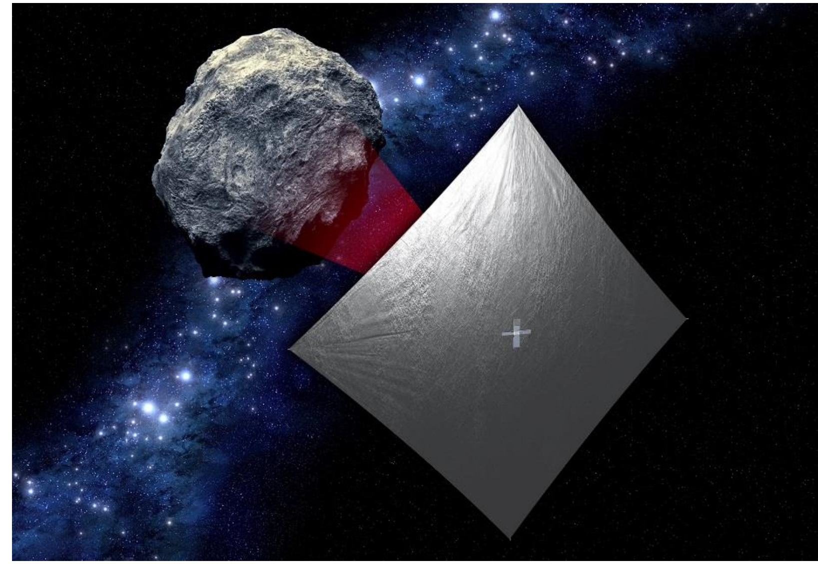
Near Earth Asteroid (NEA) Scout Overview

The Near Earth Asteroid Scout Will

- Image/characterize a NEA during a slow flyby
- Demonstrate a low cost asteroid reconnaissance capability

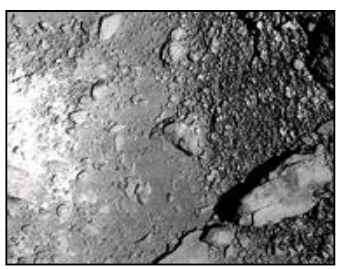


Key Spacecraft & Mission Parameters

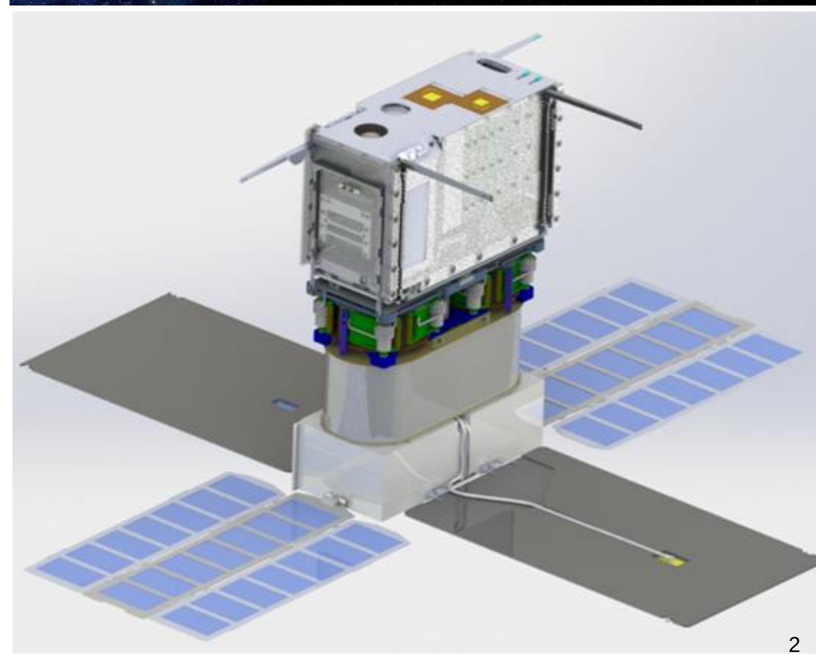
- 6U cubesat (20 cm X 10 cm X 30 cm)
- ~86 m^2 solar sail propulsion system
- Manifested for launch on the Space Launch System (EM-1/2018)
- Up to 2.5 year mission duration
- < 1 AU maximum distance from Earth

Leverages: Combined experiences of MSFC (PM, SE, Solar Sail, AMT, G&C, and Mission Operations) and JPL (Flight System Bus, Instrument, Science) with support from GSFC, JSC, and LaRC

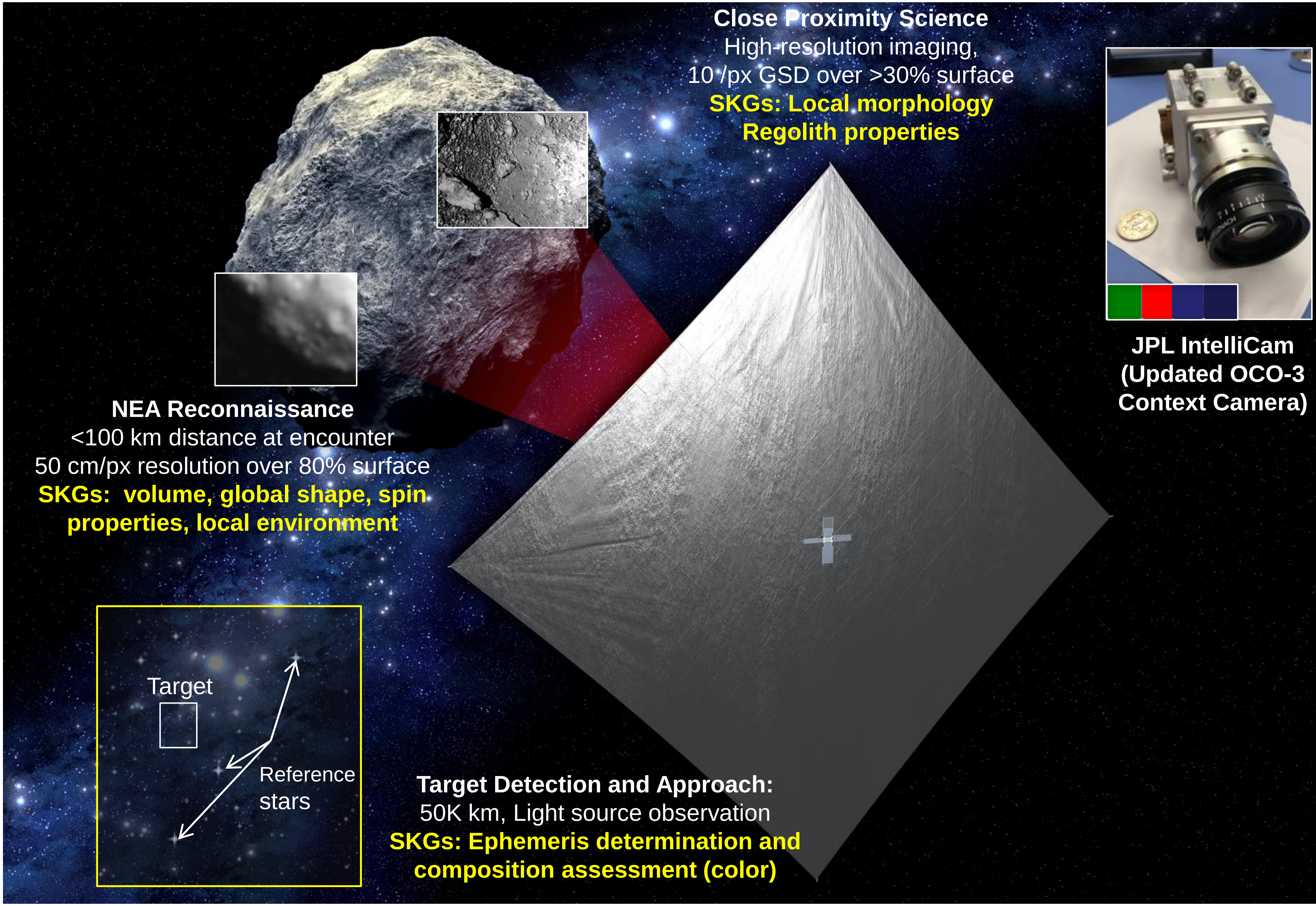
Target Reconnaissance with medium field imaging
Shape, spin, and local environment



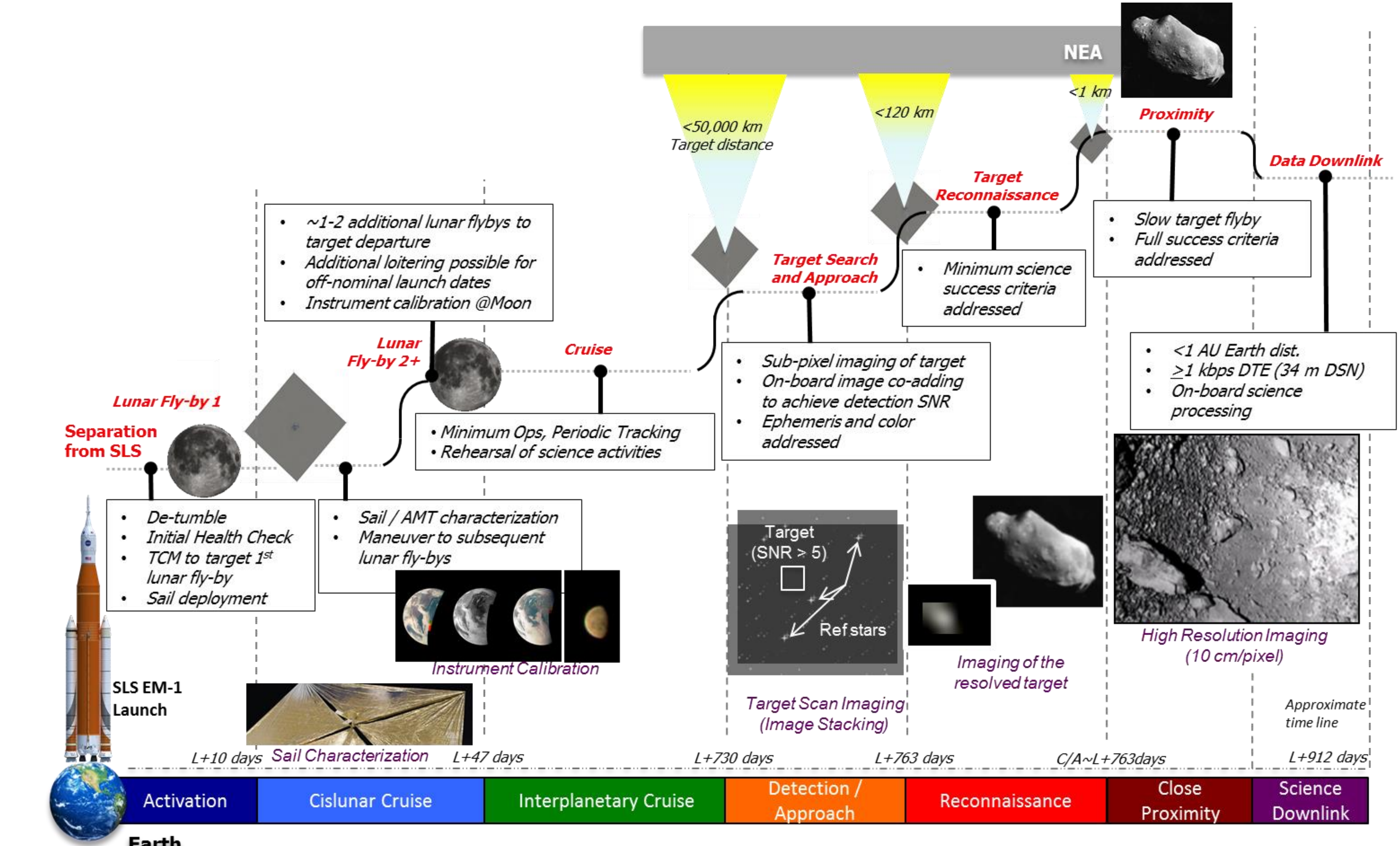
Close Proximity Imaging
Local scale morphology, terrain properties, landing site survey



NEA Scout Science

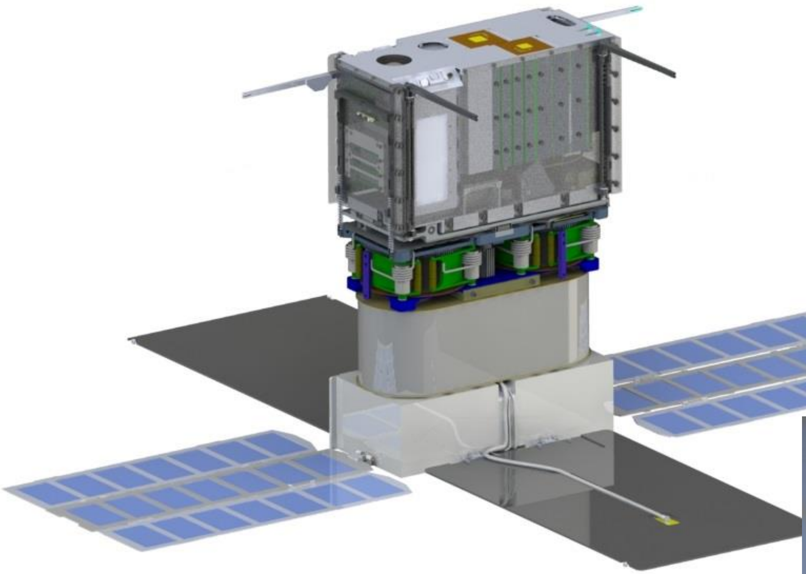


Mission ConOps



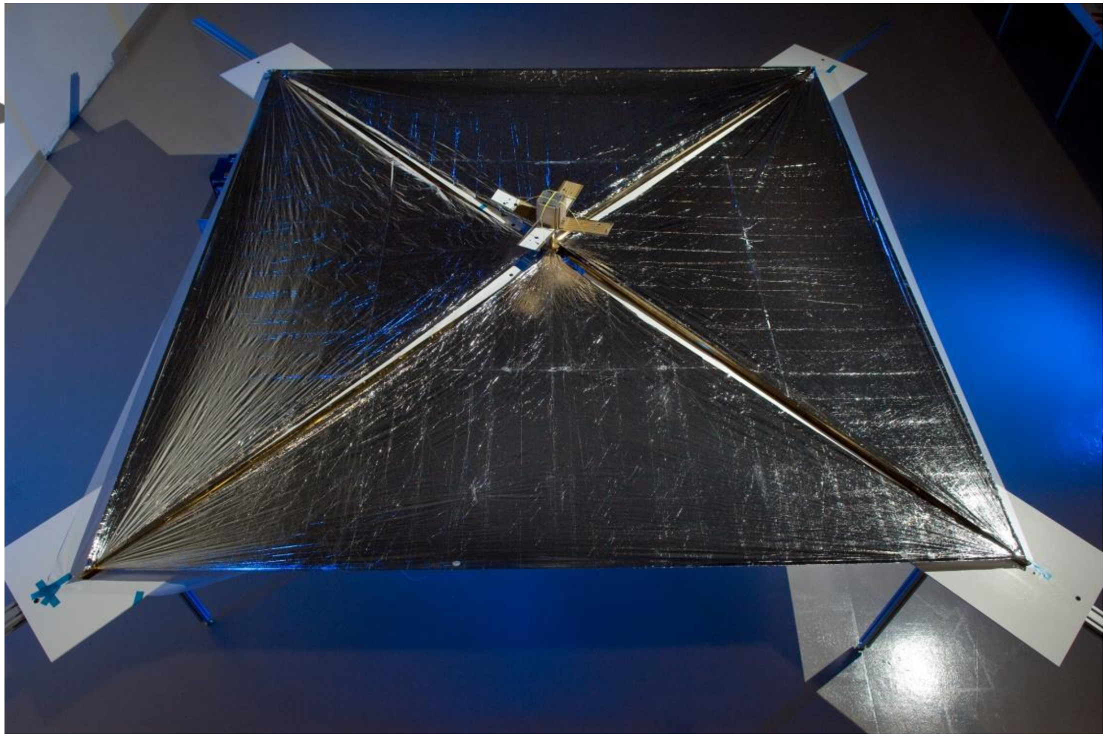
*time not to scale

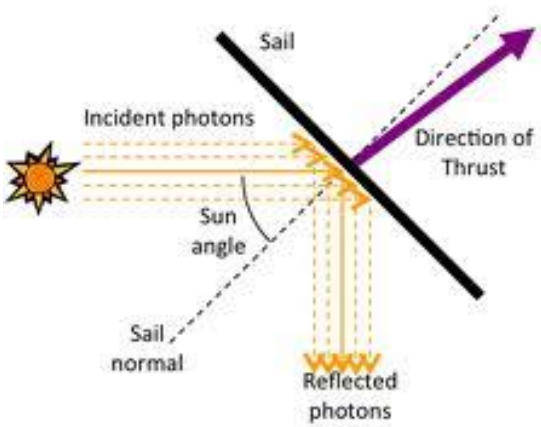
NEA Scout Solar Sail Technology



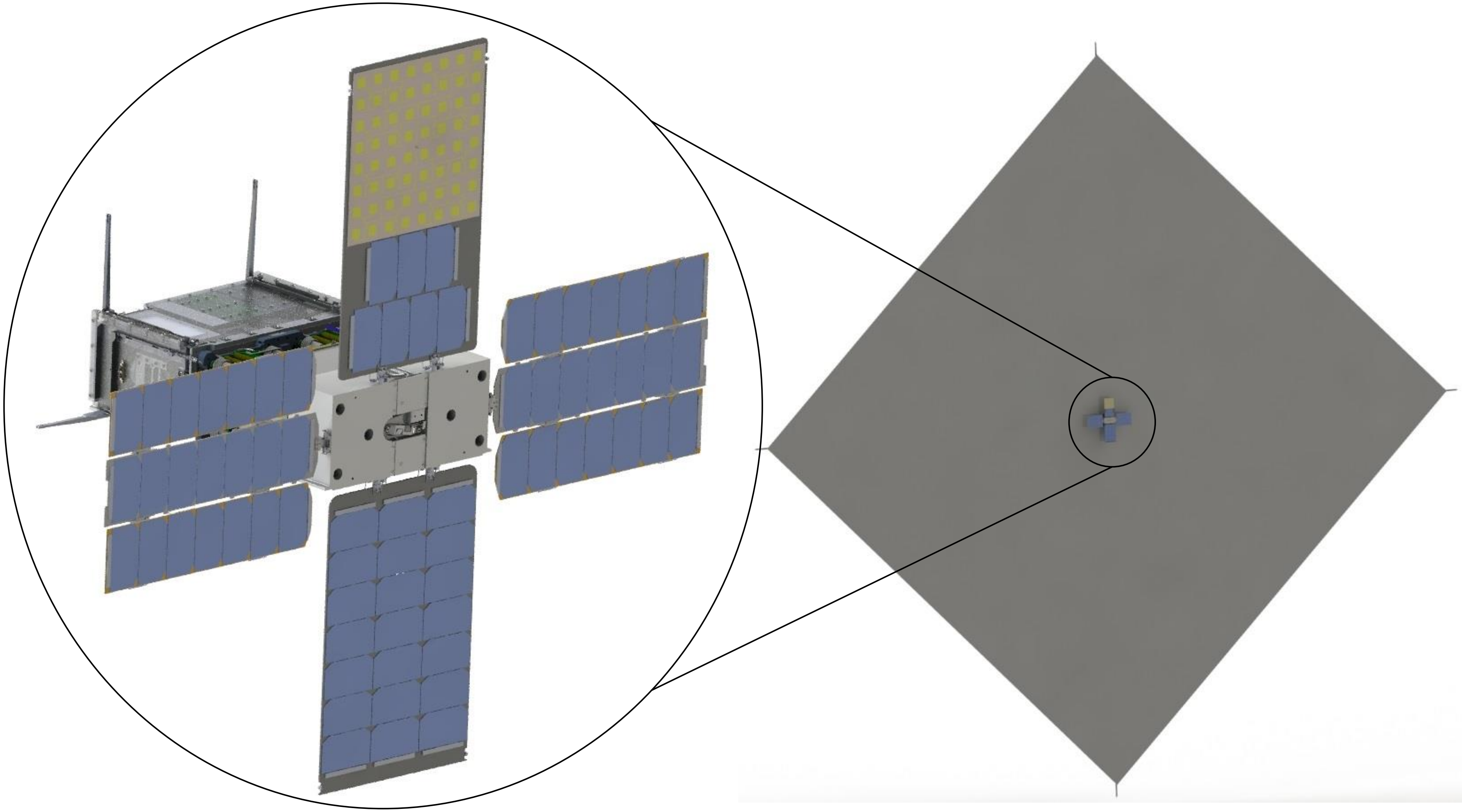
‘Propellantless’ primary propulsion method using momentum exchange with incident photons

Leverages MSFC NanoSail-D (2010) and collaborate arrangements with the Planetary Society and University of Surrey

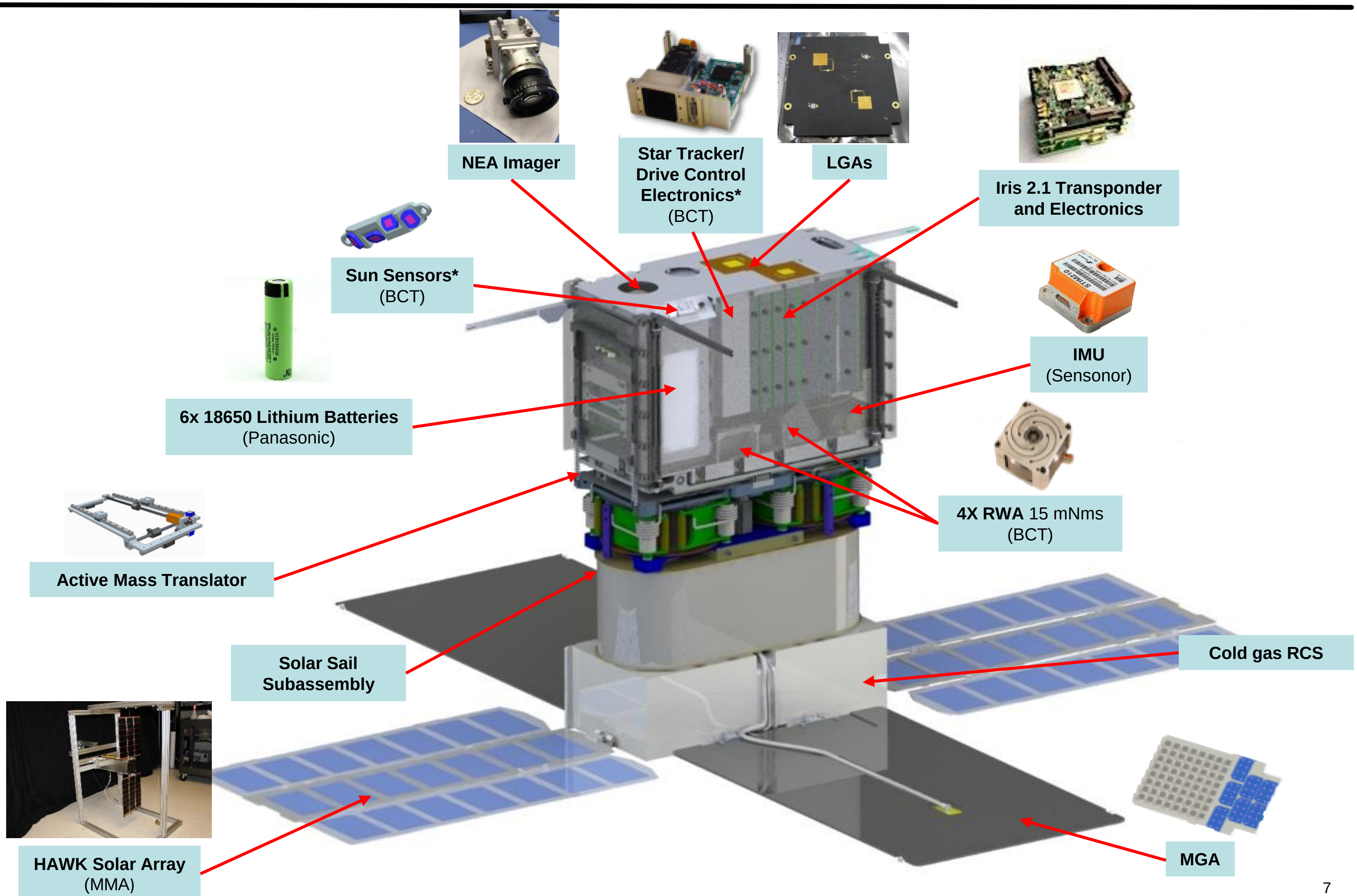




Flight System Configuration – Deployed

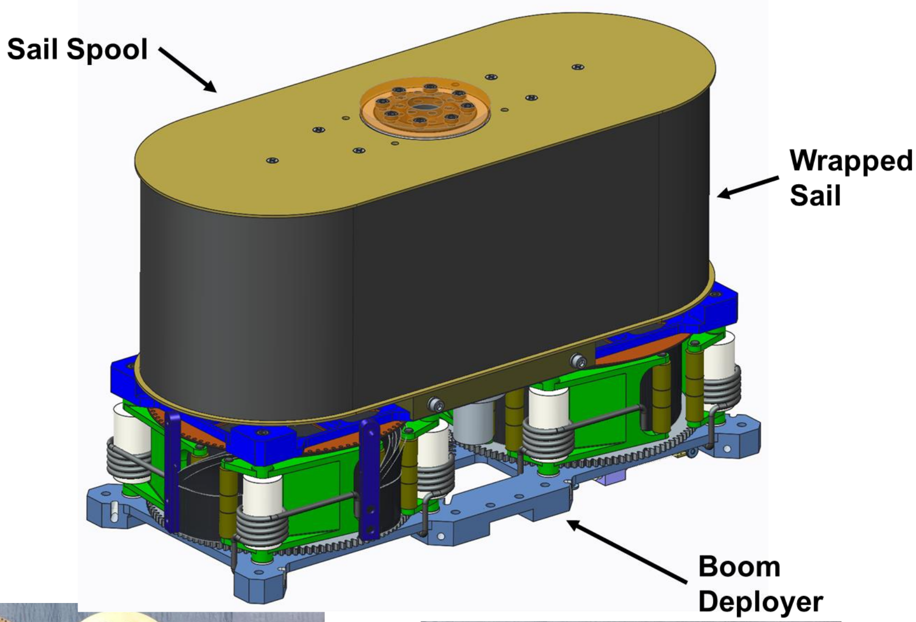


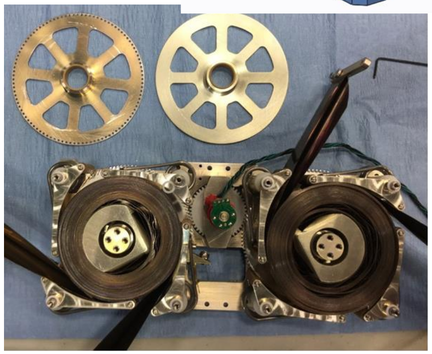
Flight System Overview

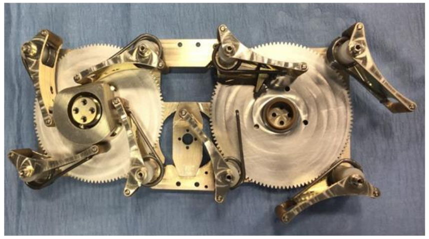


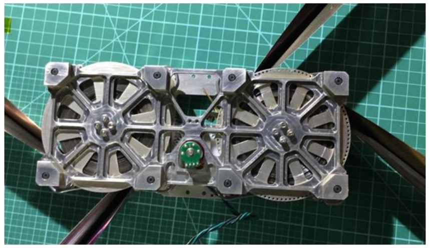
Solar Sail Mission Implementation Challenges

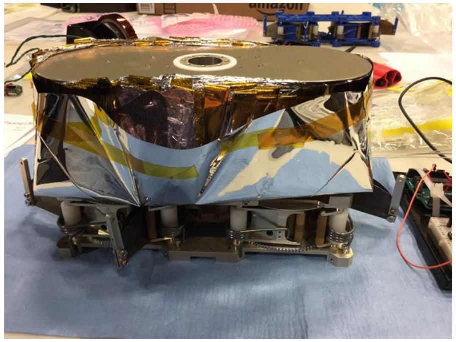
- **Solar Sail transient deployment event and ground testing**
- **Persistent generation of strong disturbance torques with limited expendable propellant**
- **Need for robust ADCS to enable trajectory, Earth-pointing slews, and NEA detection/SKG science objectives**
- **Predictable thrust modeling**



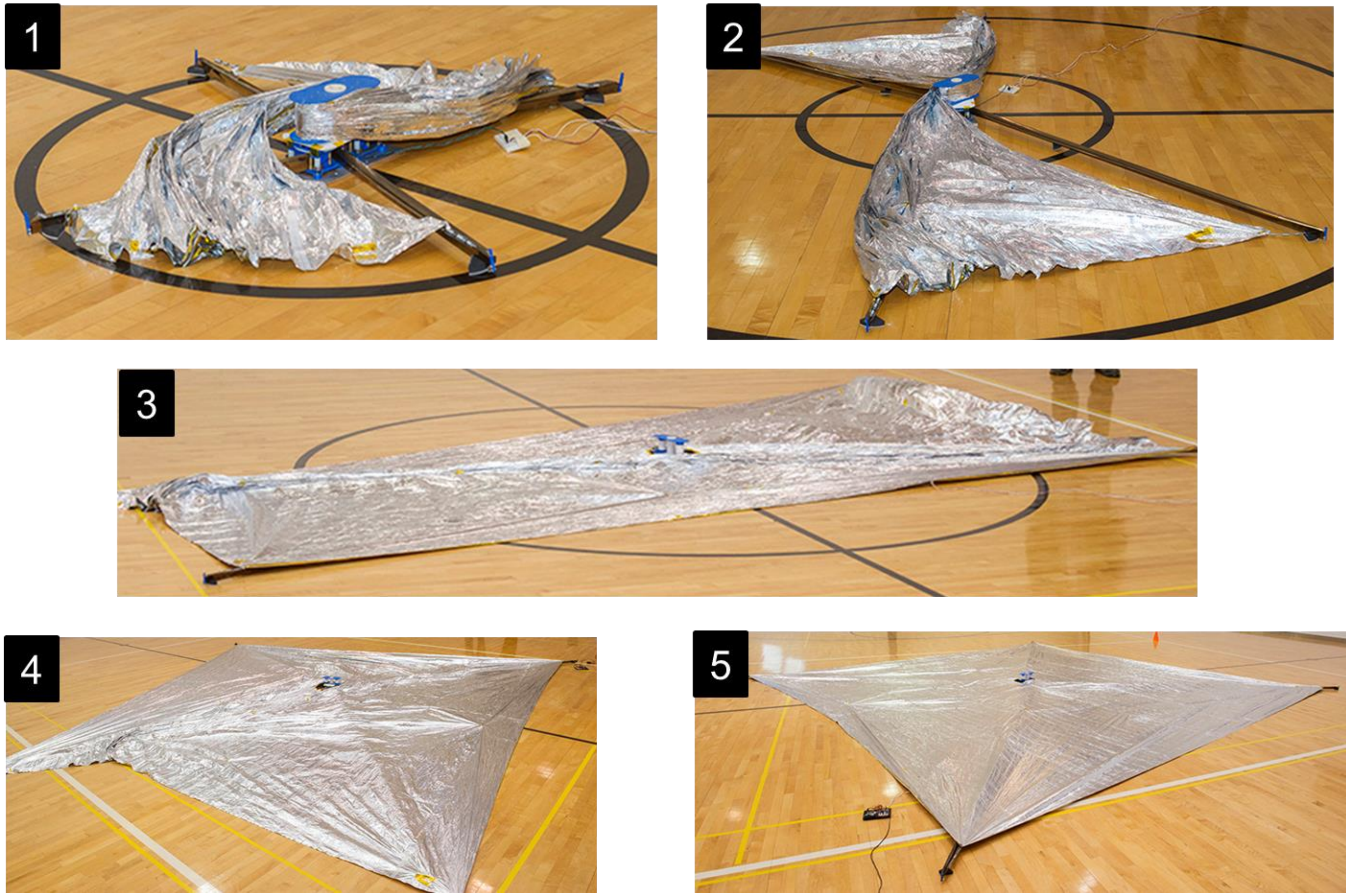






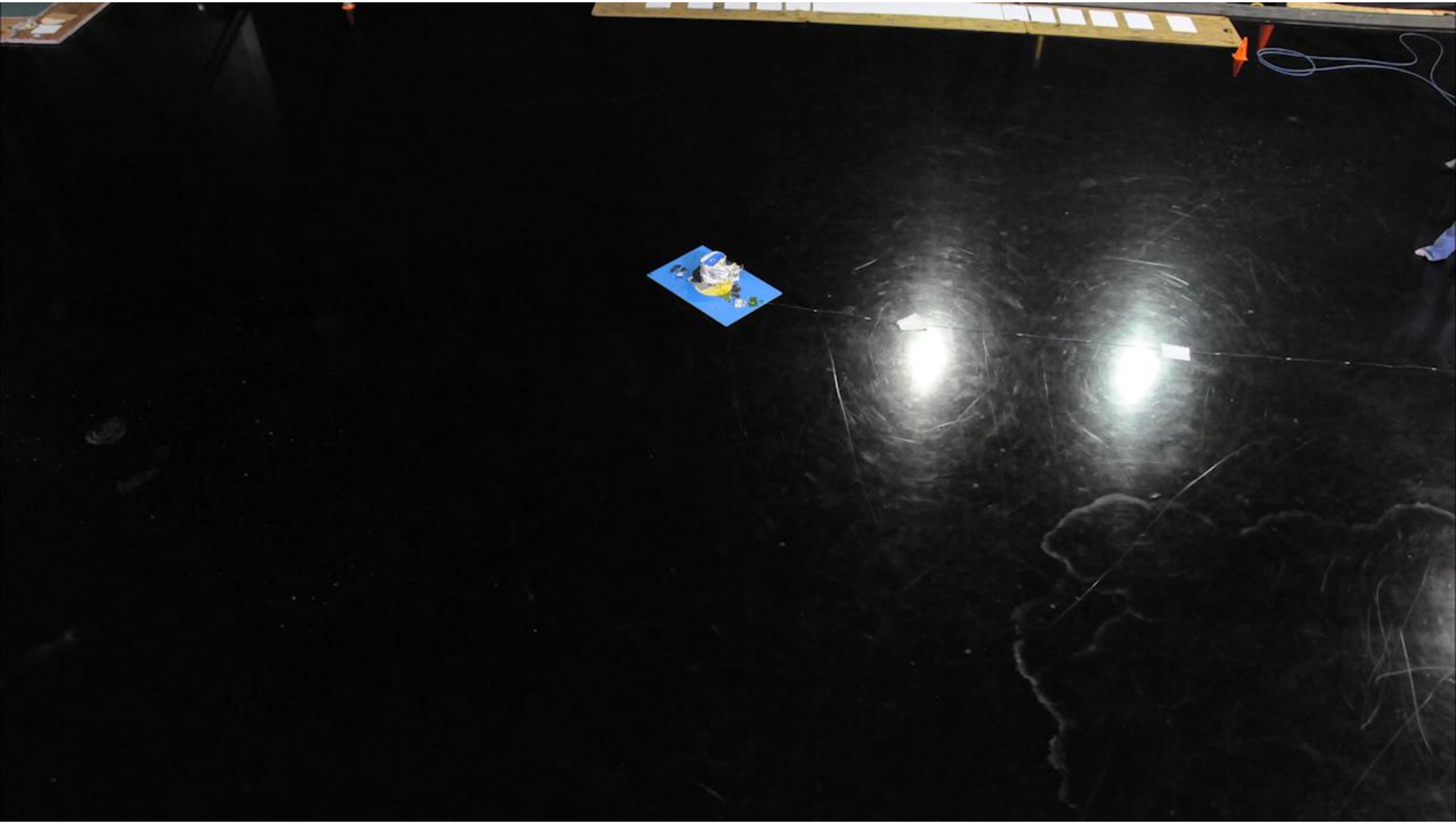


Transient Solar Sail Deployment – Shape Phases

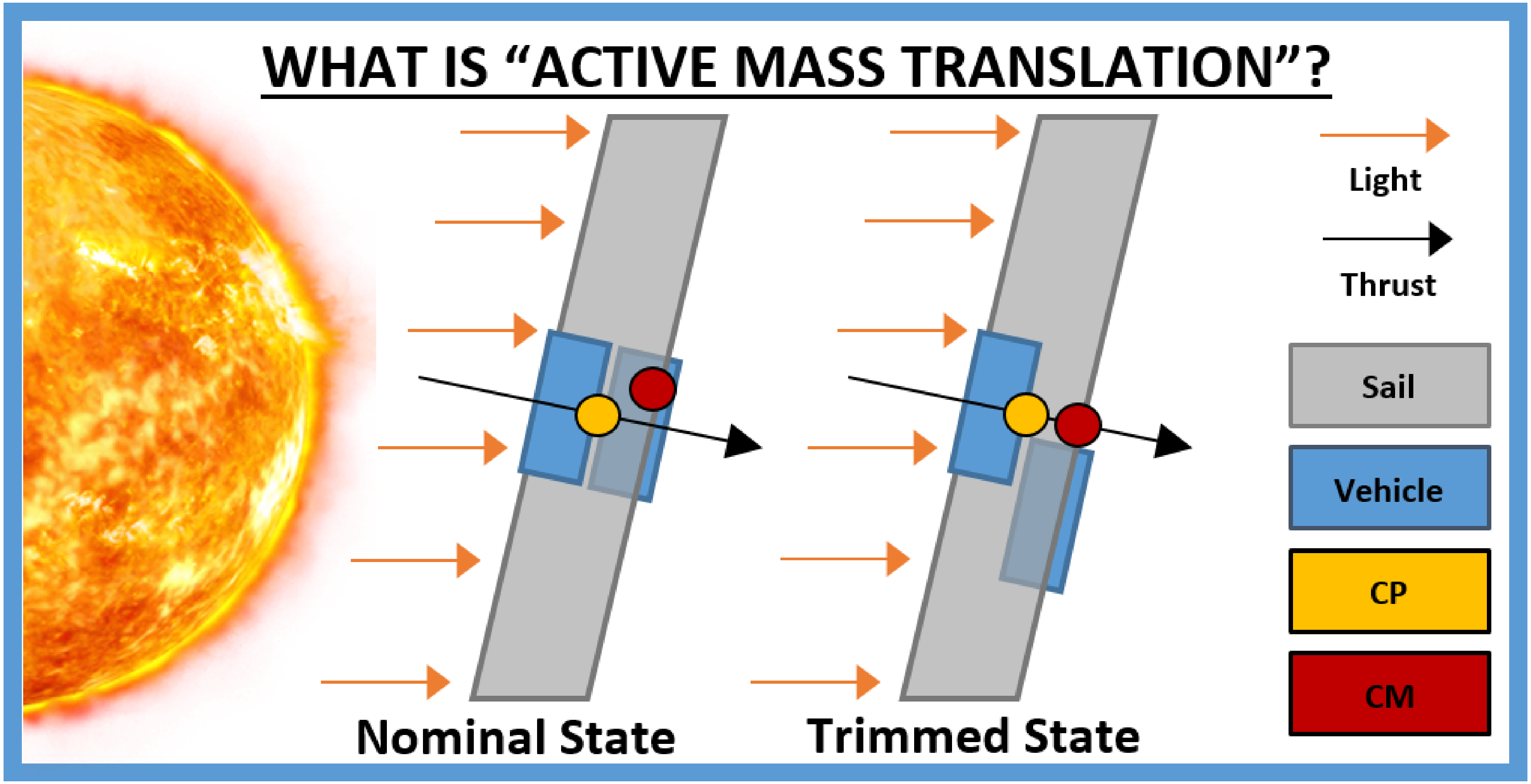


Single sail membrane drives initial ‘bow tie’ effect: Booms are do not maintain 90deg relative orientation (less predictable induced disturbance force) and direct sunlight on booms drive significant thermal deflections

1st Full Scale Solar Sail Ground Deployment



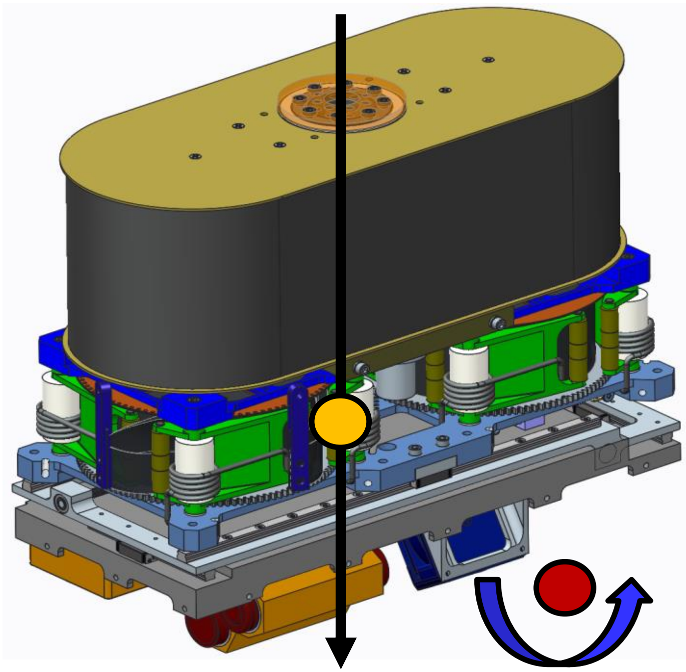
Disturbance Torques: Active Mass Translator (AMT)



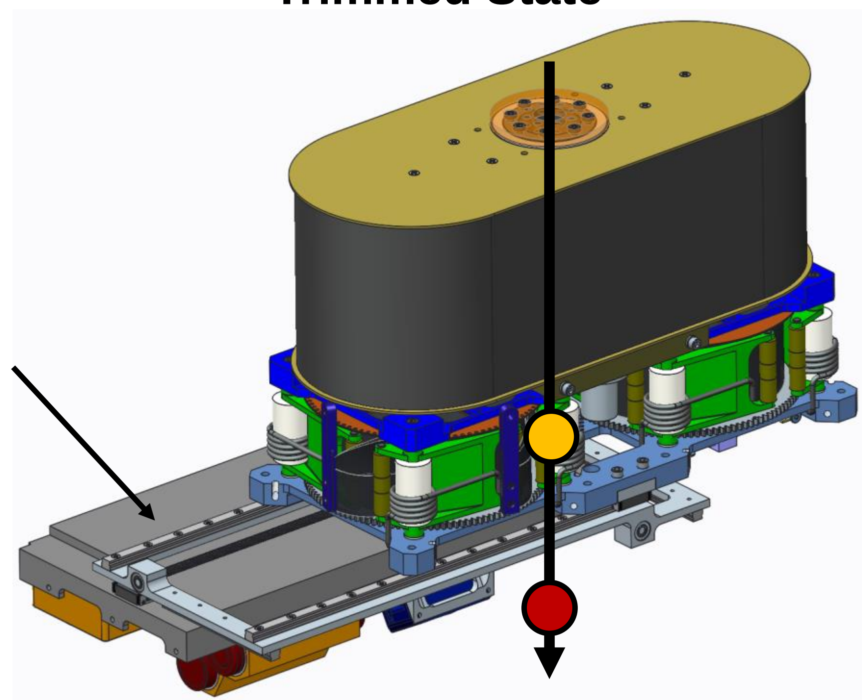
Relative adjustment of part of the spacecraft relative to the other to alter the inertial properties of the vehicle and align the Solar Sail Center-of-Pressure (CP) and Center-of-Mass (CM)

Disturbance Torques: Active Mass Translator (AMT)

Nominal State



Trimmed State



AMT

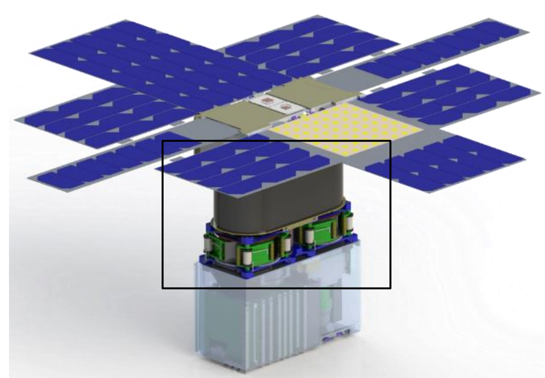
KEY

Thrust

CP

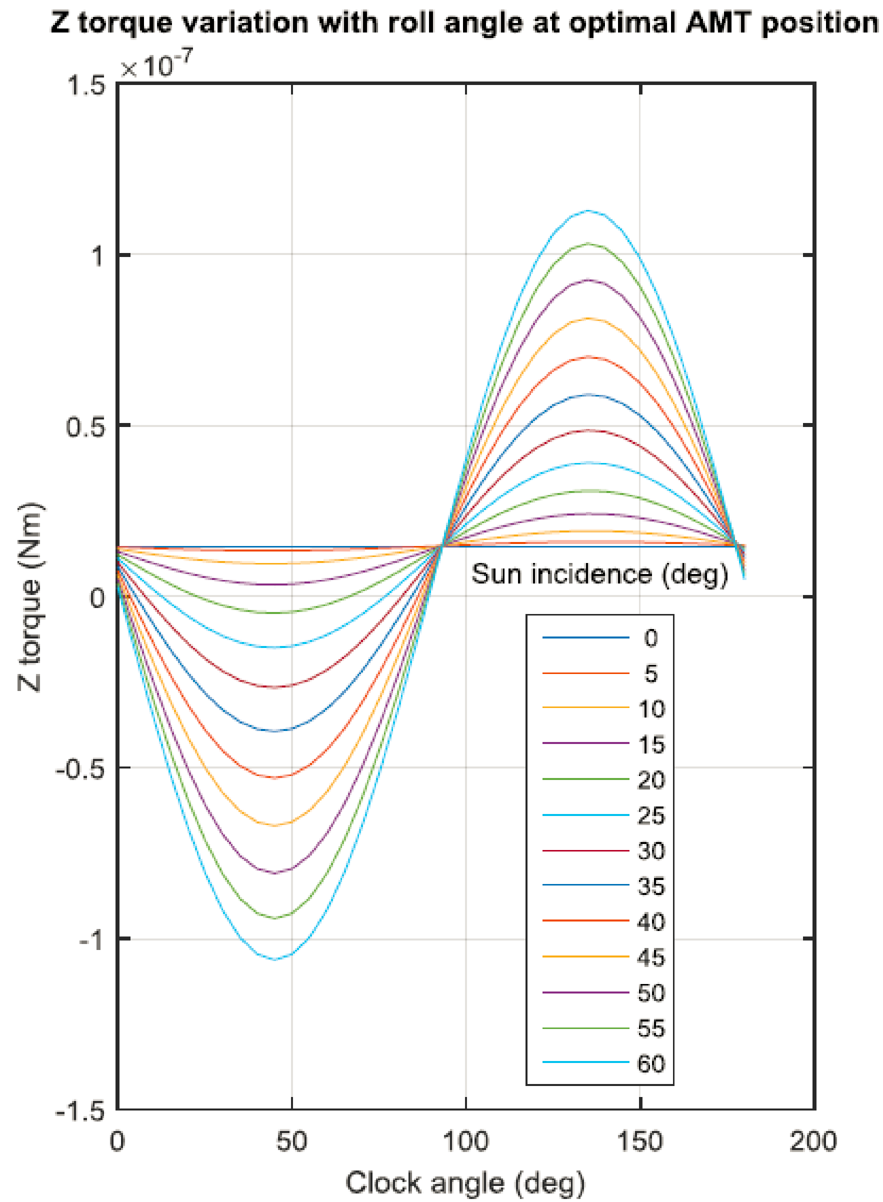
CM

Disturbance Torque



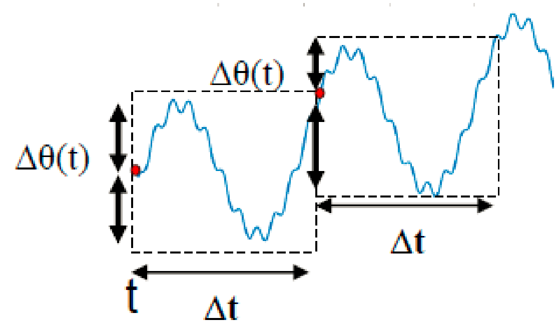
ADCS: Z-Momentum Build-up

- AMT does not completely eliminate ‘windmill’ torque about sail normal
- Generated torque varies with roll (‘clock’) angle and solar angle of incidence (AOI)
- <20deg AOI, RCS must be used for Z-momentum desaturation
- >20deg AOI, clock angle can be adjusted to manage or minimize accumulation of Z-momentum
- Underscores importance of characterization period early in the mission

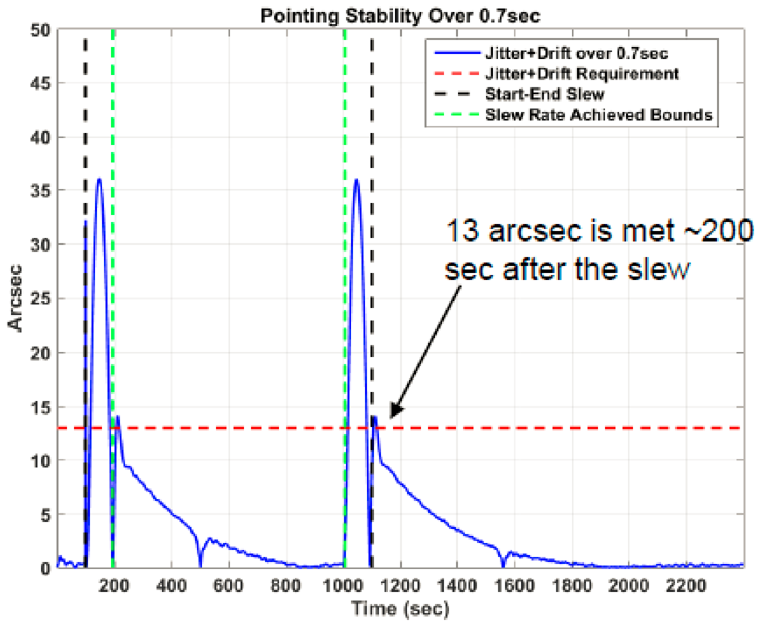


ADCS: Pointing Stability

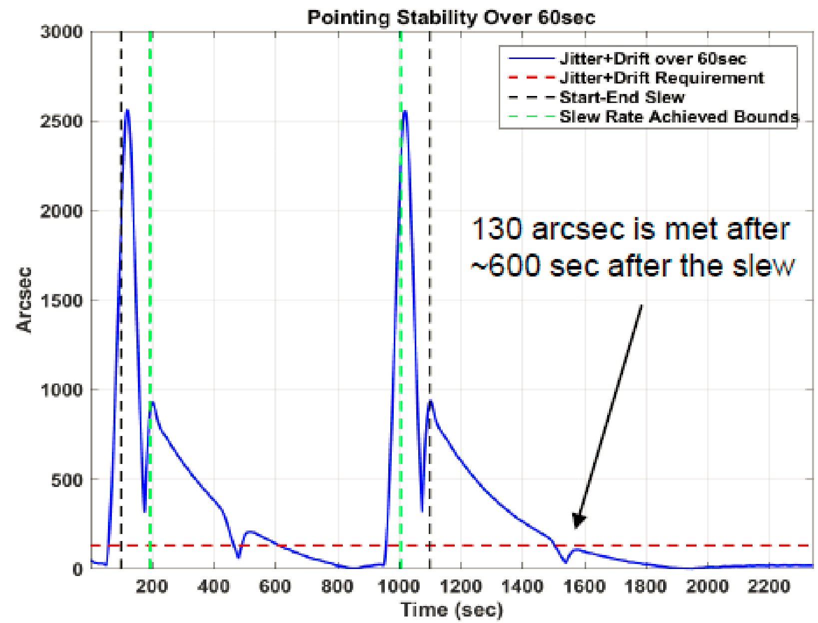
- **Pointing Stability Requirements**
  - Jitter + Drift < 13 arcsec for 0.7 sec
  - Jitter + Drift < 130 arcsec for 60 sec
- Drift+Jitter amplitudes: maximum control error during an exposure time Δt, during and after a slew at maximum slew rate of 0.1 deg/sec



13 arcsec for 0.7 sec



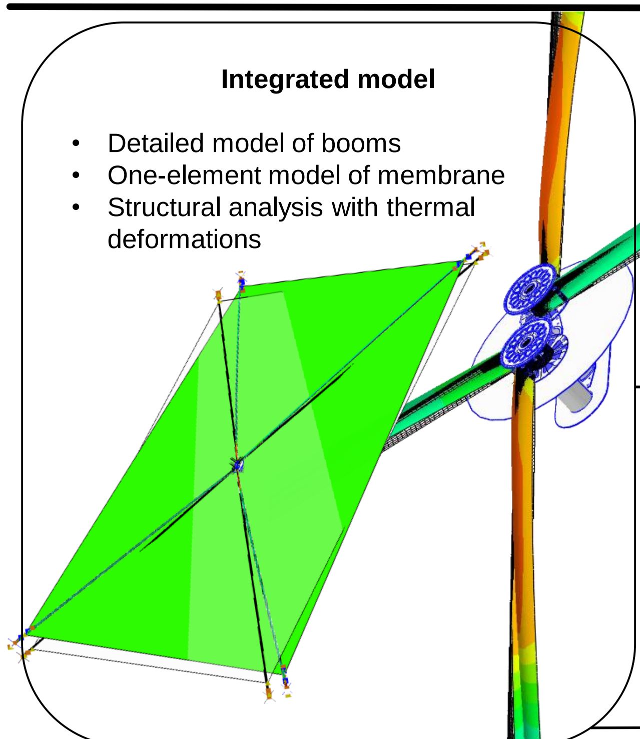
130 arcsec for 60 sec



Pointing stability requirements are met after a settling time of:

- ~200 sec for 13 arcsec in 0.7 sec
- ~600 sec for 130 arcsec in 60 sec

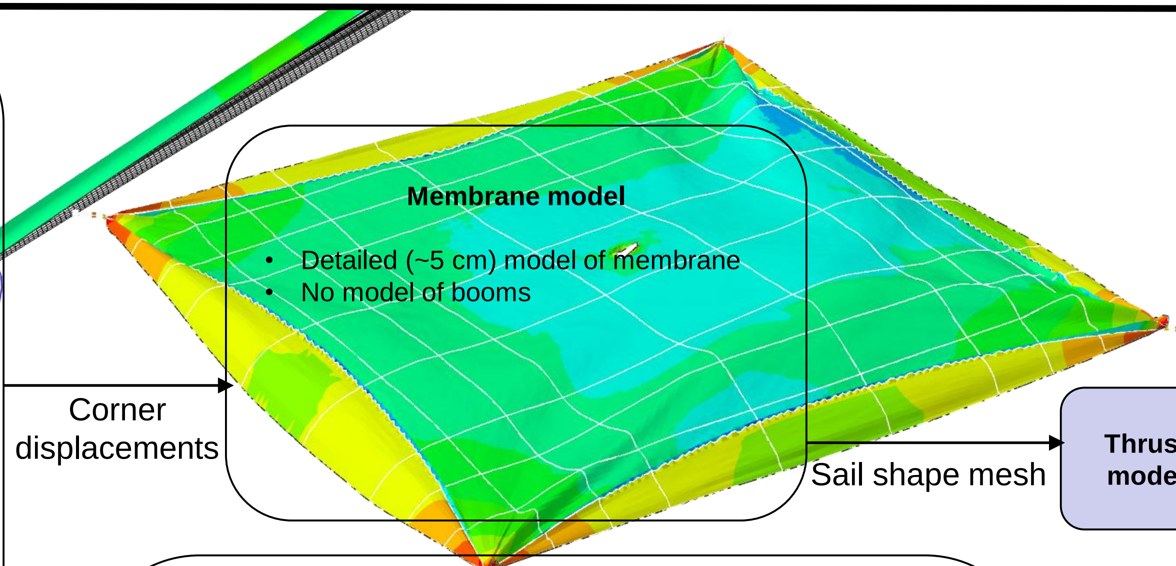
Solar Sail Thrust Model and Analysis Flowchart



Integrated model

- Detailed model of booms
- One-element model of membrane
- Structural analysis with thermal deformations

Corner displacements



Membrane model

- Detailed (~5 cm) model of membrane
- No model of booms

Sail shape mesh

Thrust model

Thermal model

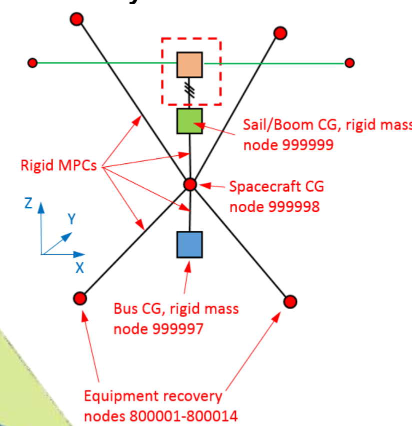
- Radiative and conductive heat transfer

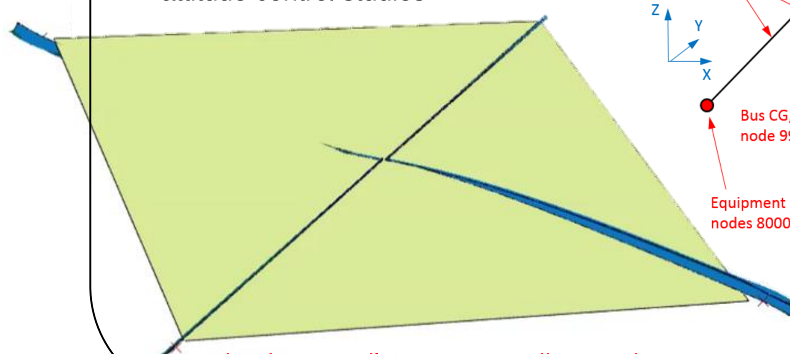
Shape solution

Dynamic model

- Fixed-bus model
- Stiffness matrix includes the effects of sail tensioning and thermal loading
- Reduced dynamic model is integrated with the spacecraft bus for attitude control studies

Reduced/simplified dynamic model





Fixed-Bus Sail System Bending Mode

Attitude control model

Summary & Project Status

- **Summary**
  - Numerous challenges exist in implementing a Solar Sail mission, particularly within a CubeSat form factor
  - Extensive design, analysis, and testing has been performed to-date to address these challenges
  - Difficulty in validating analytical models and performing ground (1G) demonstrations given gossamer nature of Solar Sails
  - NEA Scout flight on SLS EM-1 flight opportunity (2018) will provide a giant leap forward in clarifying our understanding of Solar Sail modeling and performance
- **Project Status**
  - On track for August Design Review with significant flight procurements to follow
  - Flight System integration starts June 2017
  - Manifested on SLS EM-1 for 2018 deep space flight opportunity
  - NEA flyby anticipated in 2021

BACKUP

Synergies Across Fields

HUMAN OPERATIONS

Internal structure (regolith vs. monolith)
Sub-surface properties
General mineral, chemical composition

SCIENCE

Internal structure (regolith vs. monolith)
Sub-surface properties
Detailed mineral, chemical, isotopic composition

Intersection of All

Location (position prediction, orbit)
Size (existence of binary/ternary)
Rotation rate and pole position
Particulate environment/Debris field
Electrostatic charging and Plasma field
Thermal environment
Gravitational field structure
Mass/density estimates
Surface morphology and properties
Regolith mechanical and geotechnical properties

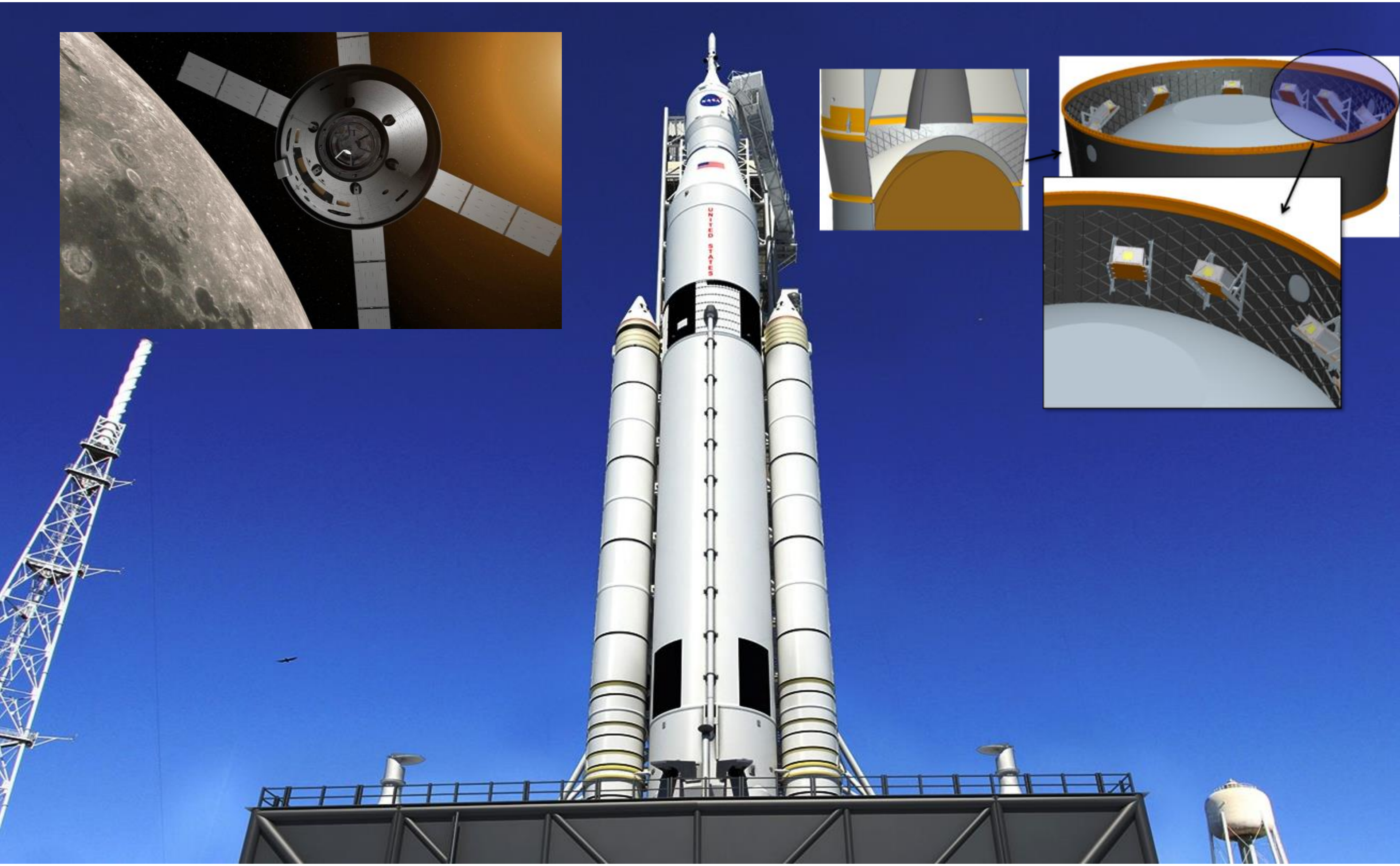
PLANETARY DEFENSE

Internal structure (regolith vs. monolith)
Sub-surface properties (→ beta)
General mineral, chemical composition

RESOURCE UTILIZATION

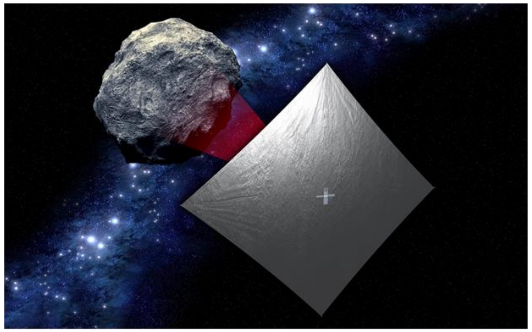
Detailed mineral, chemical composition

Space Launch System (SLS) Exploration Mission 1 (EM-1) Accommodation

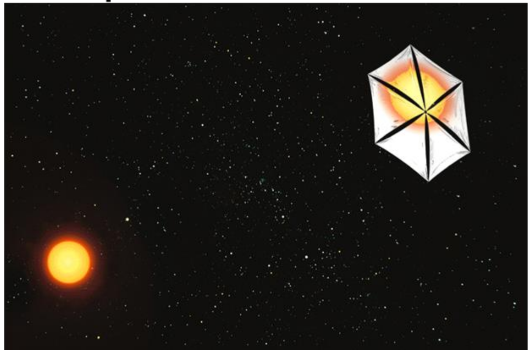


Solar Sail Mission Applications

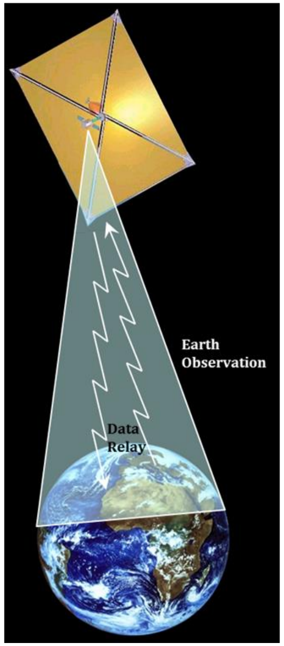
NEA Reconnaissance & Small Body Science



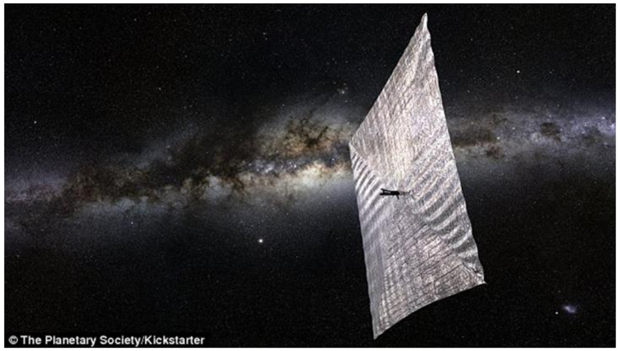
Solar & Out of the Ecliptic Science



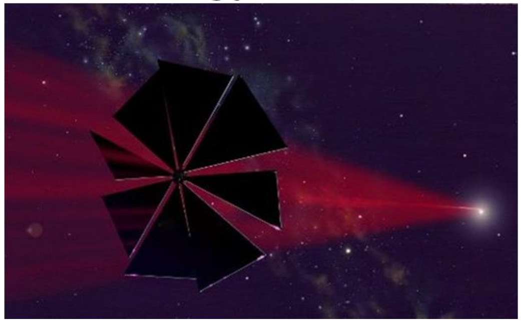
Earth Pole Sitting



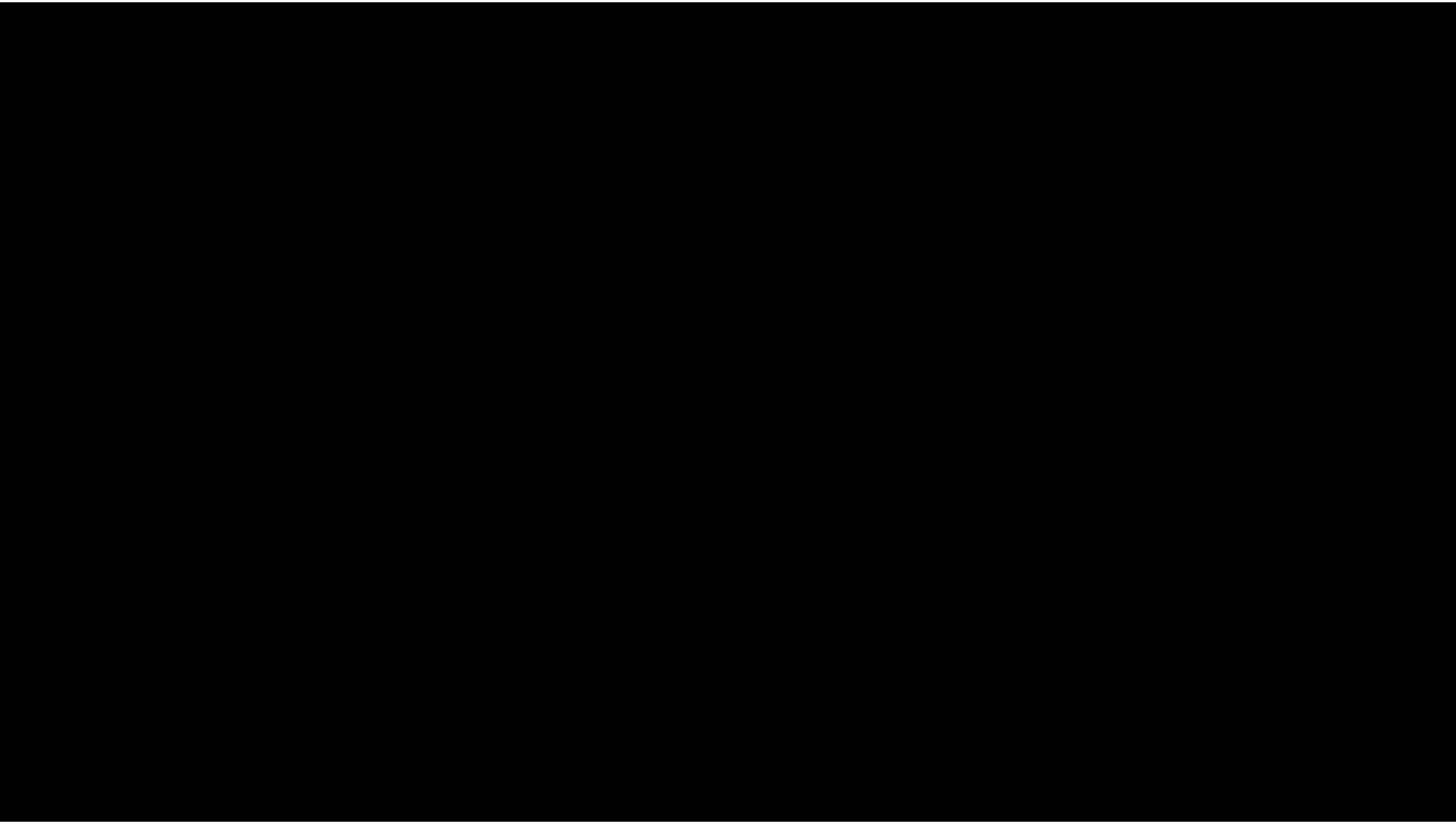
Rapid Outer Solar System Exploration and Escape



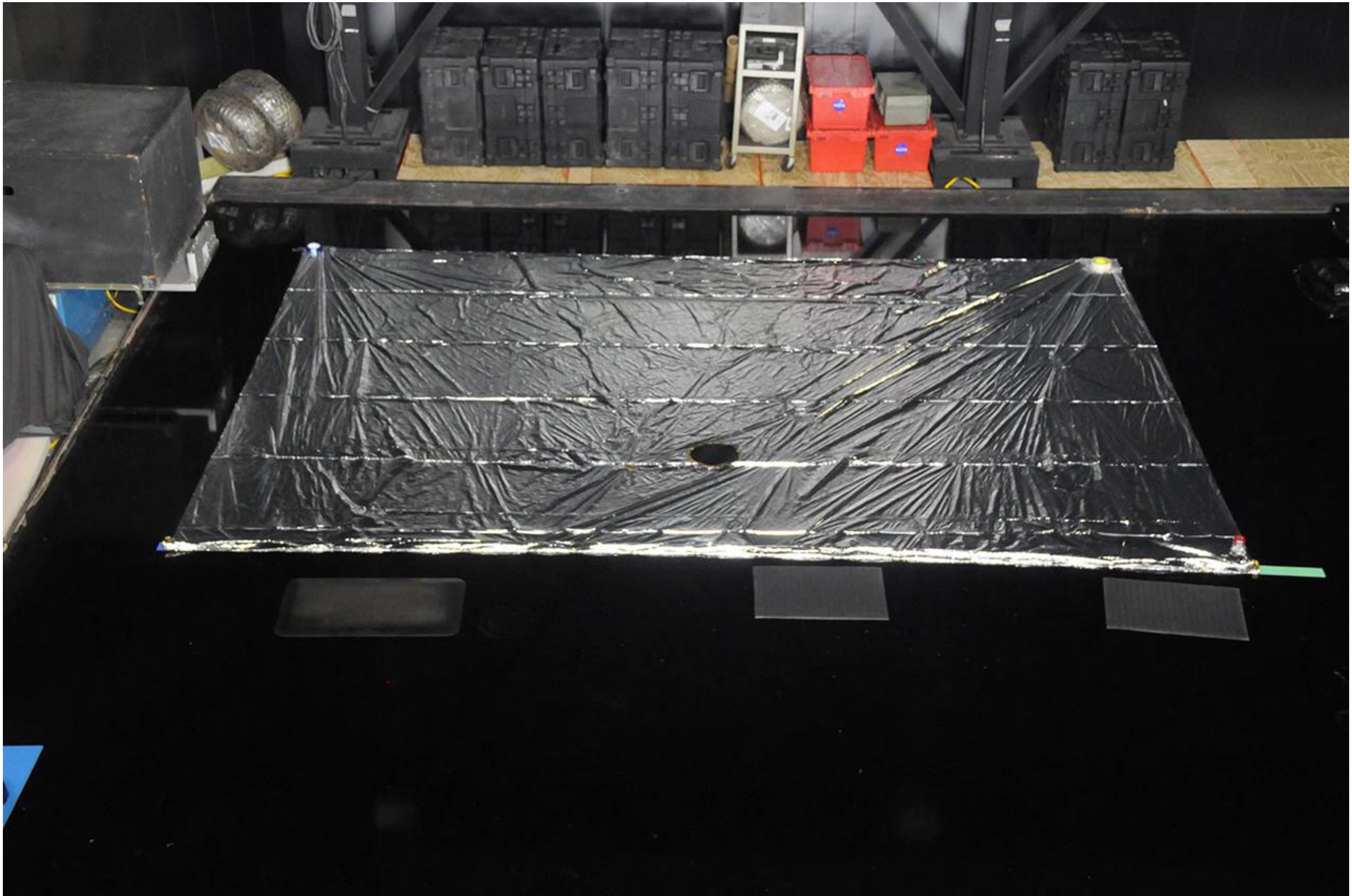
Toward Higher Performance Beamed Energy Propulsion



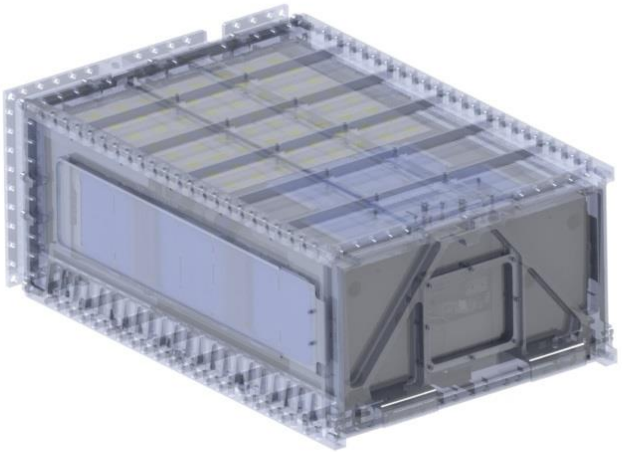
½ Scale Deployment



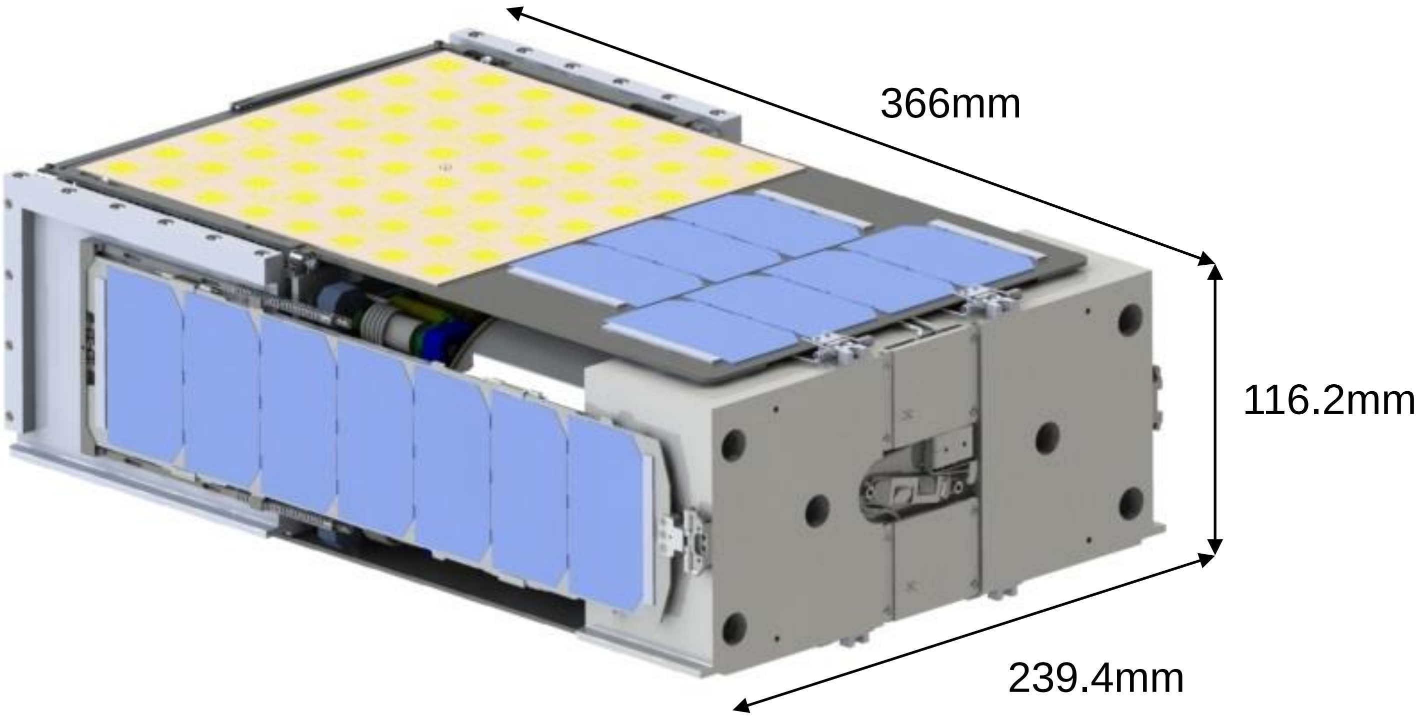
½ Scale Folding Video



Flight System Configuration – Stowed

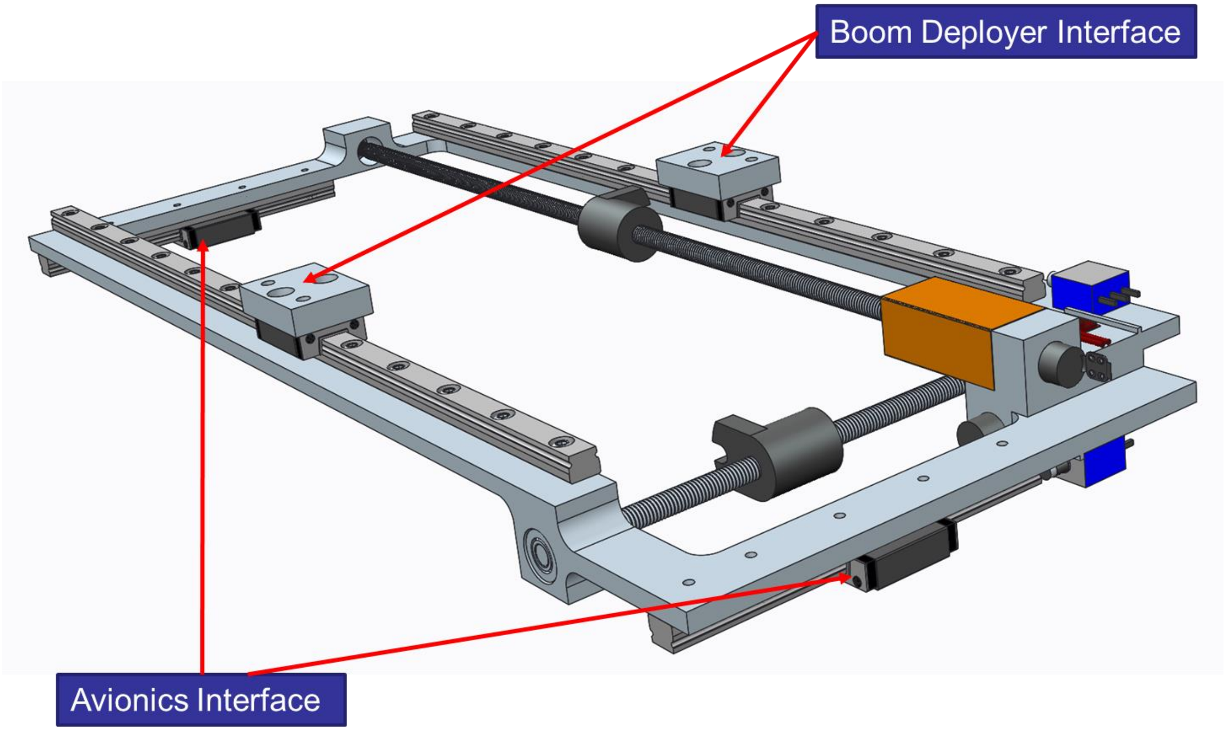


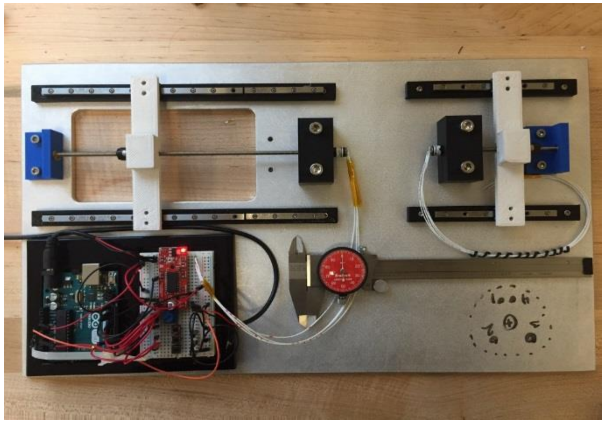
NEAS Inside PSC
6U Dispenser

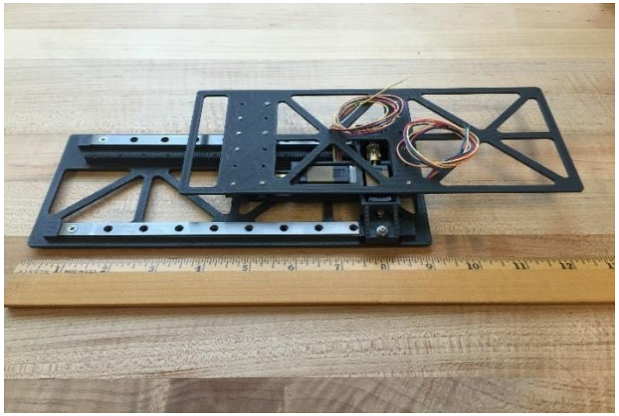


AMT Design and Breadboarding

- Breadboarding hardware development as proof-of-concept
- EDU hardware in development for environmental testing and wire harness implementation







Thrust Model: Underlying Physics

- **Flat Plate optical model published in Wright and cited by McInnes**
- **Shows tangential and normal components**
- **Tangential component important to torque**

P = solar pressure

A = area

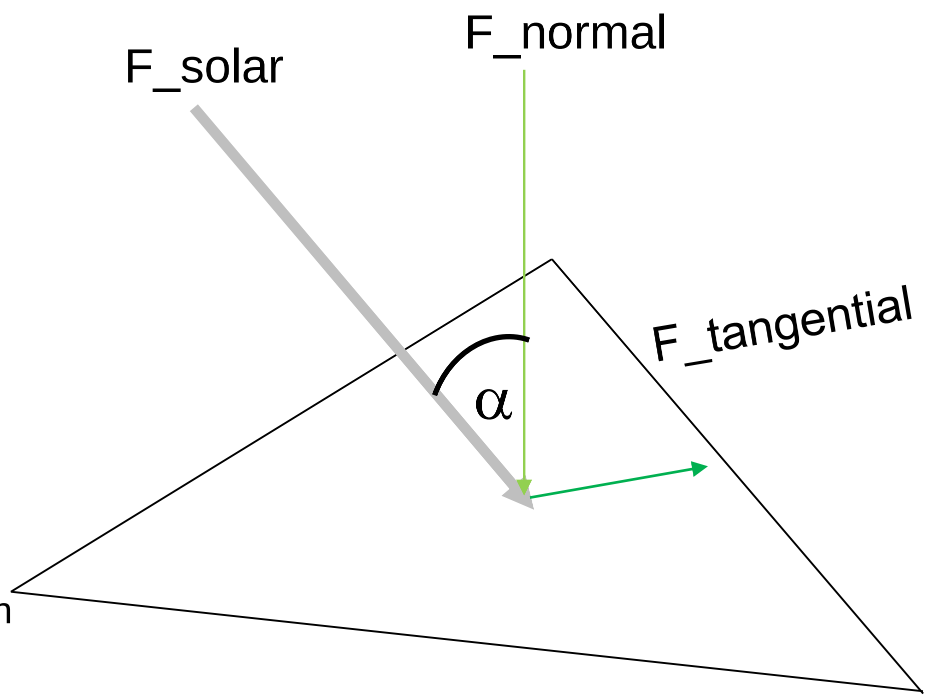
$\tilde{r}$ = total reflectivity

s = fraction of reflection that is specular

α = sun incidence angle

Bf, Bb = front and back side non-Lambertian coefficients

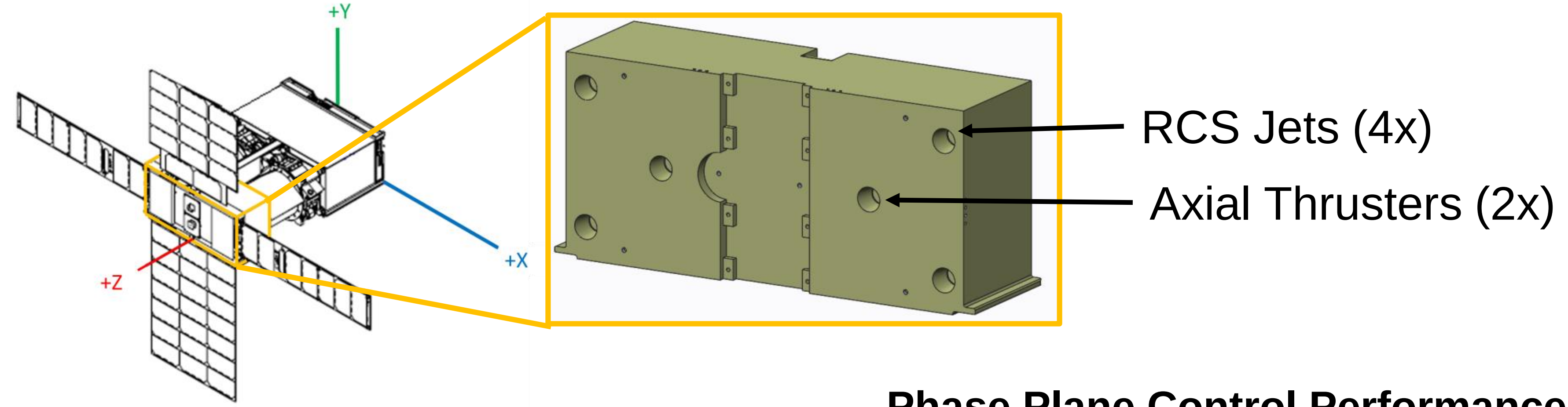
ef, eb = front and back side emissivities



$$f_n = PA\left\{(1+\tilde{r}s)\cos^2\alpha + B_f(1-s)\tilde{r}\cos\alpha + (1-\tilde{r})\frac{\varepsilon_f B_f - \varepsilon_b B_b}{\varepsilon_f + \varepsilon_b}\cos\alpha\right\}$$

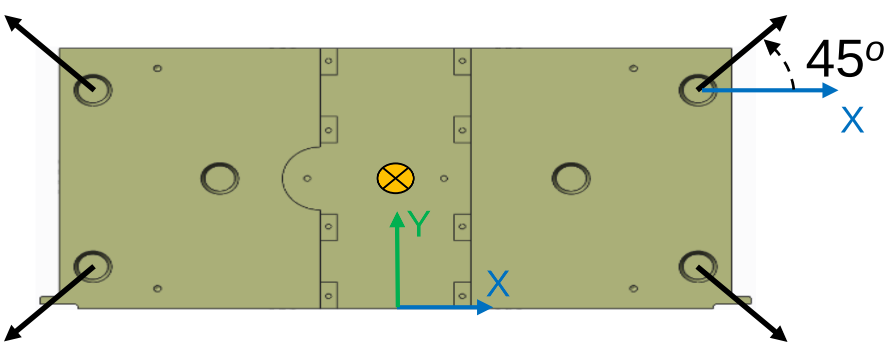
$$f_t = PA(1-\tilde{r}s)\cos\alpha\sin\alpha\, t$$

NEA Scout - Reaction Control System (RCS)



Approx. CM Location

RCS Jet Thrust



Phase Plane Control Performance