SmallSat 2016 CubeSat Pre-Conference Workshop:

Near Earth Asteroid (NEA) Scout Solar Sail Implementation

Vinh Bach²
Chris Becker¹
Jared Dervan¹
Ben Diedrich¹
Alex Few¹
Andrew Heaton¹
Travis Imken²
Tiffany Lockett¹
Duy Nguyen²
Juan Orphee¹
Brandon Stiltner¹
Olive Stohlman³
Jay Warren³

¹NASA Marshall Space Flight Center
²Jet Propulsion Laboratory
³NASA Langley Research Center
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 m² 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

Close Proximity Science
- High-resolution imaging, 10/px GSD over >30% surface
- SKGs: Local morphology, Regolith properties

NEA Reconnaissance
- <100 km distance at encounter
- 50 cm/px resolution over 80% surface
- SKGs: Volume, global shape, spin properties, local environment

Target Detection and Approach:
- 50K km, Light source observation
- SKGs: Ephemeris determination and composition assessment (color)

Reference stars

Target

JPL IntelliCam
(Updated OCO-3 Context Camera)
Mission ConOps

- ~1-2 additional lunar flybys to target departure
- Additional loitering possible for off-nominal launch dates
- Instrument calibration @Moon

- Lunar Fly-by 2+
- Minimum Ops, Periodic Tracking
- Rehearsal of science activities

- Target Search and Approach
- Sub-pixel imaging of target
- On-board image co-adding to achieve detection SNR
- Ephemeris and color addressed

- Target
  - Target Scan Imaging (Image Stacking)
  - High Resolution Imaging (10 cm/pixel)
  - Imaging of the resolved target
  - Reference stars

- SLS EM-1 Launch
- L+10 days: Sail Characterization
- L+47 days: Sail deployment
- L+730 days: Activation
- L+763 days: Cislunar Cruise
- L+912 days: Science Downlink

- Target
  - SNR > 5
  - Ref stars

- NEA
  - <50,000 km Target distance
  - <120 km Target
  - <1 km Proximity
  - Slow target flyby
  - Full success criteria addressed

- Data Downlink
  - <1 AU Earth dist.
  - >1 kbps DTE (34 m DSN)
  - On-board science processing

- Earth
  - Activation
  - Cislunar Cruise
  - Interplanetary Cruise
  - Detection / Approach
  - Reconnaissance

- Close Proximity

*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 Overview

- NEA Imager
- Star Tracker/Drive Control Electronics* (BCT)
- LGAs
- Iris 2.1 Transponder and Electronics
- Sun Sensors* (BCT)
- IMU (Sensonor)
- 6x 18650 Lithium Batteries (Panasonic)
- 4X RWA 15 mNms (BCT)
- Active Mass Translator
- Solar Sail Subassembly
- HAWK Solar Array (MMA)
- Cold gas RCS
- MGA
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

1. 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
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)
• 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 $\Delta t$, during and after a slew at maximum slew rate of 0.1 deg/sec

**13 arcsec for 0.7 sec**
- 13 arcsec is met ~200 sec after the slew

**130 arcsec for 60 sec**
- 130 arcsec is met after ~600 sec after the slew

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

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

**Thermal model**
- Radiative and conductive heat transfer

**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**

**Thrust model**

**Corner displacements**

**Sail shape mesh**

**Shape solution**

**Fixed-Bus Sail System Bending Mode**

**Attitude control model**

**NEAScout**

**NASA**
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

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

**Resource Utilization**
- Detailed mineral, chemical 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
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 Folding Video
Flight System Configuration – Stowed

NEAS Inside PSC
6U Dispenser

Dimensions:
- 366mm
- 116.2mm
- 239.4mm
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

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

\[ f_t = PA(1 - \tilde{r}s) \cos \alpha \sin \alpha t \]
NEA Scout - Reaction Control System (RCS)

RCS Jets (4x)
Axial Thrusters (2x)

Phase Plane Control Performance

Approx. CM Location
RCS Jet Thrust

$45^\circ$