Concurrent Mission Design of NEA Scout & Lunar Flashlight, Solar Sail CubeSat Missions

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Mission Concept(s)
Mission Objectives & Drivers

NEA Scout

- 6-U Cubesat form factor
- Common bus / hardware (mostly)
- Different science payloads
- Deployable solar sail
- Ride-share with EM-1
- 30 month mission
- Fly-by of near-Earth asteroid
- Telecom: LGA + HGA
- Camera for science & opnav
- Tracking & trajectory coupled (via solar sail)

Lunar Flashlight

- Illuminate craters on lunar south pole to look for frozen H₂O
- Telecom: LGA
- Sail reflects light into target craters
- Science & trajectory coupled (via solar sail)

Additional programmatic goal: identify benefits & drawbacks of parallel CubeSat mission development
Launch window up to 2 Hrs long (depends on launch day in one week window recurring every month)

End of TLI burn.

Passive Thermal Control

25 minutes

Orient for Disposal Maneuver

Blowdown while in a transverse spin to minimize delta V.

Deployment Window
Opens ~ 4-5 hours post T0

T0+8 hrs
ICPS
Batt dies

ICPS/MPCV Separation 10 minutes after end of TLI burn

Post-disposal, duration dependent on ACS propellant usage, battery life, and mission requirements. ACS fuel driven, low thrust. Engine bell forward in line of velocity vector.
Trajectory Design – Common Factors
Key Requirements & Assumptions

- **Driving**
  - 2.5 year maximum mission duration
  - Compatibility with EM-1 launch and deployment
  - Assumed launch December 2017 (now 2018)
  - Post-ejection $\Delta V$ to initialize lunar flyby $< 10$ m/s

- **Sail**
  - 11-12 kg spacecraft, 80 m$^2$ sail area
  - Design Characteristic Acceleration: 0.0601 mm/s$^2$
  - Deploy after first lunar flyby
  - Sail normal to sun angle $\leq 50^\circ$ (NEA Scout), $60^\circ$ (Lunar F)
  - Duty cycle:
    - NEA Scout = 90% (0.0541 mm/s$^2$)
    - Lunar Flashlight = 85% (0.0511 mm/s$^2$)
      - More conservative than NEAS due to lunar orbit with close perilune
Trajectory Design – NEA Scout
NS Rendezvous Target Search

- Colors (AU)
  - blue < .25
  - green < .5
  - orange < .75
  - red < 1
- Shape (OCC)
  - △ under 2
  - □ under 4
  - ▼ under 7
- Size (aprx dia.)
  - small < ~15 m
  - med. < ~30 m
  - large < ~50 m

Local minima for flight time. Flight time increases linearly with pre-escape loiter time
Flight time increases non-linearly with delayed escapes
• High thrust required to target 1\textsuperscript{st} lunar flyby
  – First nav solution within 12 hours of separation
  – First TCM within 24 hours
  – Cleanup TCM within 36 hours
• No data on disposal burn dispersions yet
  – 1+ month of solar sailing available to clean up flyby errors
• Daily tracking and trajectory updates approaching 2\textsuperscript{nd} lunar flyby reduce error
  – 12 mrad pointing control error results in \(~1 \text{ m/s flyby } \Delta V\) error
• Cruise flight time 724 days (~ 2.0 years)
• Max Earth distance ~0.7 AU
• Target position ellipse 3400/10/10 km, 1σ
  – Opportunity to recover object in 2017
**NS 1991 VG Detection, Approach & Flyby**

- **50 deg** max constraint on sail angle
- **7000-10000 km** distance @ detection
- Detection velocity ~ **0-15 m/s**

- **Flyby velocity ~ 18 m/s**
- **Flyby altitude: 500 m**
- **TOF ~ 7.5 + 12.5 days**
Trajectory Design – Lunar Flashlight
**Cruise Phase (~190 days)**
- Post-ejection $\Delta V = 9$ m/s
- 3 lunar flybys
- Lunar capture at E-M L2

**Lunar Spiral Phase (~420 days)**
- June 13, 2018 – Aug 7, 2019
- 60,000 km to 9,000 km apolune
Science Phase (~40 days)
- July 29, 2019 – Sep 7, 2019
- Begins 9 days before end of spiral
- 78 passes
- average viewing period < 10° from pole: 136 sec
- average viewing period < 6° from pole: 88 sec
- 9,000 km x 20 km orbit, orbital period 12.3 hr
- Global coverage achieved
- More than 25 passes at less than 20 km altitude

Total Flight Time (Launch to end of science) = ~630 days (1.7 years)
Flight times for other launch dates may require as much as 2.5 years
July 29, 2019

TOTAL PASSES: 1

Lunar South Pole Passes

< 20 km : 0
20-30 km : 0
30-50 km : 0
50-100 km : 0
100-150 km : 0
150-200 km : 1

Shoemaker crater median longitude: 24.6°E

perilune

light side of track

1-minute time ticks

1

< 20 km
20-30 km
30-50 km
50-100 km
100-150 km
150-200 km

LCROSS site
Lunar South Pole Passes

- < 20 km: 1
- 20-30 km: 0
- 30-50 km: 2
- 50-100 km: 3
- 100-150 km: 6
- 150-200 km: 7

TOTAL PASSES: 19

Shoemaker crater

LCROSS site

days: 9.39
Lunar South Pole Passes

- < 20 km: 34
- 20-30 km: 23
- 30-50 km: 5
- 50-100 km: 3
- 100-150 km: 6
- 150-200 km: 7

TOTAL PASSES: 78

Shoemaker crater

LCROSS site

days: 39.62
Navigation Overview

- Radiometric (both missions)
  - Doppler [range-rate]
  - SRA [range]
  - DDOR [range]
    - For critical events (e.g., post-ejection, LF orbit capture)

- Optical (NEA Scout)
  - Science camera
  - On approach to target body
Navigation – NEA Scout
Earth to negative z-axis angle for F2 One Watt
Measurement noise levels: 0.08, 0.06, 0.04 mm/sec

- LGA, 1W
- Gray regions in background indicate the quality of the navigation data
- When the blue line is in lighter shades of gray, the better the data quality
- Includes effect of SC-Earth distance and LGA boresight angle
- Can also estimate slew angle needed to increase the measurement quality
NS 20 day, Detection and Approach

After the first OpNav sets, the original 3400/10/10 km target ephemeris is reduced to ~3/10/3 km.

The mid range OpNavs will reduce the radial component, leaving 2/2/2 km downtrack, radial and out of plane.

Earliest resolution at 50 km / 1.5 hr out. Ephemeris errors have reduced to 50/800/50 m (implies 40 s flyby time uncertainty).
Navigation – Lunar Flashlight
Late Spiral: July 4 – 8, 2019
- ~1 month before start of science
- Approx. orbit period: 14 hours
- Approx. perilune altitude: 732 km
- Tracking: both sides of perilune

Perilune covariance study:
- RWA desaturation burns
- Sail pointing & modeling
- Duration of tracking passes
Nominal Case

Desats:
• 1 / week
• 0.21 m/s

Sail acceleration:
• 2 mrad / 1.1 μm/s²
• Stochastic batches
  4 hrs

Tracking passes:
• 4 hrs
Summary

- Two CubeSat missions under parallel development (currently Phase A)
  - Rideshare opportunity with SLS EM-1
  - Nearly identical hardware, including solar sail
  - Very different science objectives:
    - NEA Scout: flyby and characterization of near-Earth object
    - Lunar Flashlight: search for water ice in craters at lunar south pole
- Trajectory Design & Navigation
  - Similar solar sail models
  - Distinct gravitational regimes (after NEA Scout escape)
  - Two design teams
    - Work closely together
    - One team provides nav. support for both
- Big questions still remain (but initial signs are promising)
  - Cost savings
  - Reduction in risk
  - Constraints on trajectory / navigation
Thank you! Questions?
NEA Scout Backup
System Sensitivity for 1991 VG

**minimum flight time / no escape phase**

![Graph showing flight time vs. characteristic acceleration]

- **Sail model area for 12 kg & 10% MD margin**
  - 70 m²
  - 80 m²
  - 90 m²
  - 100 m²

- **S/C mass for 80 m² sail model & 10% MD margin**
  - 14 kg
  - 13 kg
  - 12 kg
  - 11 kg
  - 10 kg
  - 9 kg

**Baseline design point:**
12 kg and 80 m²
Resilience to Safe Mode

unplanned days pointing at Sun

- Can accommodate up to two weeks of safe mode first 1.5 years of cruise
- Mission recoverable with additional flight time last 6 months of cruise
Solar Angles

HGA, Communication

Sail, Thrusting

Power-positive when solar angle < 50 deg
(downlinks may occur on batteries)
• Delaying the initial maneuver by 1 day almost doubles the ΔV needed
McInnes Flat Plate Model

![Graph showing force magnitude at 1 AU (N) vs. angle between sunline and sail normal (sail angle) (deg), with curves labeled Flat Plate force, Ideal force, and Ideal force 93%. The area on the sail is 80 m².]
Lunar Flashlight Backup
Effect of Launch Date & Acc on Mission Duration

Loiter until phasing is right for spiral

k = 0.0558 mm/s^2
k = 0.0601 mm/s^2 (nominal)
Science Orbit Geodetic Altitude (km)
Angle between Sun-to-Moon Vector and Moon-to-S.P. Vector

- pole lit: $\theta > 90^\circ$
- pole dark: $\theta < 90^\circ$

nominal science phase