Interplanetary CubeSat Architecture and Missions

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Report on Phase 1 of a NASA Innovative Advanced Concepts (NIAC) task.
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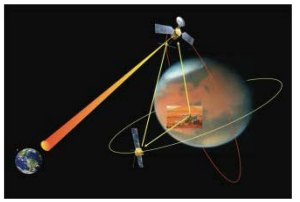
Getting to Interplanetary CubeSats

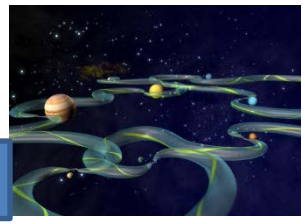
Six Technology Challenges

1. Interplanetary environment



2. Telecommunications

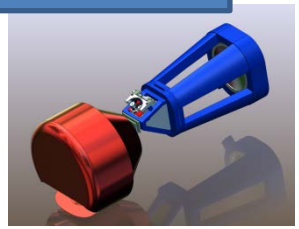
3. Propulsion (where needed)



4. Navigation

6. Maximizing downlink info content

5.Instruments



Taxonomy

- Launch off C_3>0 ~ballistic traj
  - Cruiser
- Depart from "Mothership", 10s to 100s m/sec
  - Companion
  - Orbiter
  - Lander
  - Impactor
- Self-propelled

  1 – 10 km/sec/yr
  - *Electric*
  - *Solar Sail*

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Example Missions

A. Mineral Mapping of Asteroids *[Small Body Science]*

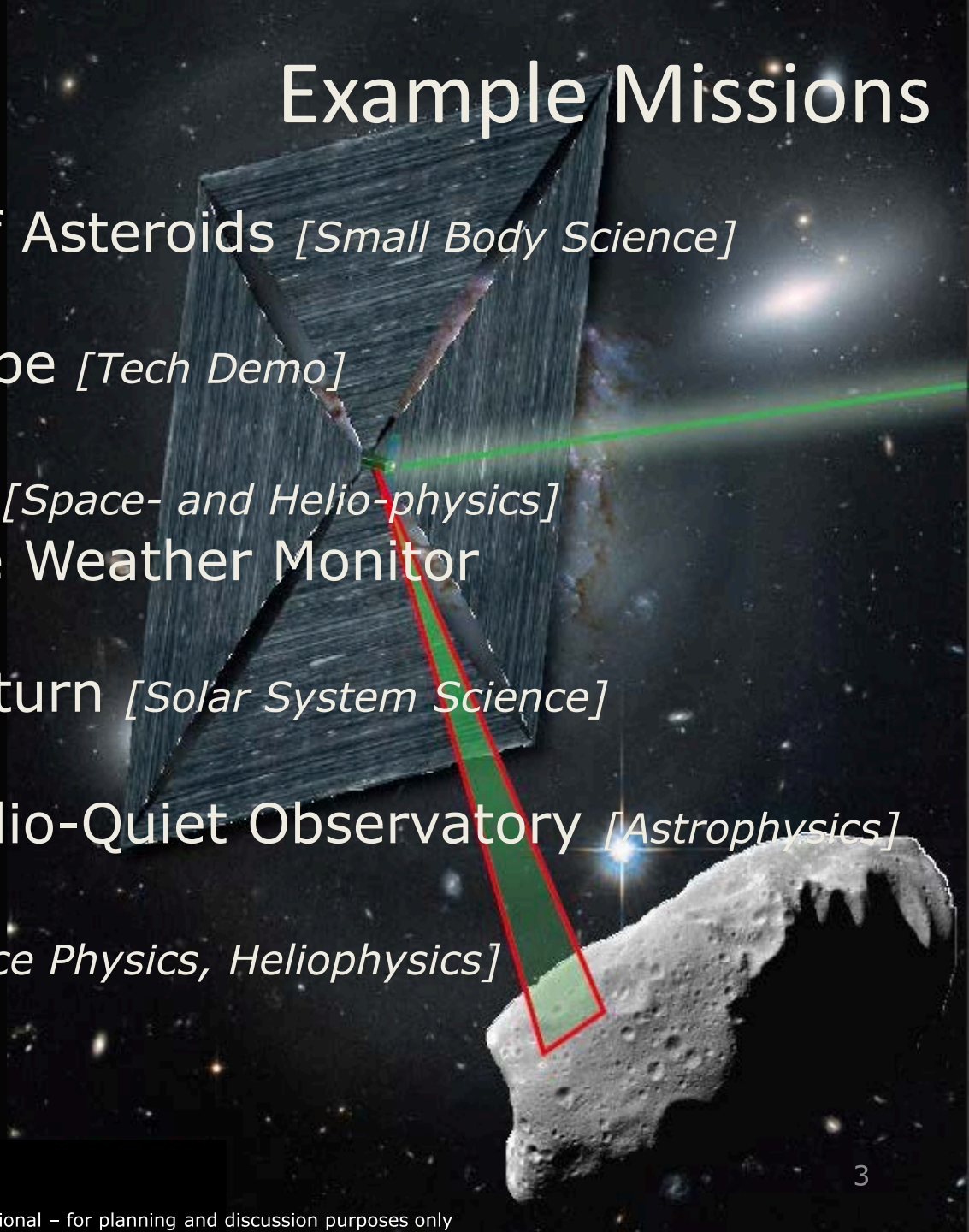
B. Solar System Escape *[Tech Demo]*

C. Earth-Sun System *[Space- and Helio-physics]*
   e.g., Sub-L1 Space Weather Monitor

D. Phobos Sample Return *[Solar System Science]*

E. Earth-Moon L2 Radio-Quiet Observatory *[Astrophysics]*

F. Out-of-Ecliptic *[Space Physics, Heliophysics]*



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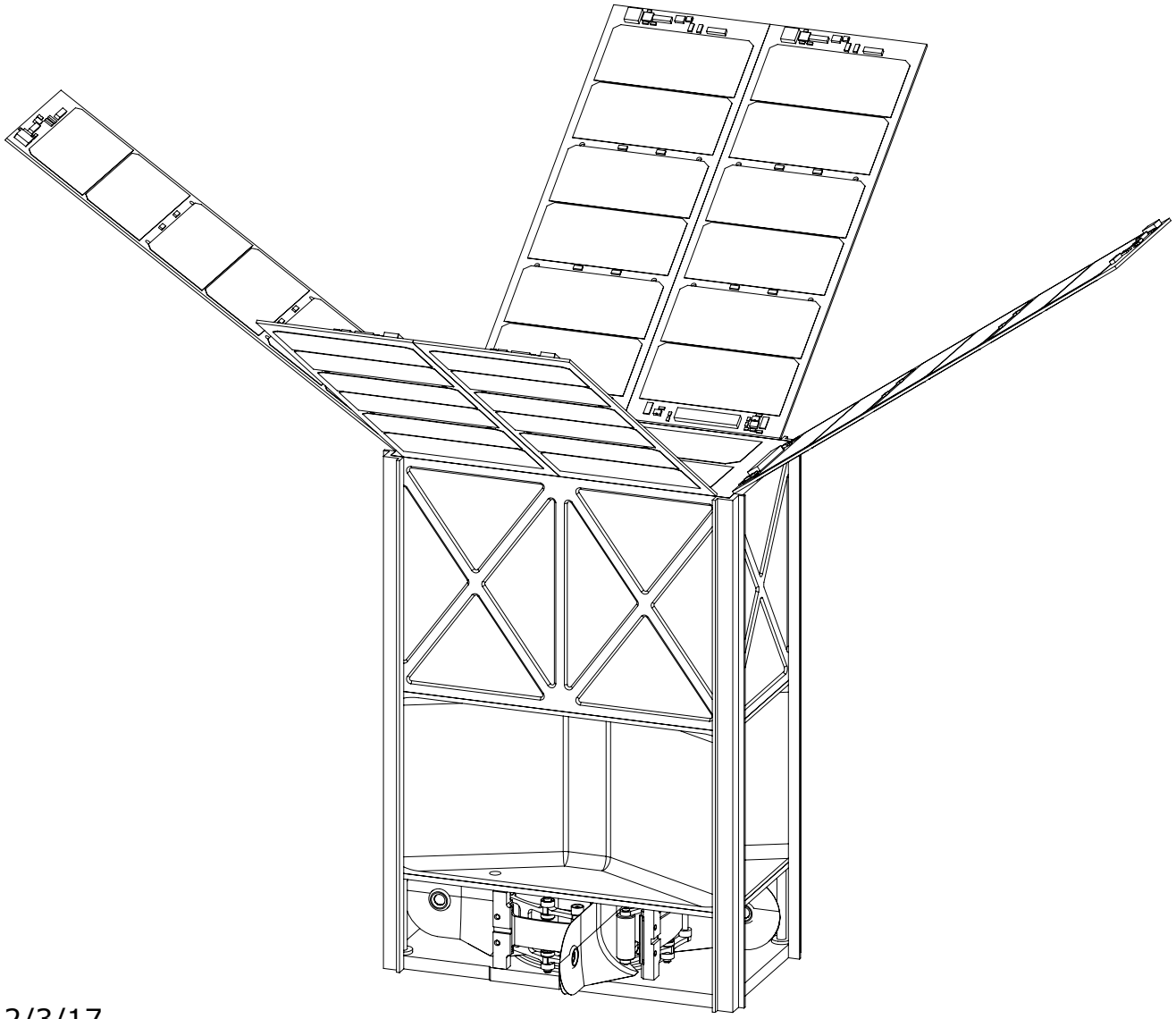
One Preliminary Configuration



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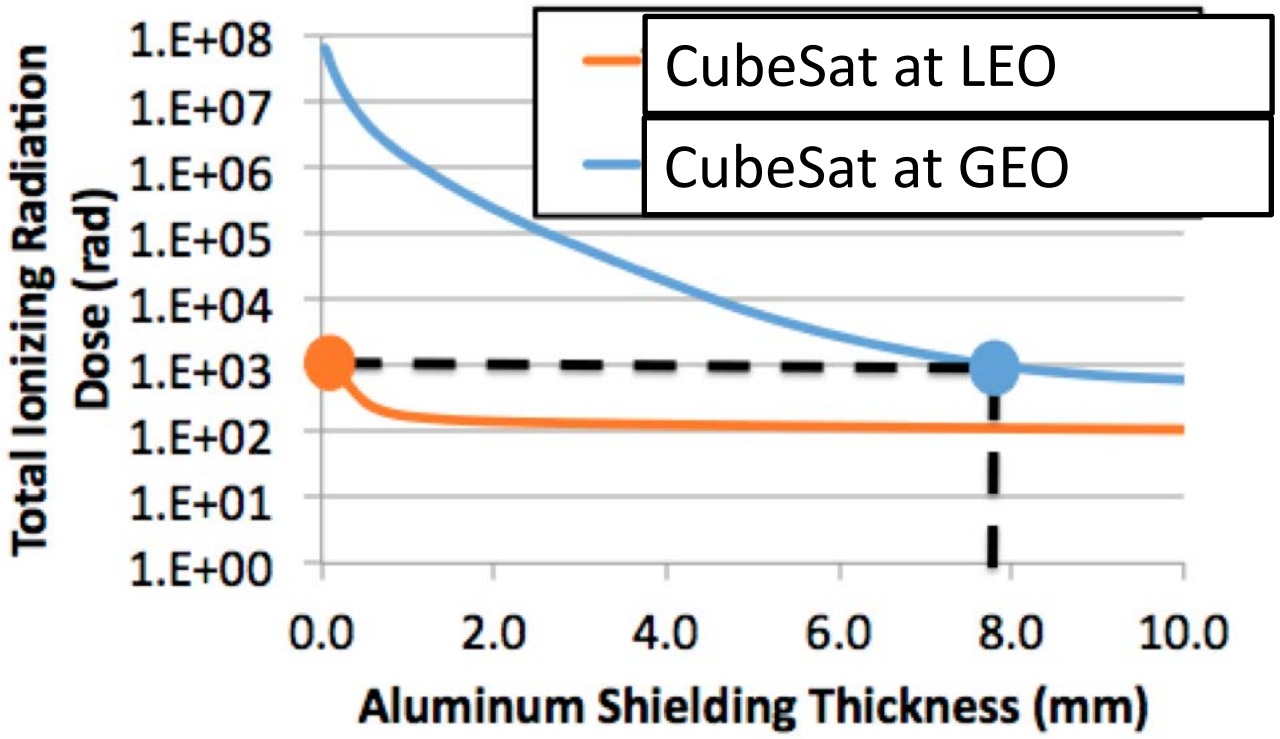
1. Interplanetary environment

- Select based on LEO experience
- Multiple computers
- Asymmetric redundant data paths
- Watchdog timers



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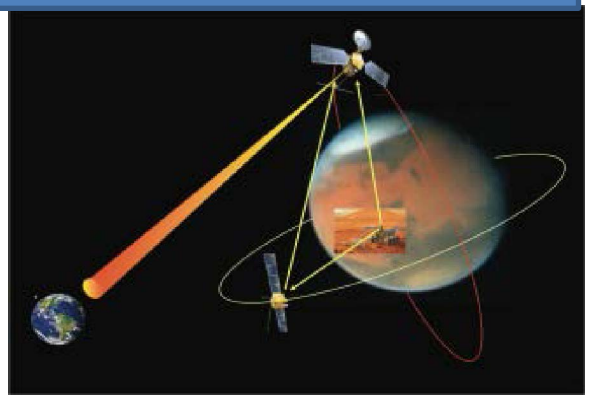
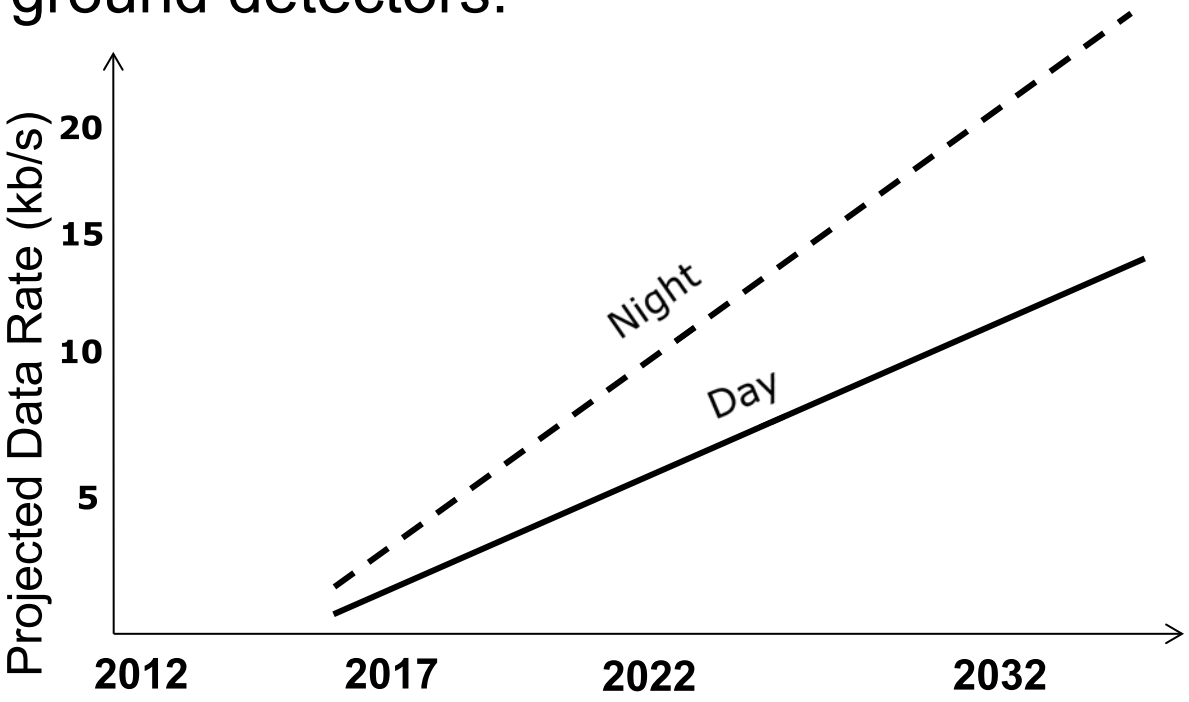
2. Telecommunications



Expected Lasercomm Data Rate Improvements afforded by larger ground telescope diameters, greater laser power on CubeSat, and higher quantum efficiency ground detectors.



But…

RF can deliver 10 b/s out to 0.2 AU with S-band, using Universal Software Radio Peripheral (USRP), and 34 meter dish. Onboard HGA can yield higher rate.

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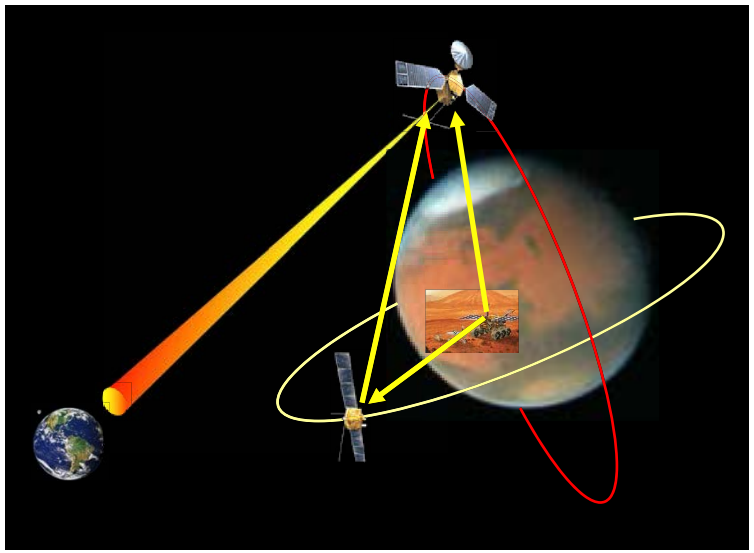
Proposed Lasercom Link Budget

Assumptions:

- Communications range: **2 AU**
- Flight laser average output power: 0.5W
- Flight transmit/receive aperture diameter: 6 cm
- Flight laser pointing loss: 5.6 to 9 dB (as a result of 20-25 urad mis-pointing)
- Modulation: PPM 256 (PPM = Pulse Position Modulation)
- Code & Code-rate: SCPPM, 0.66
- Ground telescope diameter: 5 m (Hale)
- Ground telescope obscuration: 1.8 m
- Ground detector diameter: 4 mm
- Link Margin: 3 dB



Link Budget Summary*

Daytime	**Worst**	**Nominal**	**Best**
Pointing stability (urad)	25	20	10
Detector efficiency (%)	50	60	70
Sky radiance (W/cm2/sr/nm)	9.70E-04	2.60E-04	2.60E-04
Daytime SEP (°)	50	60	60
Zenith angle (°)	75	55	55
r_0 (cm)	3	4	6
Data-rate (kb/s)	**~0.003**	**0.4**	**3.6**
Night-time	**Worst**	**Nominal**	**Best**
Pointing stability (urad)	25	20	10
Detector efficiency (%)	50	60	70
Sky radiance (W/cm2/sr/um)	0	0	0
Zenith angle (°)	75	55	55
r_0 (cm) @ 500 nm @ zenith	4	6	8
Data-rate (kb/s)	**~0.039**	**1.1**	**8.7**

*Substantially higher data-rates may be achieved by using the LBT (11.8 m) telescope in Arizona

Hamid Hemmati, 2012 March

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Laser Telecom
Uplink and Downlink Options

----------Downlink---------- ---Uplink---

A

5 m

Hale

B

11.8 m

Large Binocular Telescope (LBT)

C

1 m

Optical Communications Telescope Laboratory (OCTL)

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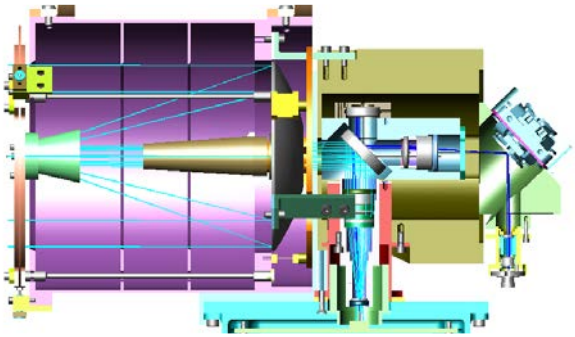
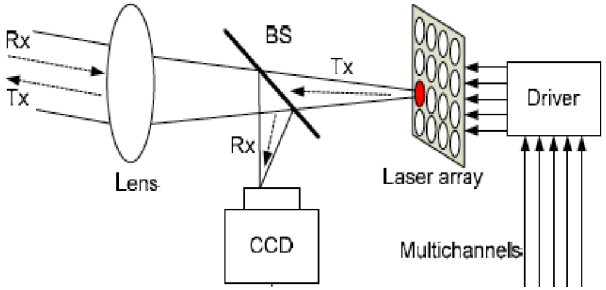
OPTICAL ASSEMBLY CONFIGURATION CONCEPTS

Several options are being traded:

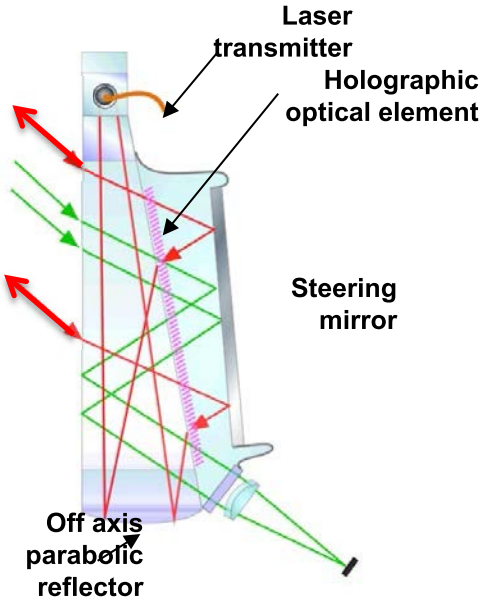
- **Conventional optical design, reduced in dimensions as much as possible**
  - Beam-pointing would be accomplished with the aid of a two-axis fast steering mirror
- **An array of laser transmitters and receivers behind a transmit/receive aperture**
  - Beam pointing would be accomplished by activating a specific laser in the array
- **A near-monolithic optical system using holographic optical elements**
  - Beam pointing would be accomplished via a two-axis fast steering mirror



Conventional optics,
6-cm diameter aperture



Laser array
transmission/reception
6-cm diameter aperture
(Ref.: Toyoshima et al,
www.intechopen.com/download/pdf/9003)



Monolithic (compact) assembly.
6-cm diameter aperture
(Ref. Terabeam, U.S. Patent # 6,724,508)

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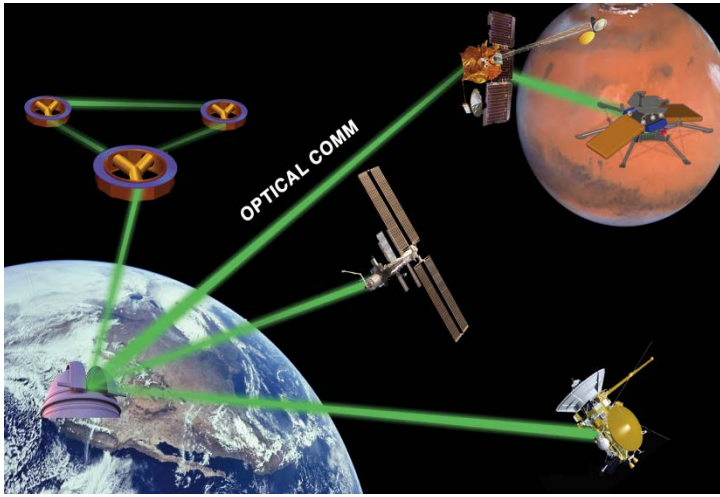
Beam Pointing Assembly Concept For Lasercom

- **Assumed to be body-mounted**
  - No coarse pointing gimbal
  - Spacecraft would coarse point the terminal to about 3 to 9 mrad (for telecom, deep-space spacecraft typically point the RF antenna to <3 mrad) (9 mrad ~0.5˚ **)**
- **Incorporates a 1˚ (17.5 mrad) class field-of-view (FOV) camera** that could acquire an Earth beacon laser signal in the presence of the 3-9 mrad disturbance (peak-to-peak)
  - A 1000 pixel CCD array, for example, would have a FOV of 17 milli-radians
- With adequate beacon signal signal-to-noise ratio, **should be able to centroid to 1/10th pixel accuracy**
- Depending on the disturbance spectrum of the platform, **an FSM** would be incorporate into the flight system **to keep the downlink beam pointed back to Earth with mis-point of 10-20 micro-radian** (i.e. 3-6 micro-rad rms)



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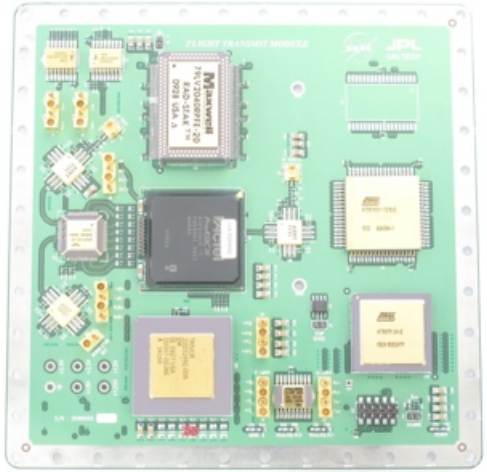
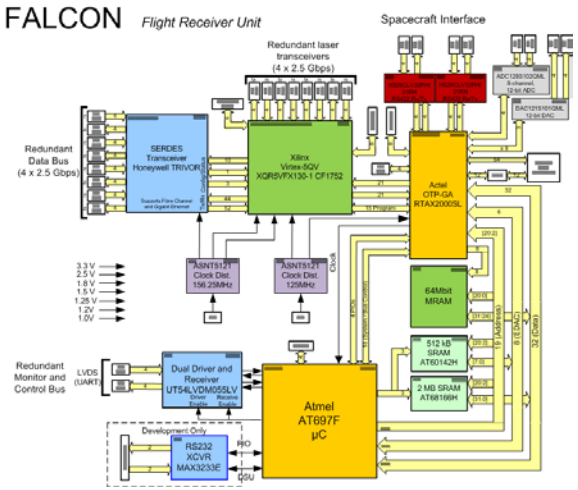
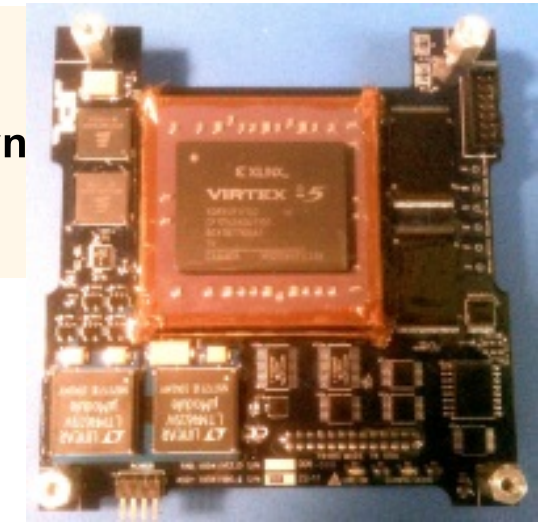
Electronics Concept for Lasercom

JPL-developed small form-factor modem using flight grade parts





JPL-developed processor board developed and flown on CubeSat



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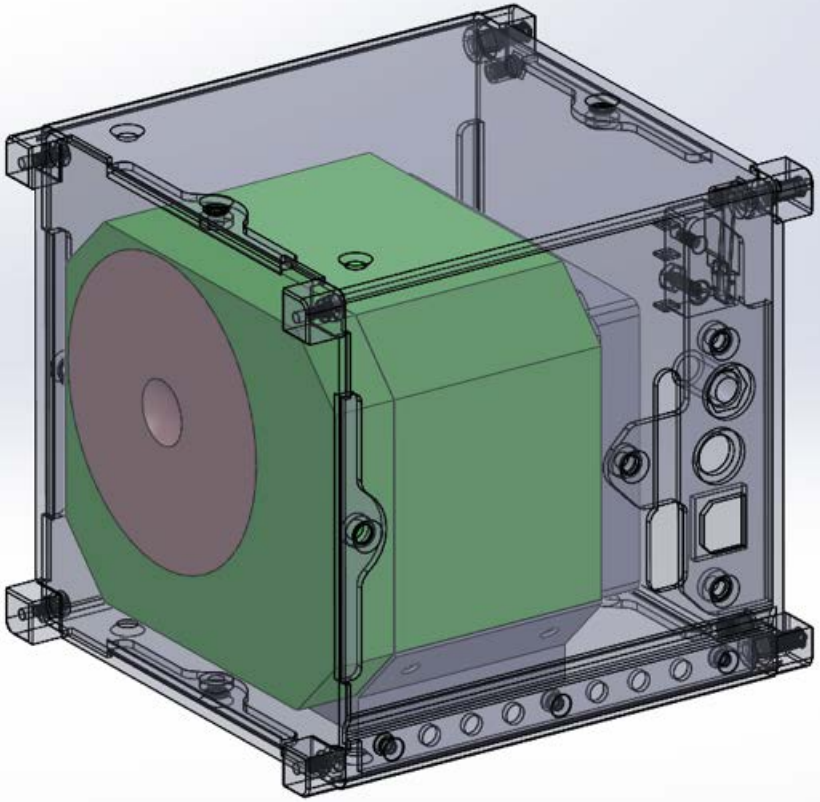
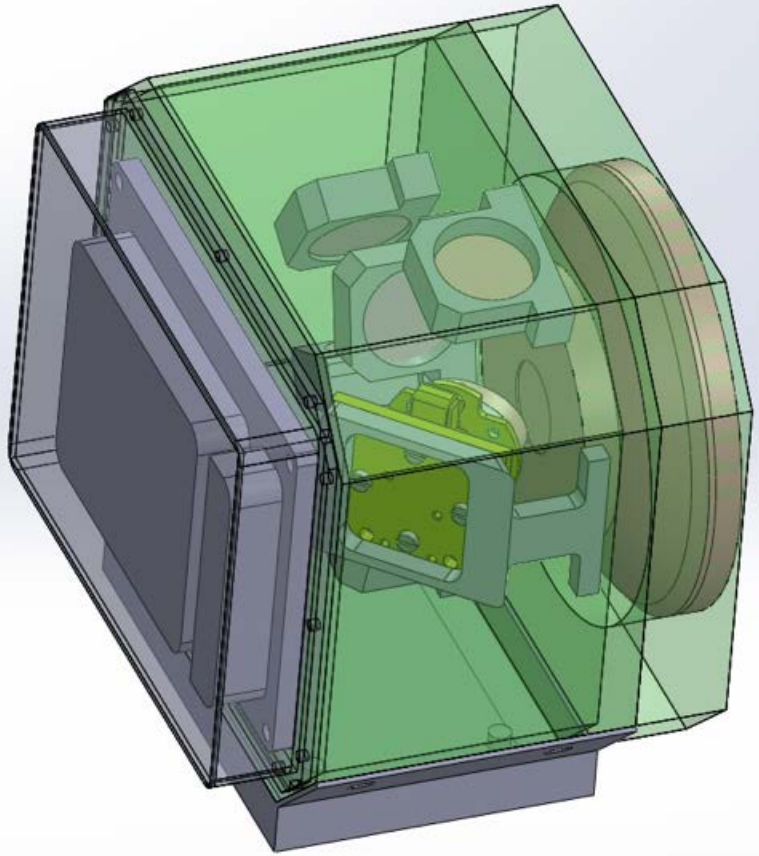
Monolithic optical transceiver for CubeSat 1U form factor





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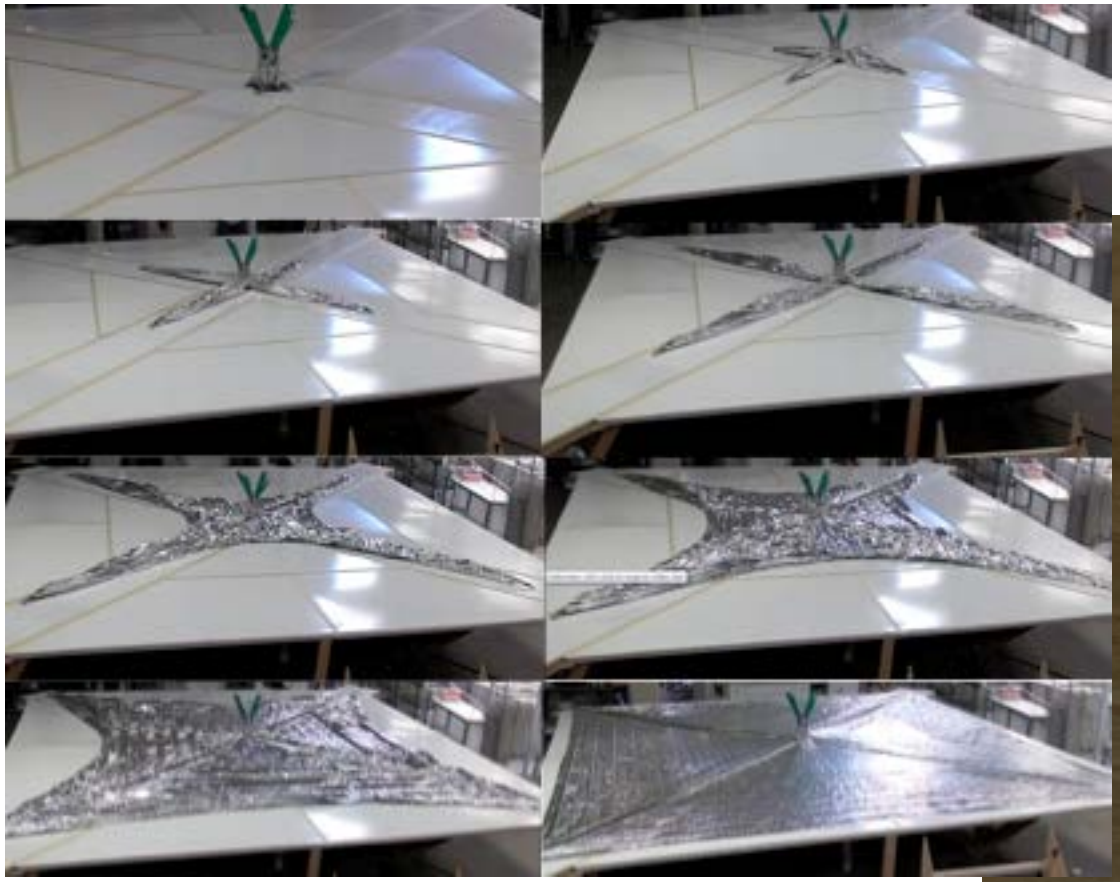

3. Propulsion

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Solar Sail Earth Escape Trajectories from GEO

- Sail at 85% Efficiency
- 5.6m sail at 4.6 kg
- 10m & 20m sail at 10 kg
- Benefits of lunar gravity assist not accounted

…if you can't find a ride to Earth escape or better

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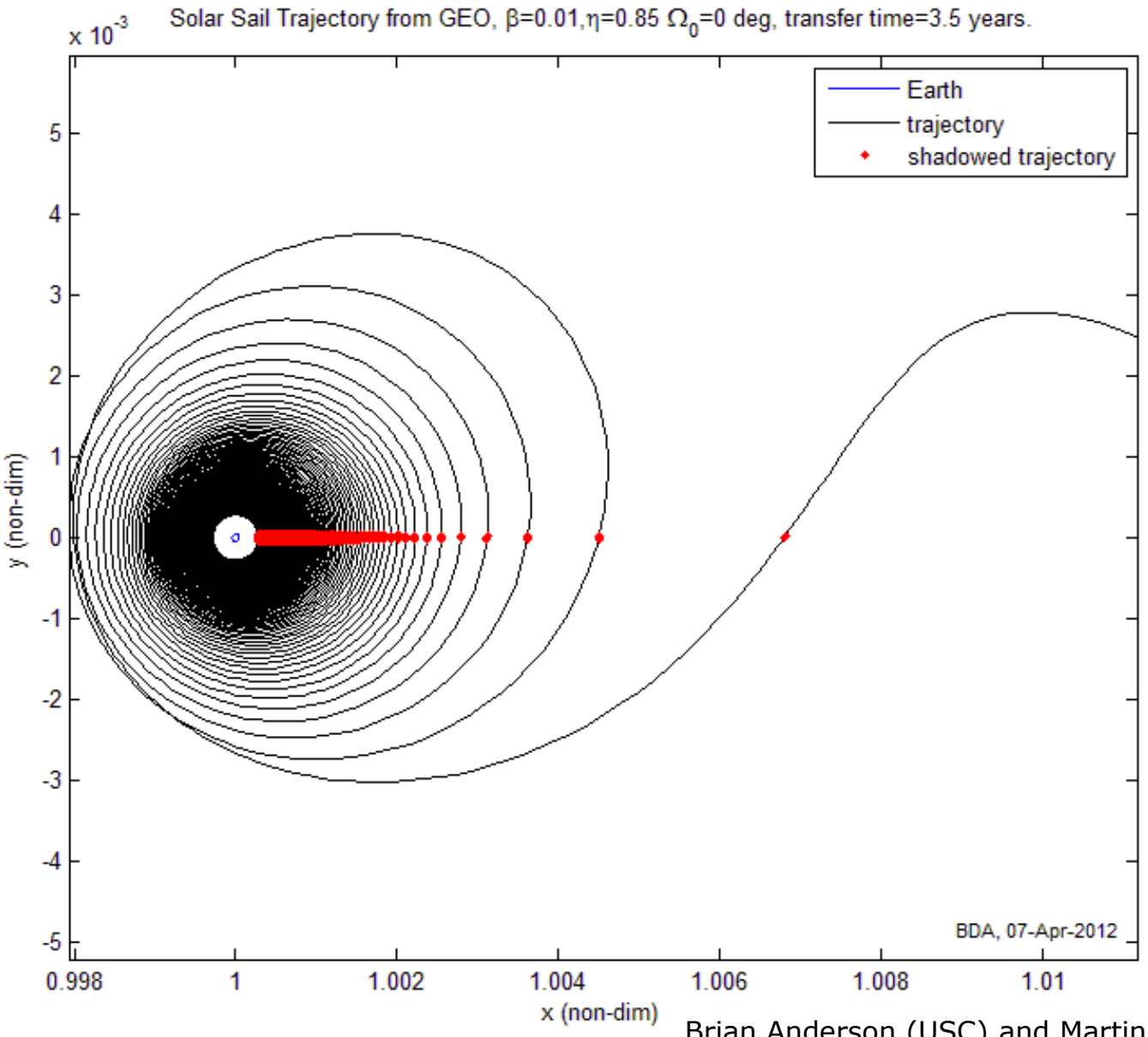
Earth Escape 5.6m Solar Sail, 3.5 Yrs.



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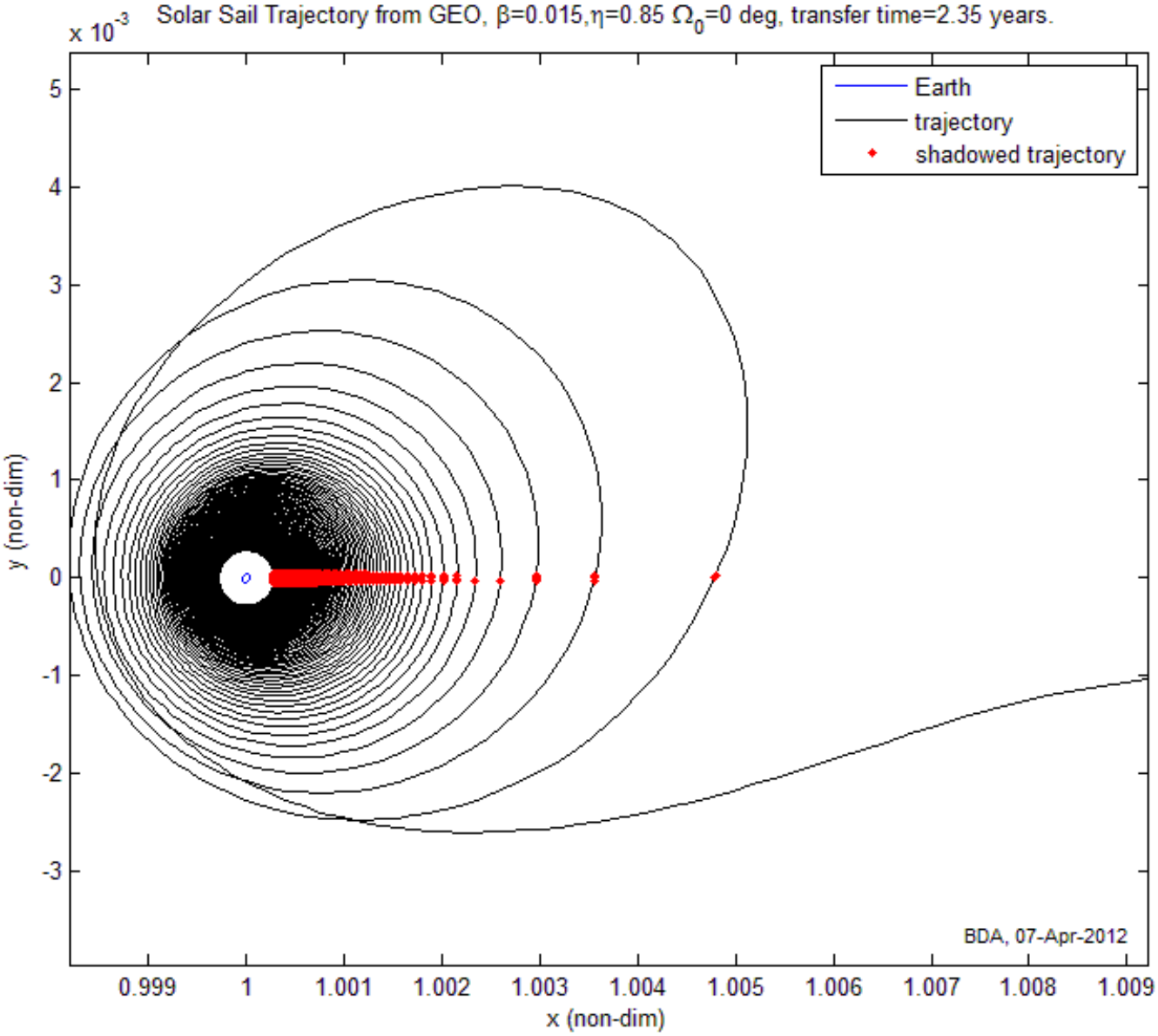
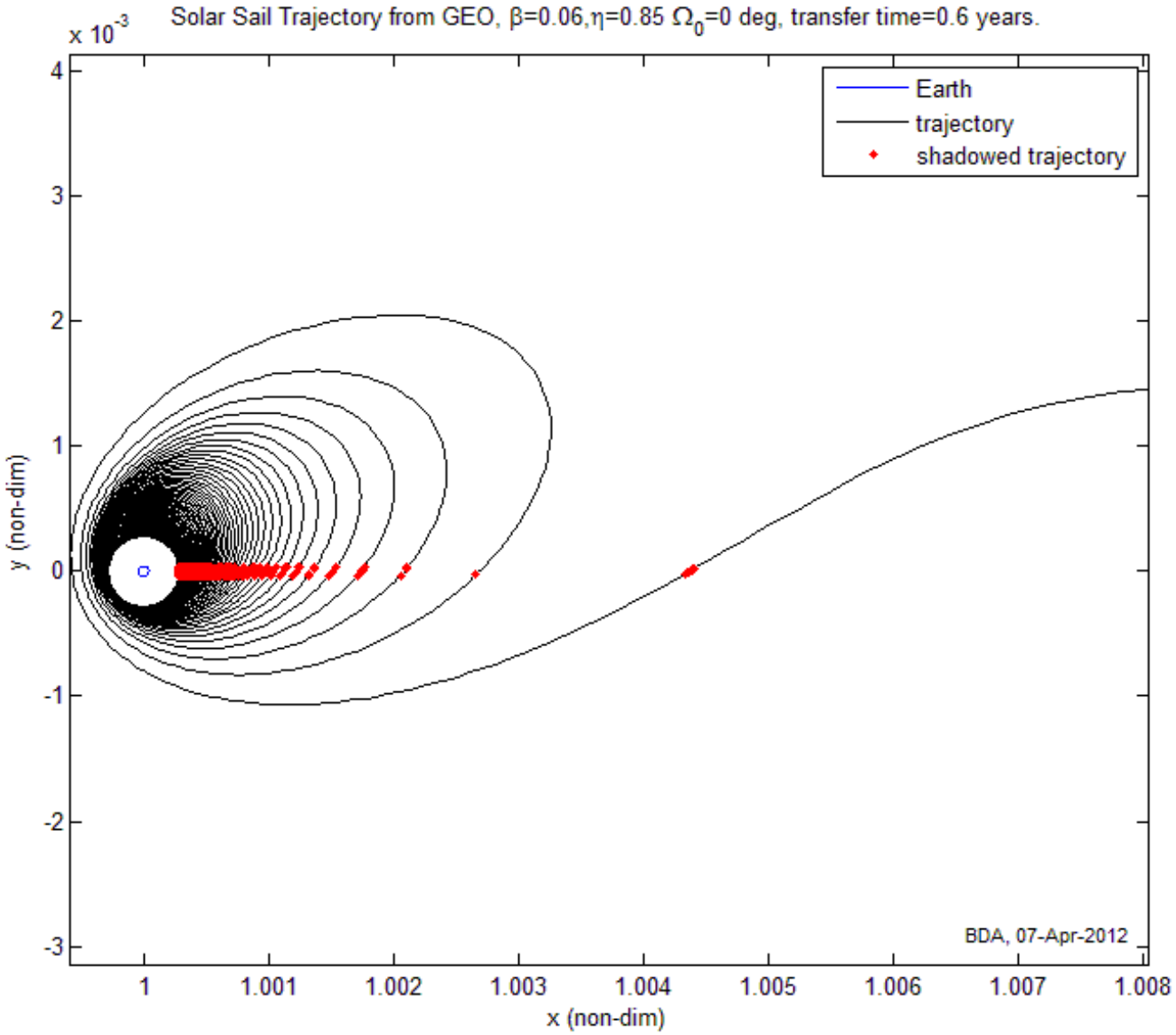
Earth Escape 10m Solar Sail, 2.35 Yrs



Earth Escape 20m Solar Sail, 0.6 Yrs.



Brian Anderson (USC) and Martin Lo

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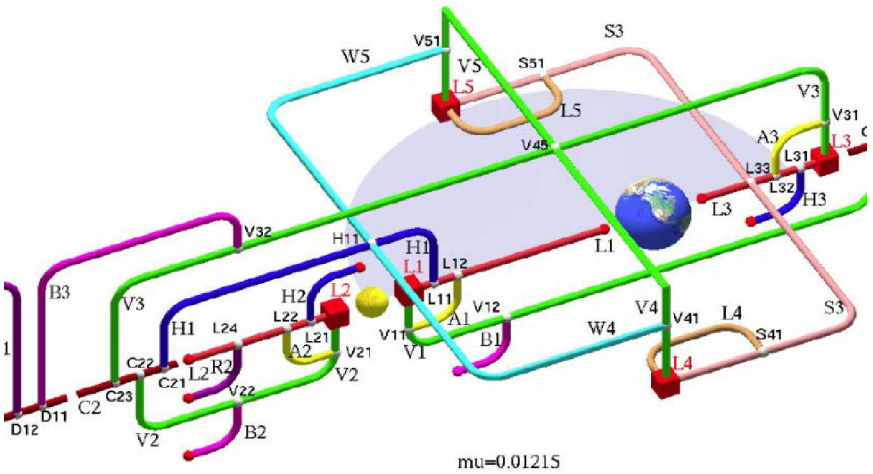
Interplanetary Superhighway Trajectory Technology Roadmap

- Earth-Moon Example (Doedel et al.)
  - Orbit Families Around L1,L2,L3,L4,L5



4. Navigation

- Currently Only Halo Orbit Families Are Used
  - Only around Earth-Moon L1 and L2
- Many Identified Families Yet To Be Used
- Many Other Families Yet To Be Identified & Mapped
- Families for Other Planets and Moons To Be Mapped

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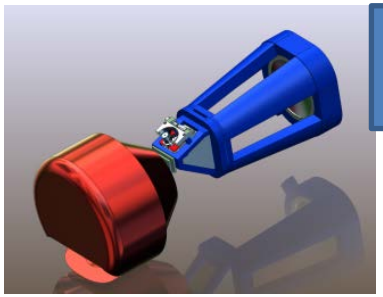
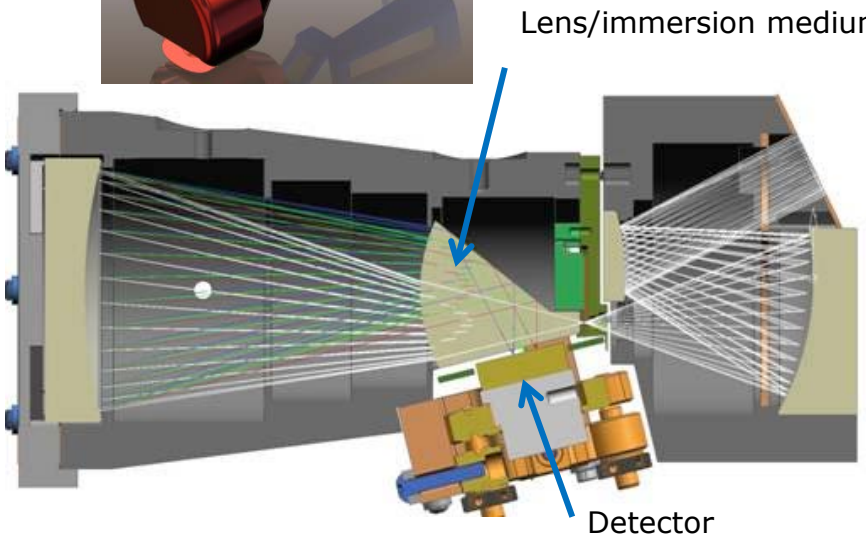
5.Instruments





Overview

The spectrometer is a miniaturized version of the compact Dyson design form that is currently under development at JPL and elsewhere. Our work will extend our concept from the PRISM airborne spectrometer, tested in early 2012, and a fast, wide-field imaging spectrometer demonstrated as a laboratory breadboard through NASA's PIDDP program.

Instrument Electronics

- Detector similar to the one flown on PRISM (Portable Remote Imaging Spectrometer)
- Data processing based on a heritage design
- Consumes ~1W of average power
- Detector interface and data storage would be a new design feature

Parameter	Value
Wavelength Range	450-1650 nm
Wavelength Sampling	10 nm
Detector Type	Thinned InGaAs array
Pixel Pitch	25 µm typ.
Angular Resolution	0.5 mrad
Field of View	14°
Detector Operating Temp	270 K
Response Uniformity	'95%

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6. Maximizing downlink information content

CubeSat Onboard processing Validation Experiment (COVE)*

- Funded by NASA Earth Science Technology Office (ESTO)
- JPL payload aboard University of Michigan's M-Cubed CubeSat
- Launched 2011 Oct 28 with NPP

- Intended to demonstrate Xilinx V5QV FPGA with an algorithm to reduce output data rate from MSPI's 9 multi-angle cameras by more than 200x.
- ?Executed unintentional first autonomous docking with Montana State's E1P CubeSat?
- Funded for re-build/re-flight.

* Dmitriy L. Bekker, Paula J. Pingree, Thomas A. Werne, Thor O. Wilson, Brian R. Franklin, *The COVE Payload – A Reconfigurable FPGA-Based Processor for CubeSats*, USU SmallSat Conf, Logan, UT 2012 August.

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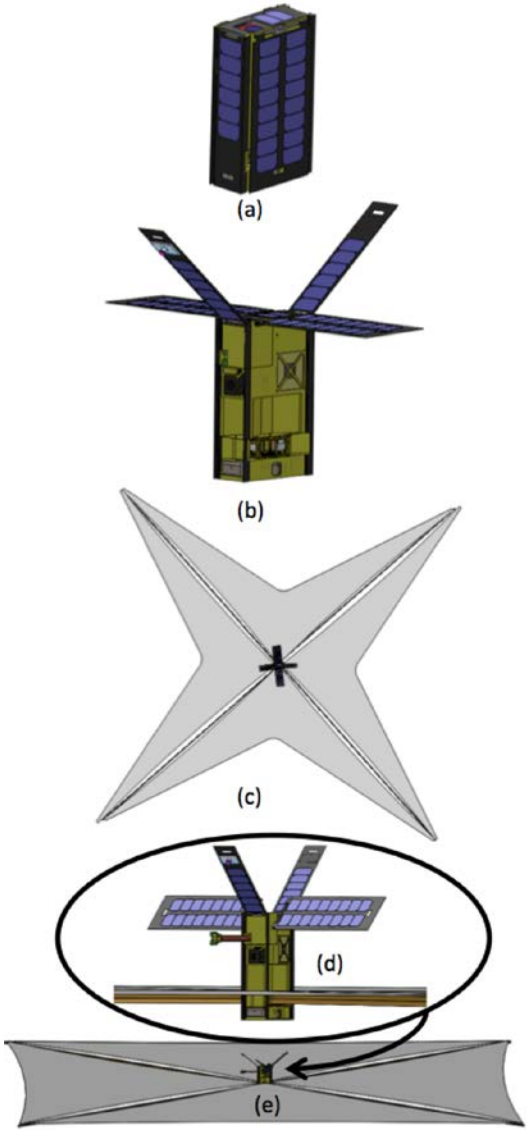
A Workable Interplanetary CubeSat System Architecture emerges from the maturation of six key technologies

LightSail 1[tm]: Planetary Society, Stellar Exploration, CalPoly-SLO

RAX-2: University of Michigan



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Example Missions

A. Mineral Mapping of Asteroids *[Small Body Science]*

B. Solar System Escape *[Tech Demo]*

C. Earth-Sun System *[Space- and Helio-physics]*
   e.g., Sub-L1 Space Weather Monitor

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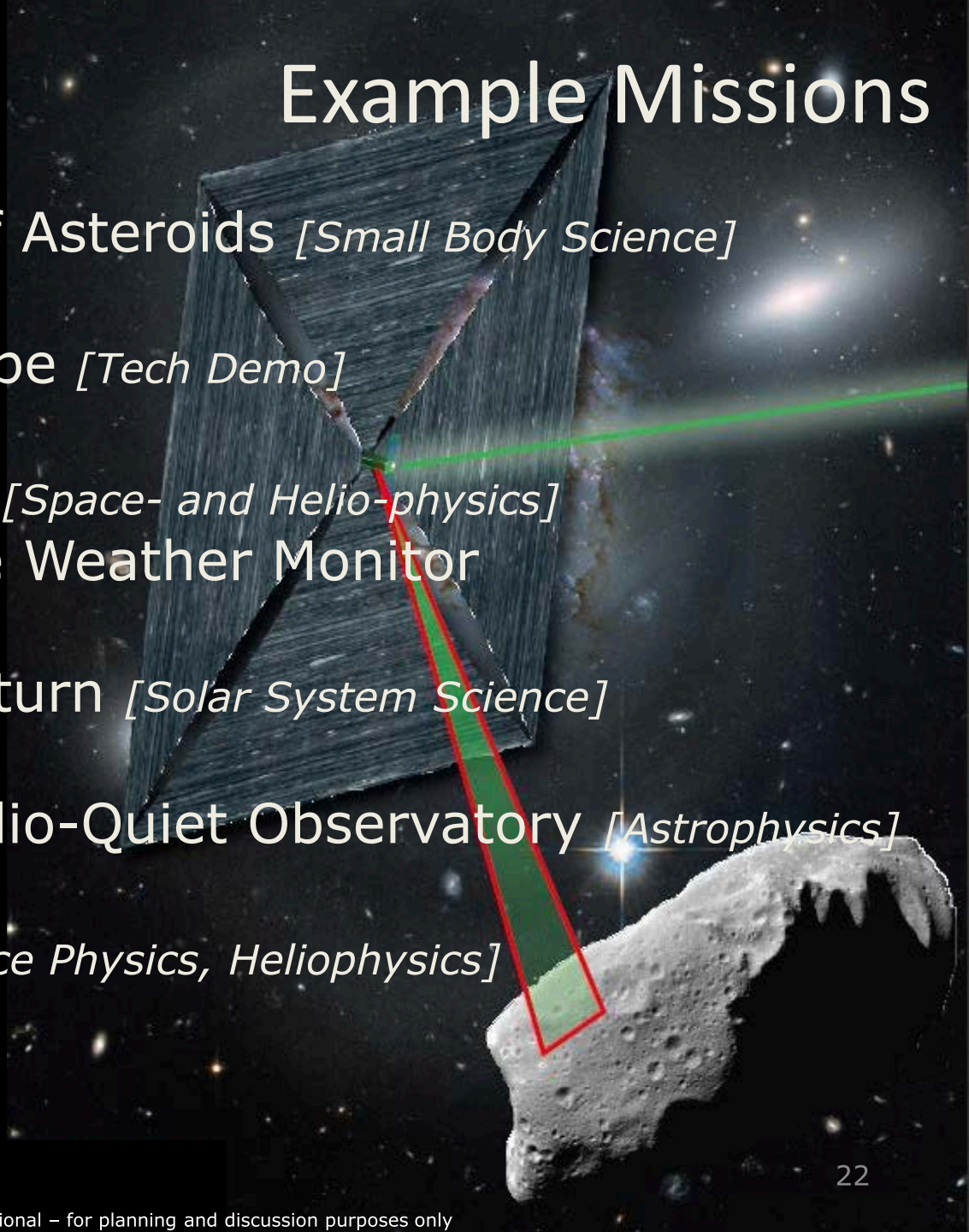
F. Out-of-Ecliptic *[Space Physics, Heliophysics]*



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Mineral Mapping of Asteroids*

Proposed Mission overview

- 6U CubeSat launched on a GEO satellite or Mars-bound mission as a secondary payload.
- solar sail to reach near Earth asteroids.

Proposed Science objectives

Map surface composition of ~3 asteroids at 1-20 m spatial resolution.

Trajectory overview

- Launch to Earth escape (C_3>0), or
- Spiral 2-3 years from GEO to Earth escape.
- Use Moon, Mars & Earth flybys following Earth escape.
- Slow flyby or rendezvous at succession of near-Earth asteroids, ≤1-2 years between asteroids.

Instrument summary

- ~spatial IFOV of 0.5 mrad
- spatial sampling 0.5 m -10 m depending on the encounter range.
- Spectral sampling 10 nm
- Imaging Spectrometer, 0.4 – 1.7 μm. Perhaps extend to 2.5 μm w/ HOT-BIRD or other advanced detector and achievable cooling.

CubeSat bus

6U CubeSat:
2U imaging spectrometer instrument
2U solar sail
1U optical communications
1U satellite bus subsystems

Diana Blaney, Pantazis Mouroulis, Thor Wilson, 2012 March

*Proposed Mission

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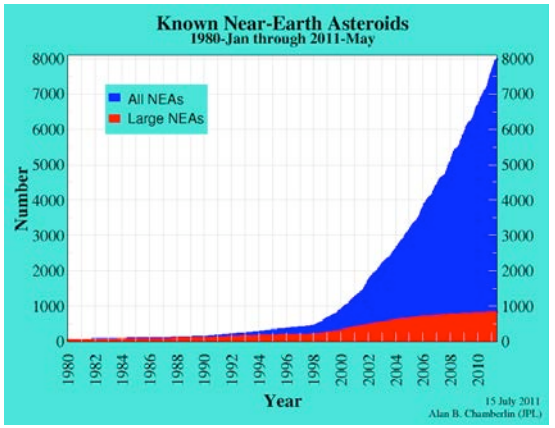
Proposed Mission Overview



Why Asteroids?

Important targets for understanding:

- Presolar processes recorded in the materials of primitive bodies
- Condensation, accretion, and other formative processes in the solar nebula Effects and timing of secondary processes on the evolution of primitive bodies
- Assess the nature and chronology of planetesima differentiation.

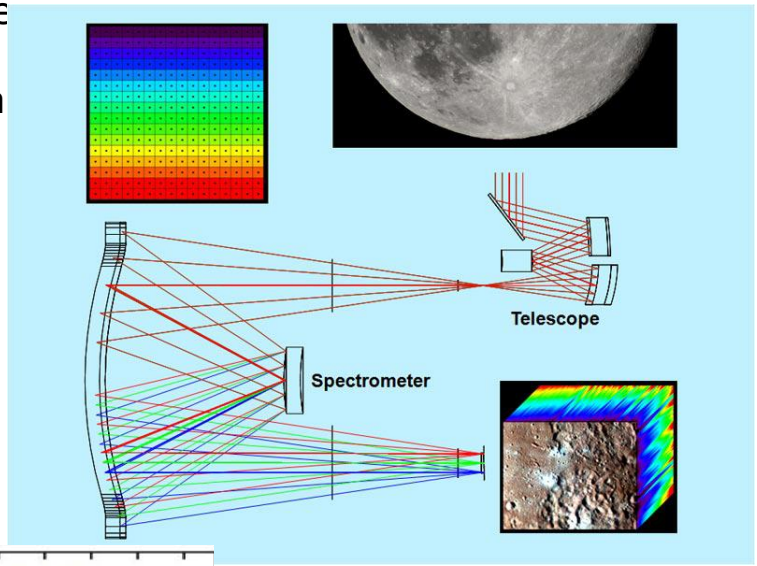
Targets of interest for future human exploration

Large Number of Near Earth Asteroids (NEA)

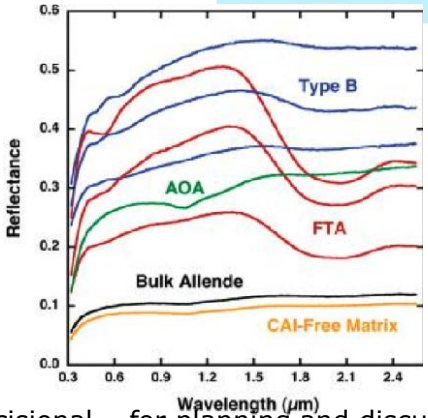
CubeSat approach to NEA exploration could enable a program of inexpensive exploration of a large number of diverse NEA.

Measurement Approach

Close flybys of Near Earth Asteroid (NEA) with spacecraft imaging spectrometer to map surface mineralogy at geologic scales. Data collected then stored on board and returned to Earth post-encounter.



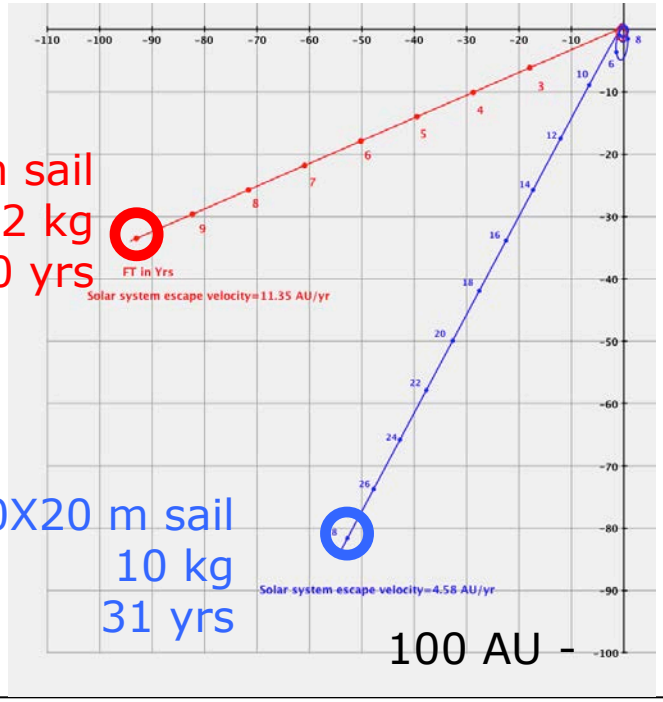
Building an Image Cube: Moon Mineralogy Mapper Example



Example infrared spectra of the materials in the meteorite Allende from Sunshine et al. 2008.

Proposed Solar System Escape Technology Demonstration*

- Would use large area/ low mass spacecraft for high speed trajectory
- Low perihelion
- Explore interplanetary environment, heliosheath and perhaps heliopause
- Test communications, power, pointing and miniaturized instrument technologies



Instrumentation

- Plasma, solar wind
- Energetic particles & cosmic rays
- Magnetometer
- Cameras to observe sail interaction with environment

***per Kendra Short/JPL NIAC "Printable Spacecraft", 2011-12*

Technology Steps

- Larger, lighter sail
- Tolerate high thermal load (0.3 or 0.2 AU)
- (Option) Printed s/c** components on sail surface
  - Solar cells & rf antenna
  - Electrochromic actuators for stabilization
  - Batteries
- Very low duty cycle tracking
- ?Radioisotope power to be evaluated?

Louis Friedman, Paulett Liewer, Chen-Wan Yen, Robert Staehle 2012 April

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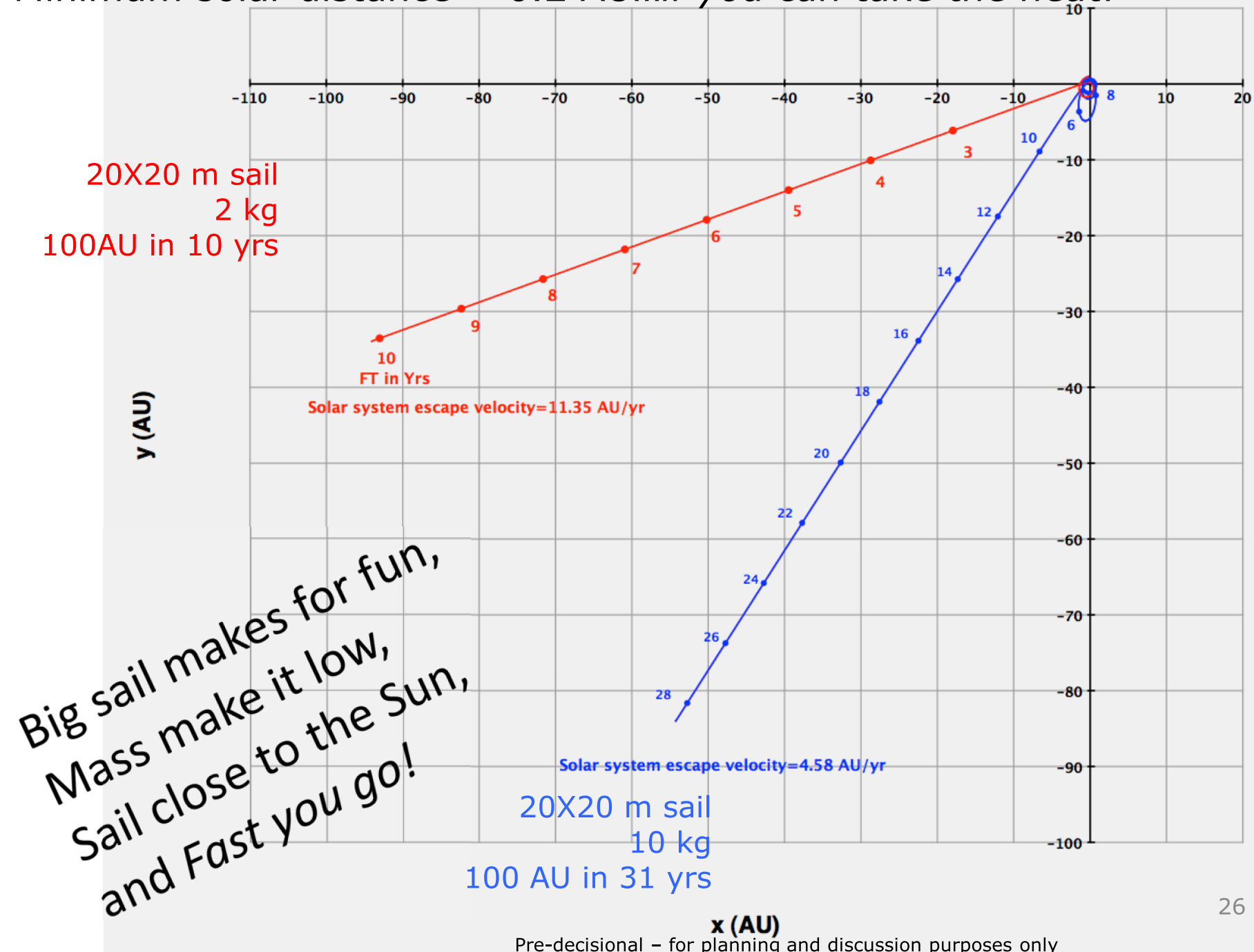
*Proposed Mission

Minimum solar distance = 0.2 AU…*if you can take the heat!*



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Solar Sail Possibilities

1 μg @1 AU ➔ theoretical ~300 m/sec/yr

- Current technology
  - *Ikaros* (2010: 1 μg), *LightSail*[tm] *1* (2013?: 6 μg),
  - Electrochromic surfaces for 2-axis control
  - Switch to Kapton[tm] from Mylar[tm] would yield multi-year life

- Next 5-10 year projection (2021: 20 μg)
  - Tip vanes configured to provide 3-axis electrochromic control without moving parts.
  - Material thickness decrease 2-3X to enable larger sail packed into limited CubeSat volume.
  - Advanced (more expensive) material booms to enable longer boom to handle larger sail for same boom mass & volume.

- Next 10-20 years (2026: <100 μg?)
  - Even thinner materials, sublimating substrate, more advanced booms.
  - High temp materials to allow close solar approach, high ΔV in short time.
    - (a 91 μg (at 1 AU) sail starting from 0.3 AU reaches 100 AU in 17 yrs; 0.2 AU ➔ 13 yrs)
  - Most spacecraft functions printed on inner part of sail.*

* As discussed at Kendra Short/JPL 2012/3/19 NIAC Printable Spacecraft Workshop

Pre-decisional – for planning and discussion purposes only

Earth-Sun Sunward-of-L1 Solar Monitor *

Proposed Mission Overview

Measure strong Coronal Mass Ejections or other space weather from Sunward-of-L1 position to provide additional warning time to Earth.

Science Objectives

Plasma and magnetometer readings of solar wind from sunward-of-L1 position to compare with L1 values from ACE or follow-on.

Trajectory Overview

- GEO Launch.
- Spiral to lunar flyby for Earth escape to Earth-Sun L1 at ~0.01 AU from Earth.
- Solar Sail supplies constant thrust to move and hold s/c 0.02 AU from Earth.

Instrument

1U Deployable magnetometer and plasma instrument (density & velocity)
B-field direction especially important.

Enabling Technology

Solar Sail control and navigation.
Deep space tracking.
Small instrumentation.

CubeSat Bus Concept

6U CubeSat:
1U instrument
2U solar sail
2U avionics, telecom
1U attitude control

rf link closes easily at 0.02 AU to modest high gain antenna on Earth

Bruce Betts, Andy Klesh, 2012 April

*Proposed Mission

Pre-decisional – for planning and discussion purposes only

Solar Polar Imager CubeSat Constellation*

Proposed Mission Overview

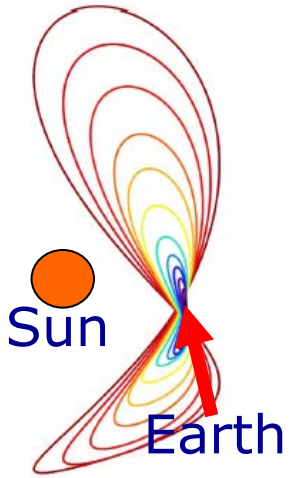
6 S/C in highly inclined constellation.
Out-of-Ecliptic Vertical Orbit, ~0.99 AU, or go close to Sun and crank inclination.
Use solar sail to reach high inclination.

Proposed Science Objectives

Dynamo: Helioseismology & magnetic fields of polar regions.
Polar view of corona, CMEs, solar radiance
Link high latitude solar wind & energetic particles to coronal sources.

Trajectory Overview

- Spiral, Earth & Moon flybys to nearly Earth escape.
- Enter Vertical Family of orbits at Earth-Sun L_1.
- Inclination target ~75°.
- Begin science right after launch.
- Vertical trajectory family remains to be explored.
- Time: tbd



Instrument Details (6 S/C)

S/C1: Plasma + Mag Field
S/C2: Energetic Particles + Mag Field
S/C3: Cosmic Rays,
S/C4: Magnetograph/Doppler Imager
S/C5: EUV Imager
S/C6: Coronagraph/heliospheric imager

Enabling Technology

Solar Sail
Miniaturized Instruments
New Vertical Orbit Trajectory Technology

CubeSat Bus Concept

6 CubeSat Constellation:

6U CubeSat:
1U for bus
2U for instruments
2U for solar sail
1U for optical communications

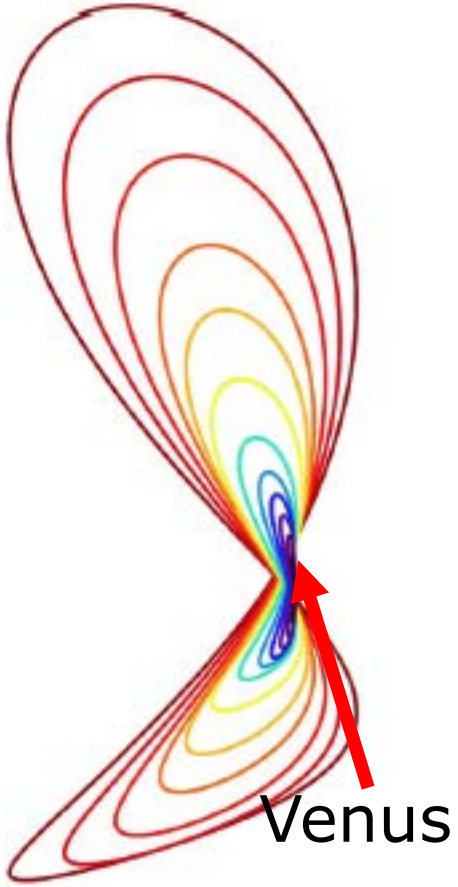
Paulett Llewer, Neil Murphy, Martin Lo, 2012 March

*Proposed Mission

Pre-decisional – for planning and discussion purposes only

Possible Alternative Trajectory: go to Venus first

- Vertical L1/L2 family reaches all inclination
  - Target ~75° inclination
  - Orbital Period: ~ Venus
  - Time to target inclination: tbd
- Launch: Piggyback on
  - GEO: tbd Days Transfer to Escape
  - Venus Mission: tbd Days Transfer
  - Science begins after launch
- tbd Venus flybys raise inclination



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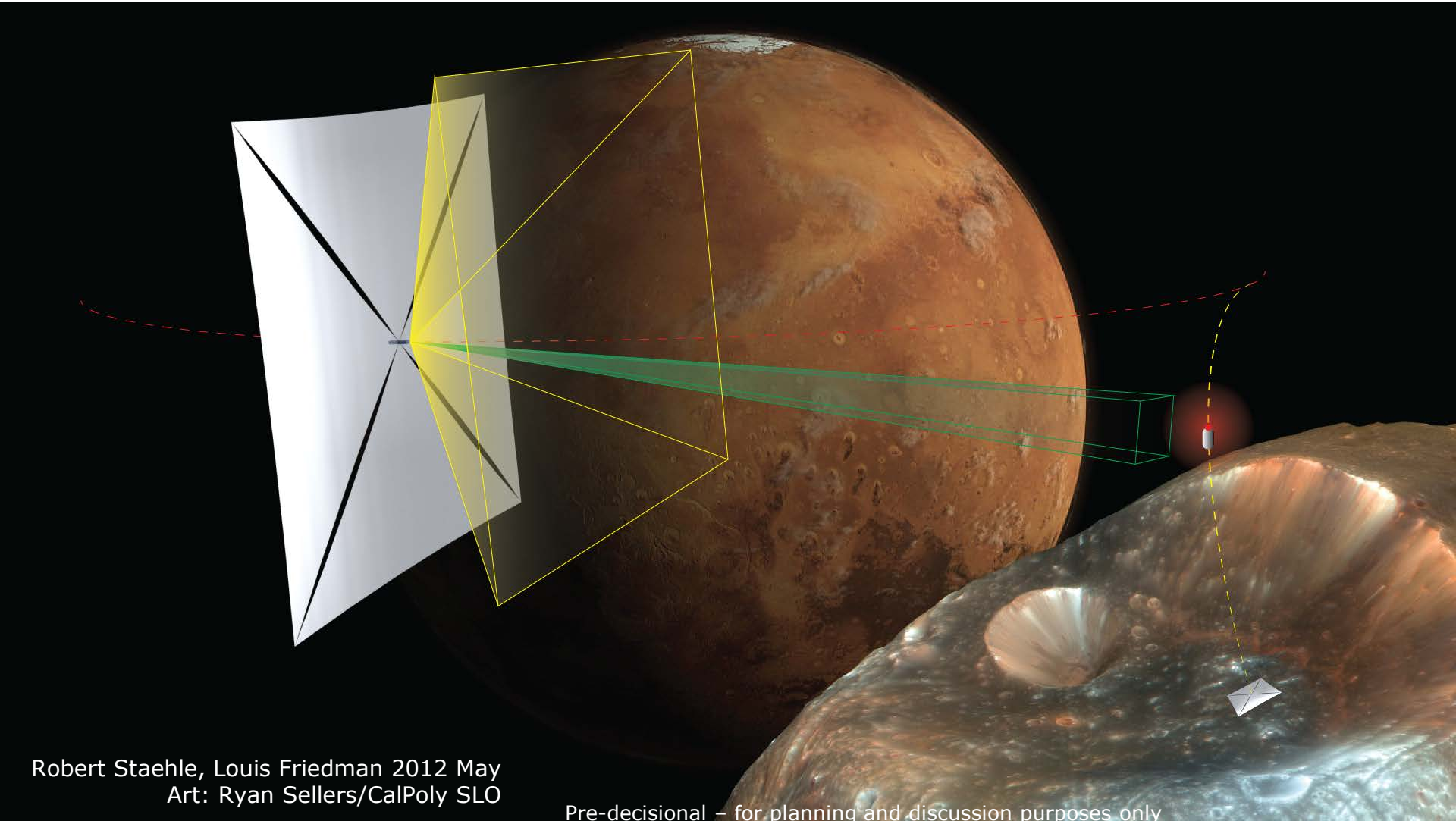
Far-out concept:
Can two Interplanetary CubeSats retrieve a sample from Phobos or Deimos?



Robert Staehle, Louis Friedman 2012 May
Art: Ryan Sellers/CalPoly SLO

Pre-decisional – for planning and discussion purposes only

Conceptual Phobos Sample Return*

Proposed Mission /Science objectives

- Two 6U CubeSats launched to GEO or > C_3.
- Collect Phobos regolith 200 – 500 g sample.
- Based on extant images and spectroscopy, sample assumed to include Martian dust.
- Martian dust represents surface to cratering depth from large impacts.
- Phobos dust/grains record evolution of asteroid into Mars satellite.
- Return sample to Earth for detailed analysis.

Trajectory phases (all low thrust)

1) Launch as secondary payload.
2) Earth escape through lunar flyby.
3) Capture to Mars orbit rendezvous w/ Phobos.
4) "Collector" CubeSat "settles" to surface, impact at 10-20 cm/sec would collect sample.
5) Spring or small thruster would eject sample can upward > Phobos V_{escape} into Mars orbit.
6) "Return" CubeSat pursues sample can, rendezvous, capture, spiral out of Mars orbit, to Earth.
7) Capture, retrieval near Earth-Moon L2 or tbd.

Instrumentation

- Target the landing from existing imagery.
- Simple Visible Camera to ID descent location, provide high res (~1 mm) at "settling site."
- Sample collection mechanism -- for dust "excitation" (impact, gas pressurization) and "collection" (sticky surface, trap) -- details TBD

CubeSat bus & architecture

6U CubeSats configured with approx

- 2U solar sail
- 1U optical telecomm
- 1U for satellite bus + Vis camera.
- Collector: 2U sample collection, can + spring or thruster to boost <~ 12 m/sec
- Return: 2U rendezvous sensor, precision thrusters, capture mechanism

Tomas Svitek, Robert Staehle, 2012 April

*Proposed Mission

Pre-decisional – for planning and discussion purposes only

Radio Quiet Lunar CubeSat: RAQL*

Proposed Mission Overview

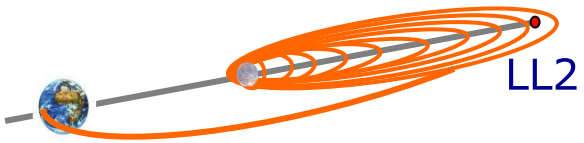
Assess radio quiet volume in shielded zone behind the Moon for future redshifted 21 cm cosmology missions.

Proposed Mission Objectives

- Usable volume behind the Moon for high sensitivity 21 cm cosmology observations determines utility of lunar surface vs. orbiting missions

Trajectory Overview

- GEO Launch
- Spiral to Earth Escape to Moon
- Flyby Loose Capture into HEO (Highly Elliptical Orbit) at Moon
- Spiral Mapping Orbit Behind Moon
- Solar Sail Navigation & Control



Instrument Details

- Radio antenna and receiving system
  - Would operate in HF/VHF band
  - Antenna implemented on solar sail (TBD)

Enabling Technology

Small, low-mass receiver
Solar Sail as radio antenna
Trajectory

CubeSat Bus Summary

6U CubeSat configured with:
2U for antenna electronics,
2U for solar sail,
1U for communications?, and
1U for satellite bus.

Other Features

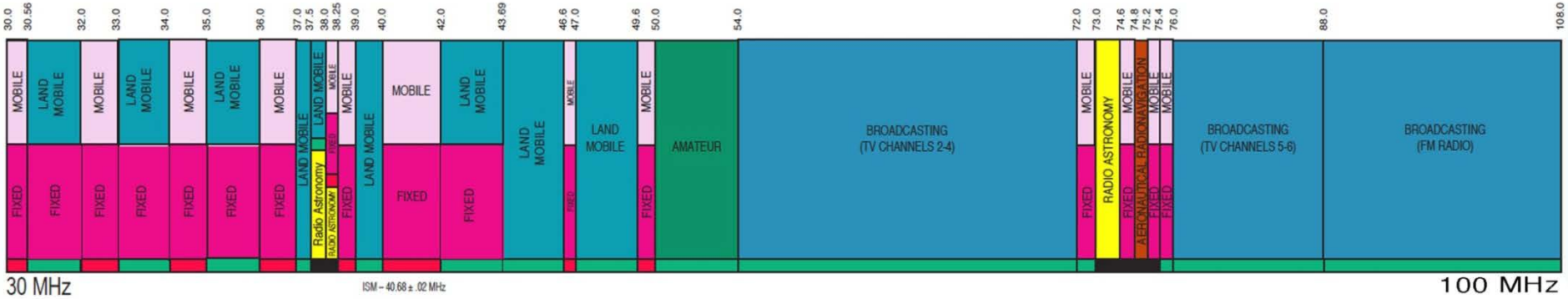
- Data Rate < 10 Mbps
- Onboard processing?

Joseph Lazio, Dayton Jones, Martin Lo, 2012 March

*Proposed Mission

Pre-decisional – for planning and discussion purposes only

Mission Rationale



50 Myr since Big Bang

Portion of radio spectrum relevant for 21 cm observations of Cosmic Dawn and Dark Ages

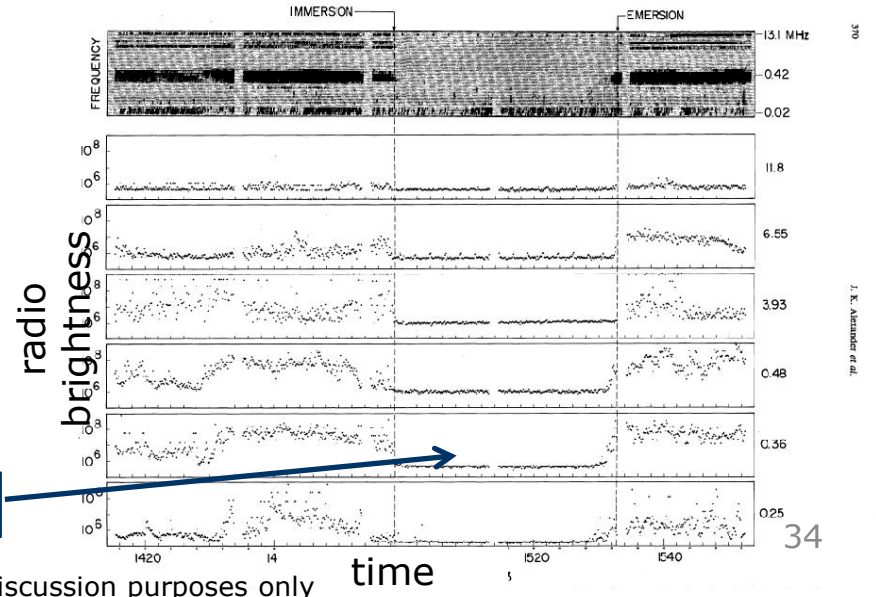
- Yellow = reserved for radio astronomy

330 Myr since Big Bang

Data from Radio Astronomy Explorer-2, when it passed behind the Moon, illustrating cessation of terrestrial emissions

- *Apollo* command modules lost communications when behind the Moon.

➢ **Measurements not at frequencies relevant for 21 cm observations**



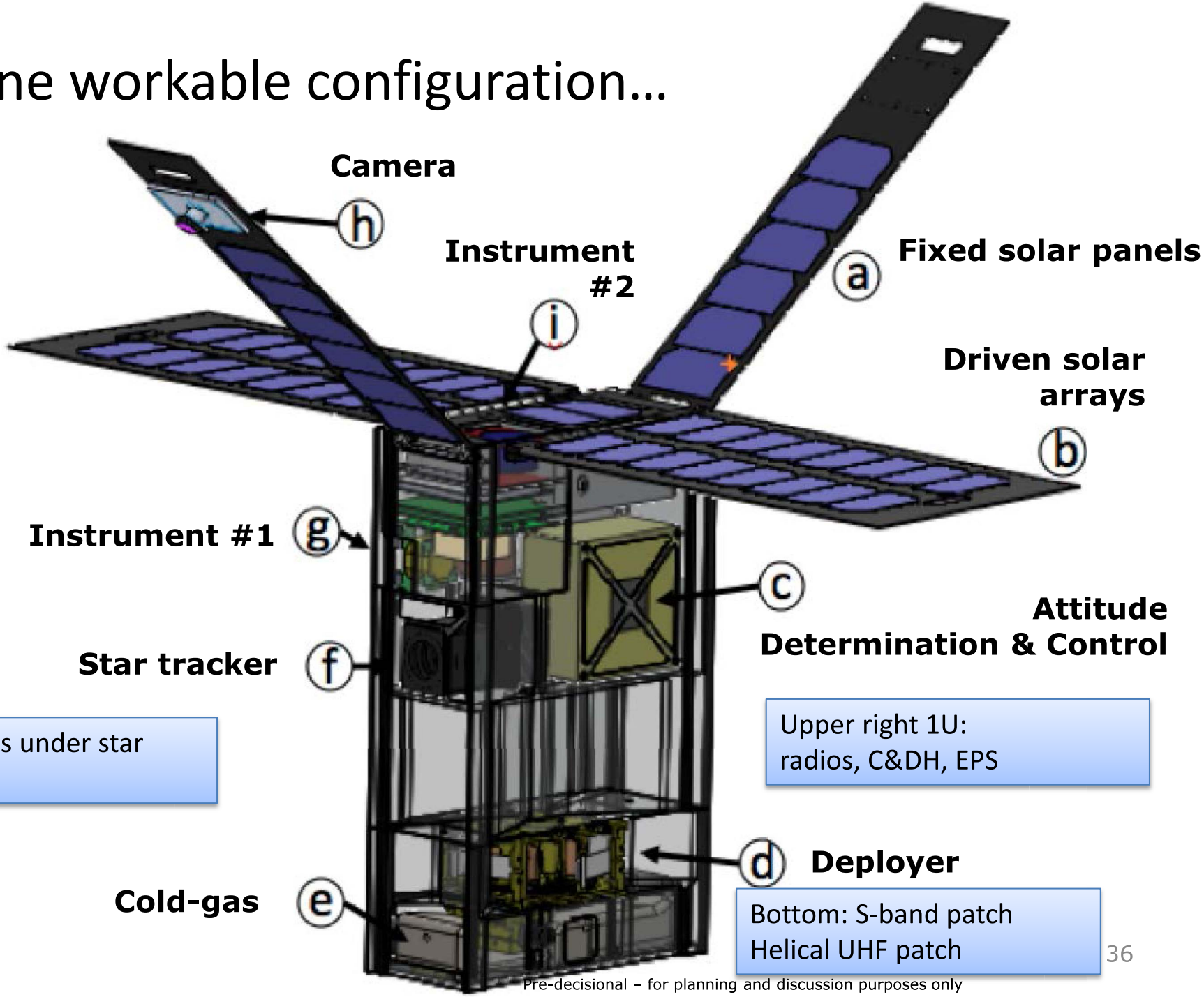
RAE-2 behind Moon

Some Plausible Interplanetary CubeSat Mission Concepts to Support Human Exploration

- Solar Storm Advance Warning
- Radio-quiet Zone Mapper for Earth-Moon L2 Region
- Lunar Surface Water Ice Mapper
- Lunar Subsurface Ice Prospectors
- Near-Earth Asteroid Composition Mapper
- Near-Earth Asteroid NanoSat Lander
- Phobos Sample Return

Pre-decisional – for planning and discussion purposes only

One workable configuration…



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The world is ready for Interplanetary CubeSats.

- Interplanetary CubeSats could perform a wide variety of exciting missions at much lower cost than today's Solar System exploration missions, but with much narrower scope per mission.
- Interplanetary CubeSats are much more challenging than "typical" LEO CubeSats, but the required technologies and skill sets are developing for the first steps beyond Earth.
- Scientists who would like to use the new capability are excited.
- Institutions that can provide the new capability are excited.
- Continuing technology investments could yield a broad and rapid increase in the community of institutions having the capability to perform affordable, independent science investigations in interplanetary space.
- NASA could enable dramatic new capability by making launch slots and funding available to support CubeSats on all launches to $C_3 > \sim 0$, and as hosted riders aboard some fraction of geostationary satellites.

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Interplanetary CubeSat Architecture and Missions

?Questions?

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