Update for Low-frequency Astronomy: Missions Enabled by an Interplanetary CubeSat Architecture

Keck Institute for Space Studies (KISS) Workshop
2012 July 11
California Institute of Technology

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The Planetary Society

Tomas Svitek
Stellar Exploration

Brian Anderson, Channing Chow
University of Southern California

Preliminary progress report:
The NASA Innovative Advanced Concepts (NIAC) task on which this reports is still in progress. No mission described herein has been approved or funded.

Getting to Interplanetary CubeSats

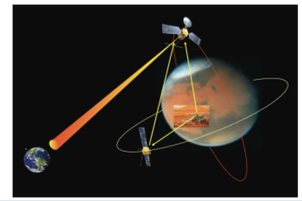
Taxonomy

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

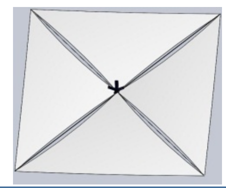
  1 – 10 km/sec/yr
  - *Electric*
  - *Solar Sail*

Six Technology Challenges

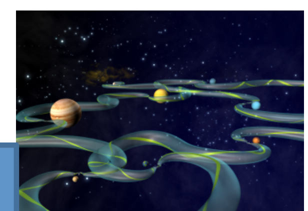
1. Interplanetary environment



2. Telecommunications

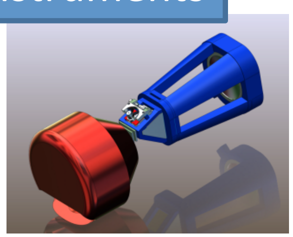


3. Propulsion (where needed)



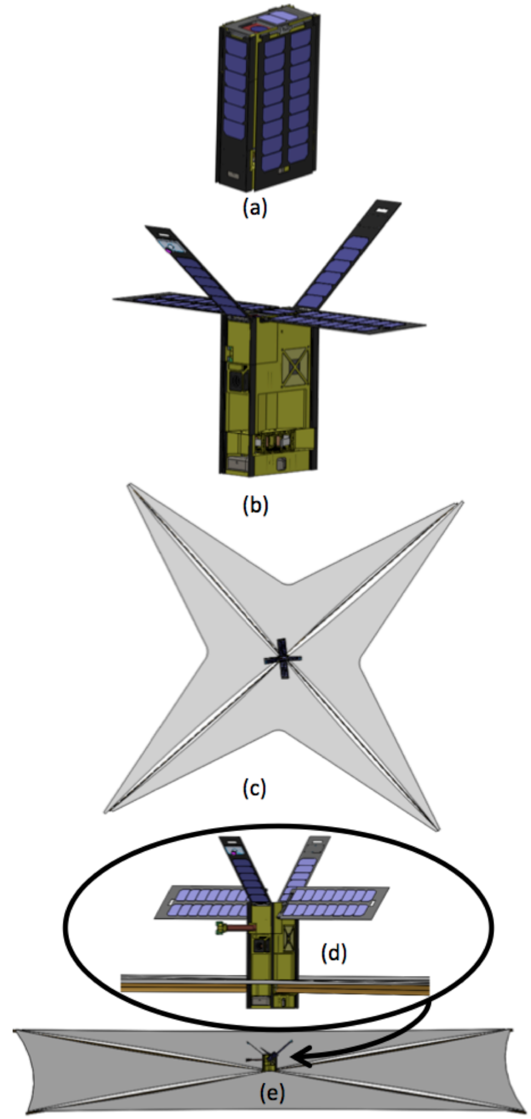
4. Navigation

5. Instruments



6. Maximizing downlink info content

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



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

RAX-2: University of Michigan

Example Missions

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

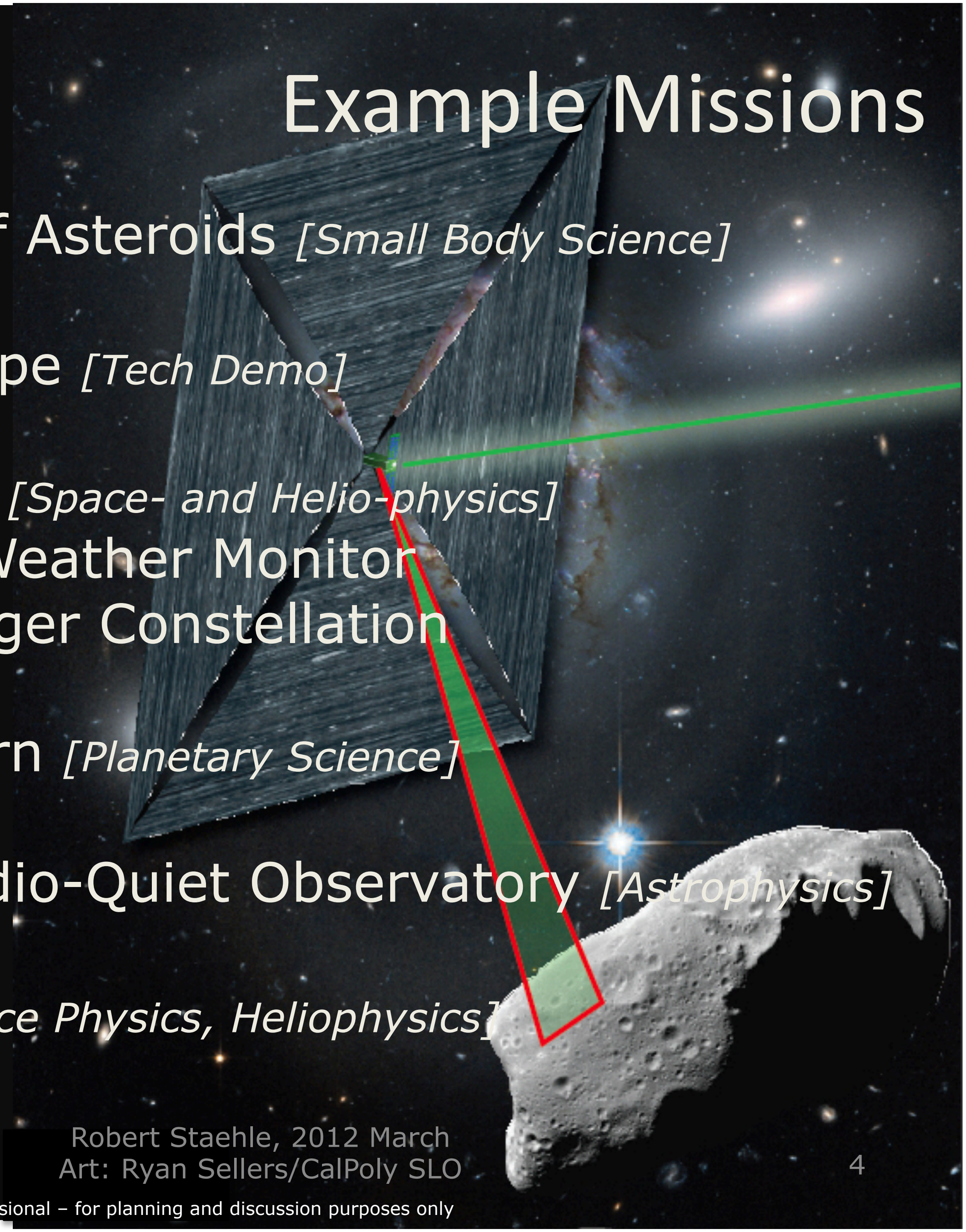
B. Solar System Escape *[Tech Demo]*

C. Earth-Sun System *[Space- and Helio-physics]*
   1) Sub-L1 Space Weather Monitor
   2) Solar Polar Imager Constellation

D. Mars Sample Return *[Planetary Science]*

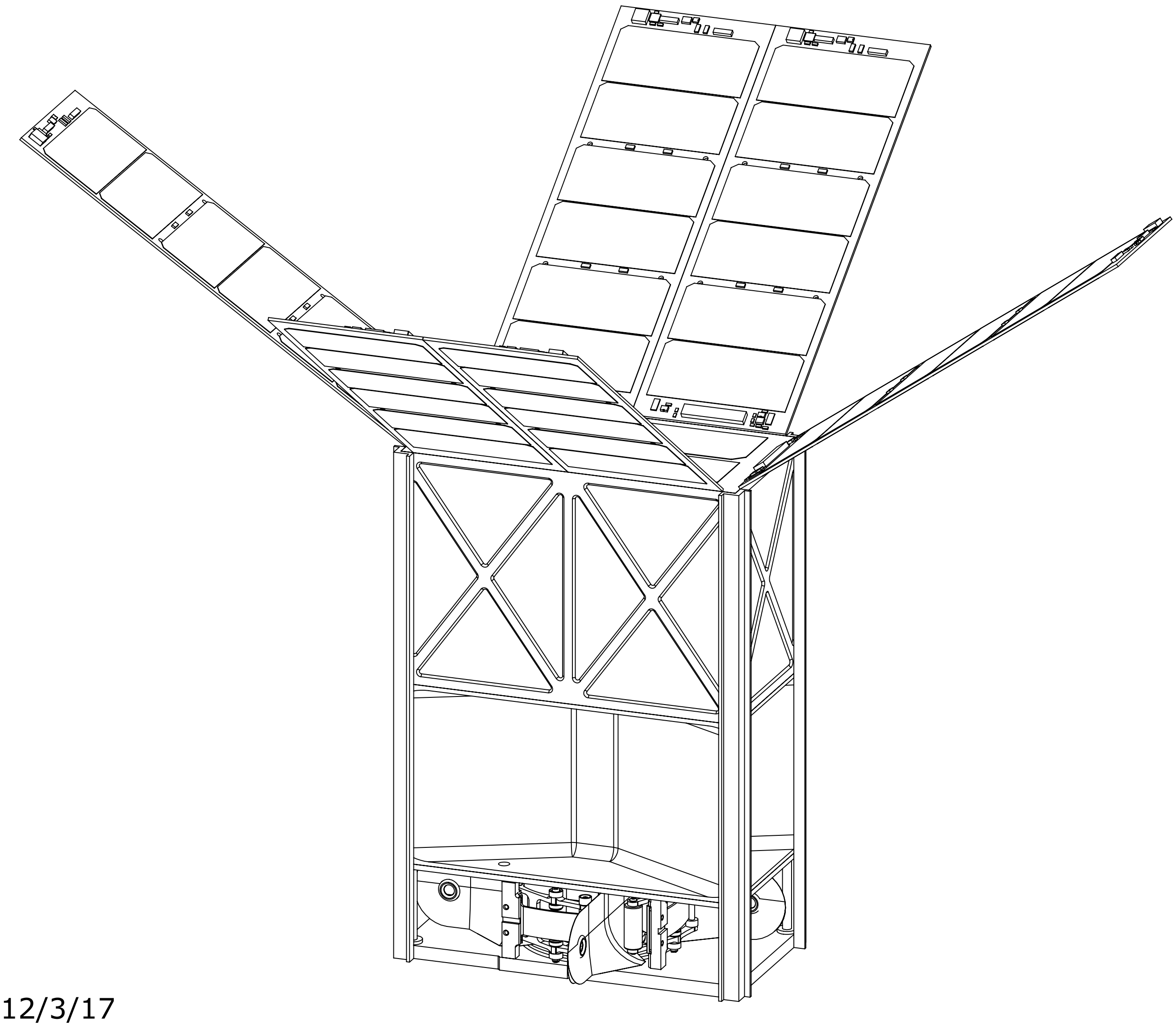
E. Earth-Moon L2 Radio-Quiet Observatory *[Astrophysics]*

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



Robert Staehle, 2012 March
Art: Ryan Sellers/CalPoly SLO

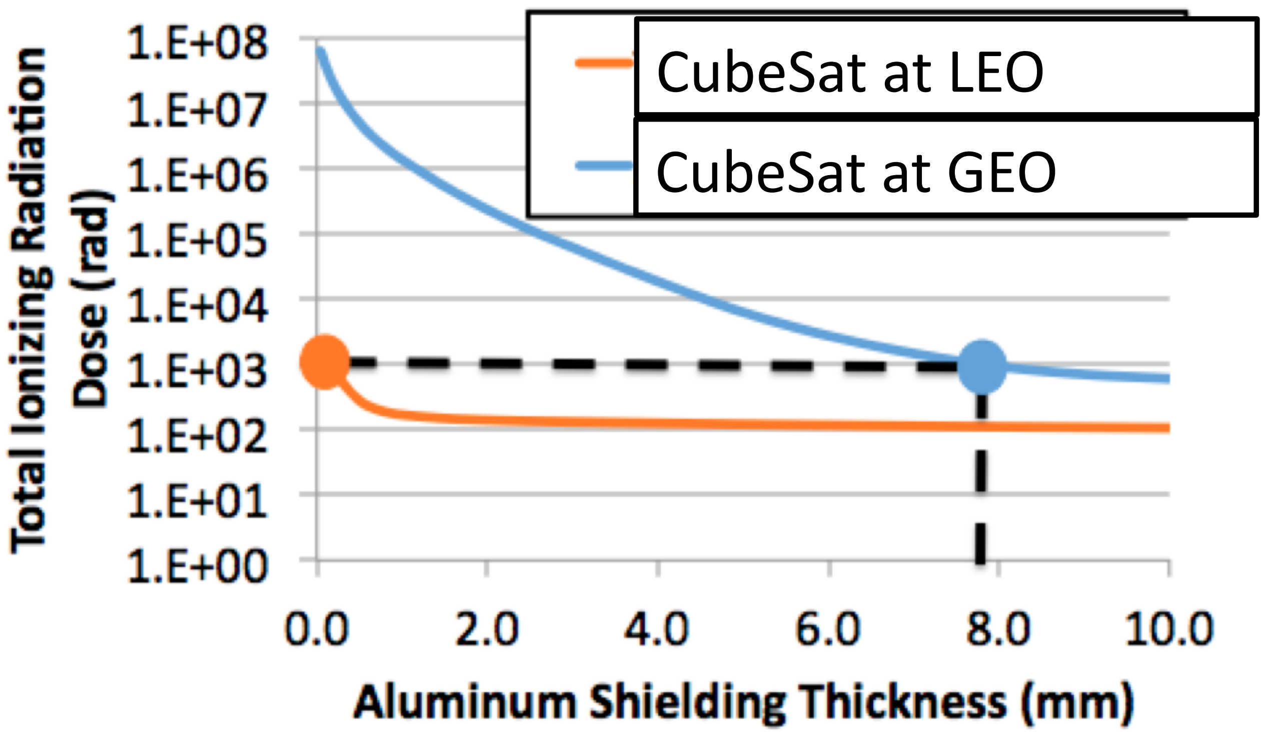
One Preliminary Configuration



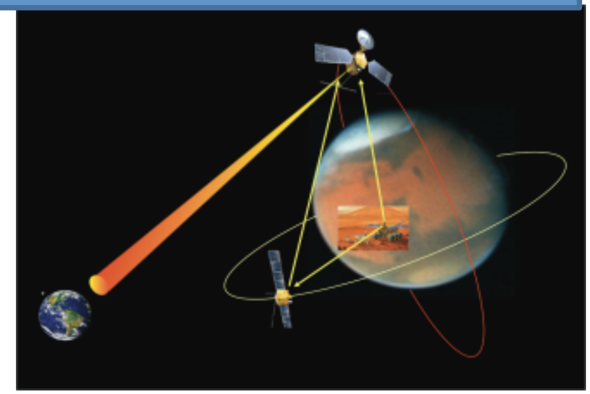
Tomas Svitek, 2012/3/17

1. Interplanetary environment

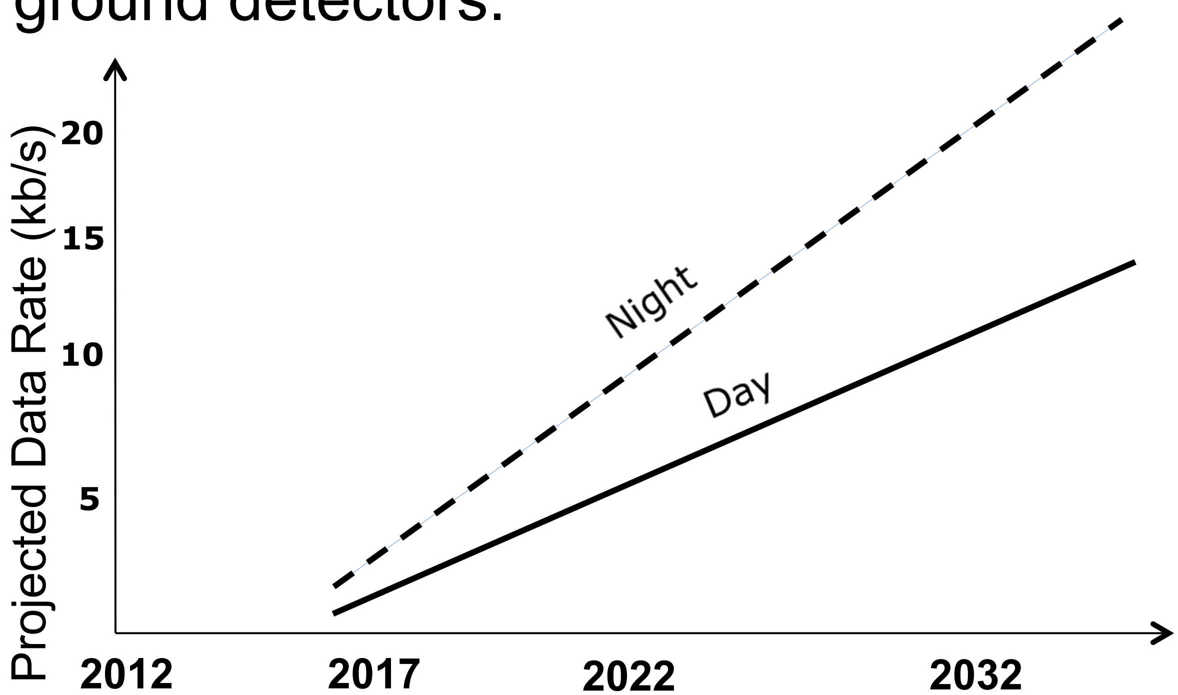
- Select based on LEO experience
- Multiple computers
- Asymmetric redundant data paths
- Watchdog timers



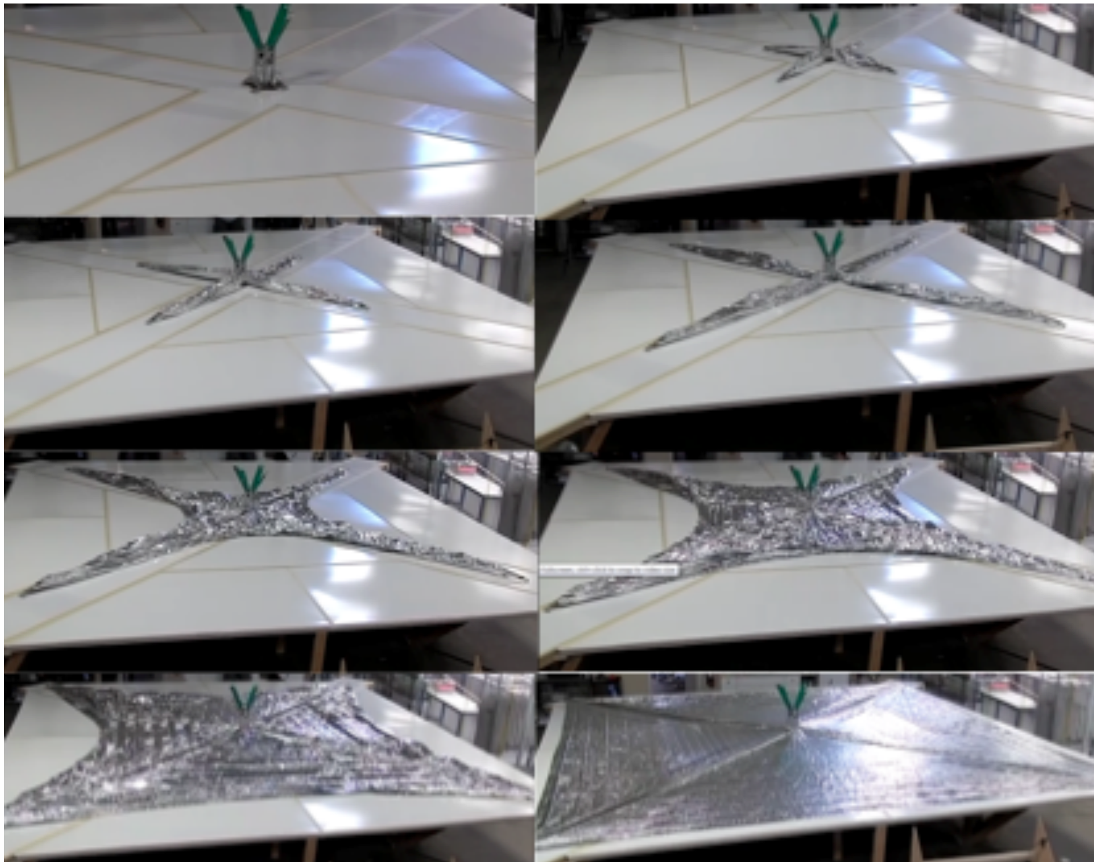
2. Telecommunications



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



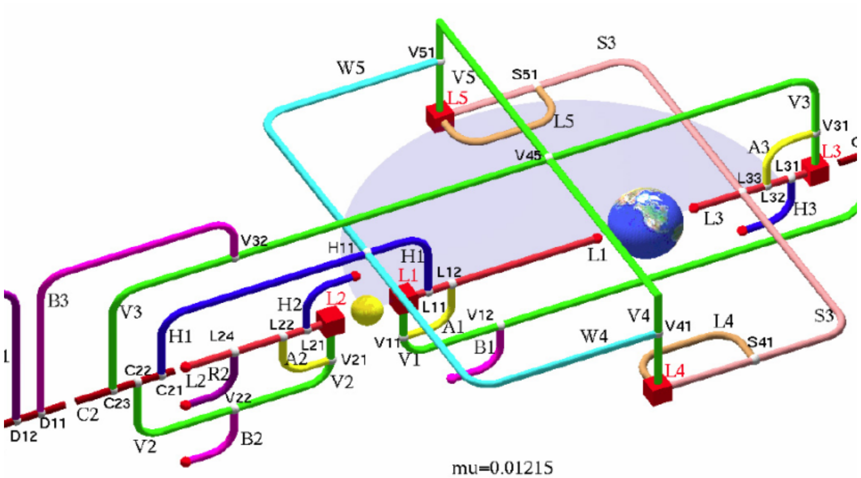
But…
RF can deliver 10 b/s out to 0.2 AU with S-band, using Universal Software Radio Peripheral (USRP), and 34 meter dish. Onboard HGA & X-band can yield higher rates.

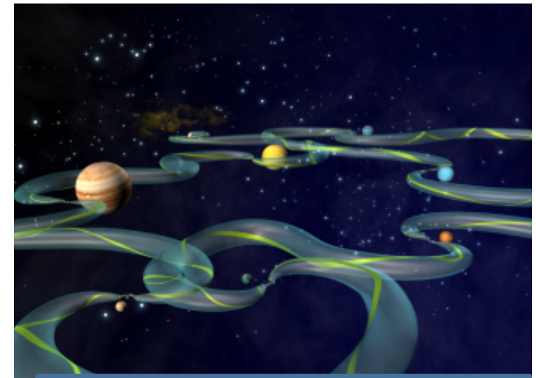


3. Propulsion

Interplanetary Superhighway Trajectory Technology Roadmap

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





4. Navigation

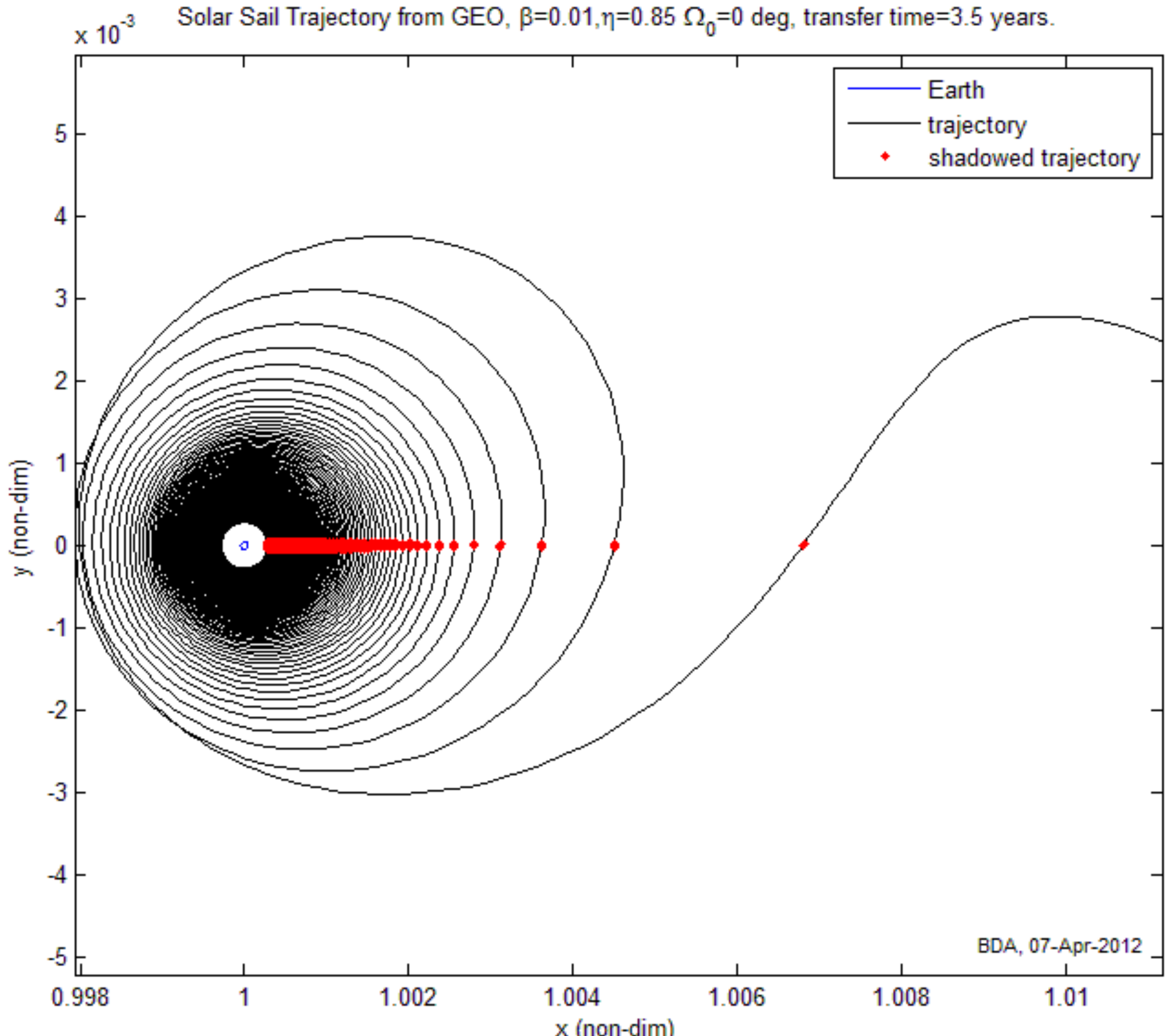
- Currently Only Halo Orbit Families Are Used
  - –Only around Earth-Moon L1 and L2
- Many Identified Families Yet To Be Used
- Many Other Families Yet To Be Identified & Mapped
- Families for Other Planets and Moons To Be Mapped

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

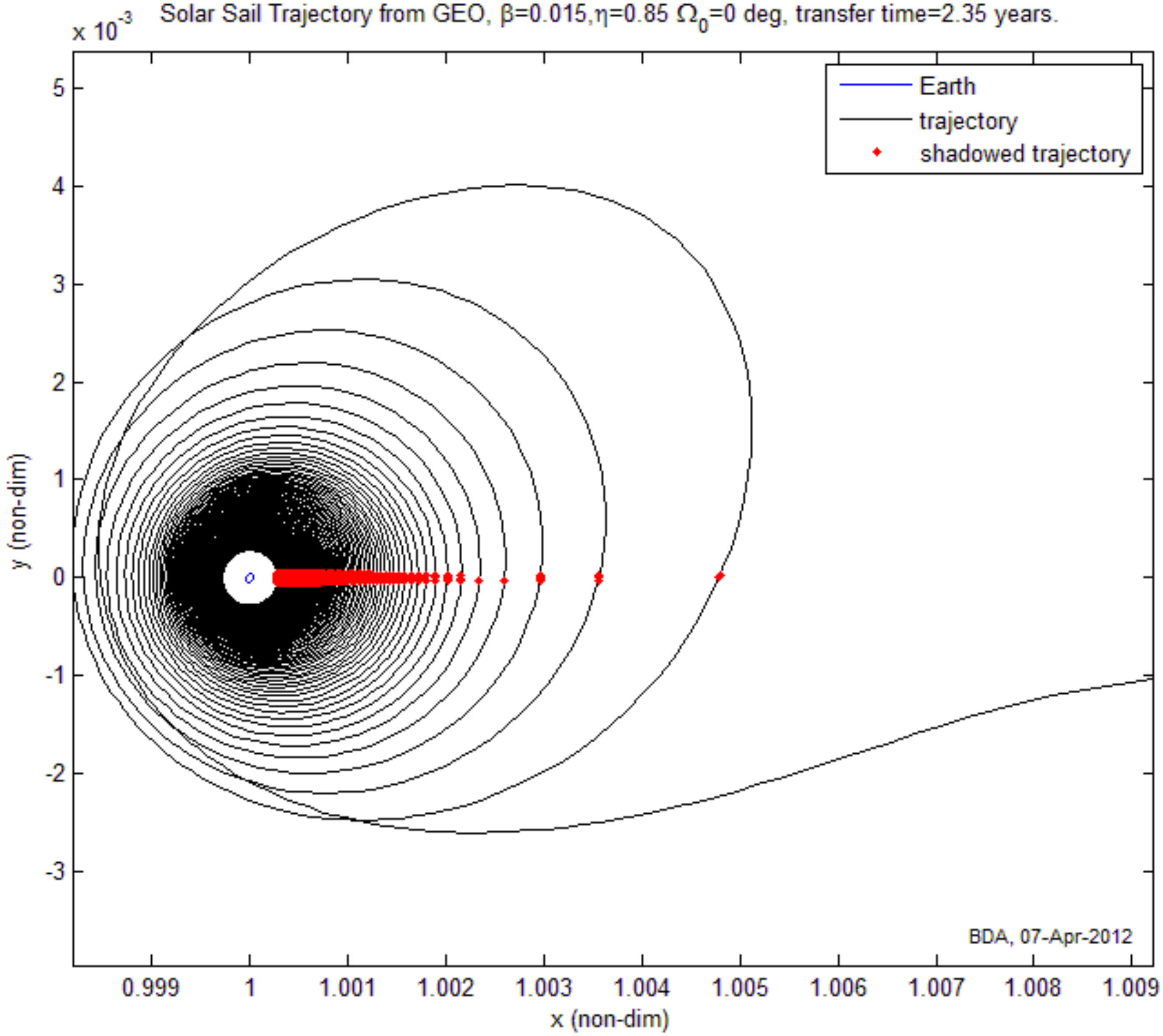
…if you can't find a ride
to Earth escape or better

Earth Escape 5.6m Solar Sail, 3.5 Yrs.



Brian Anderson (USC) and Martin Lo

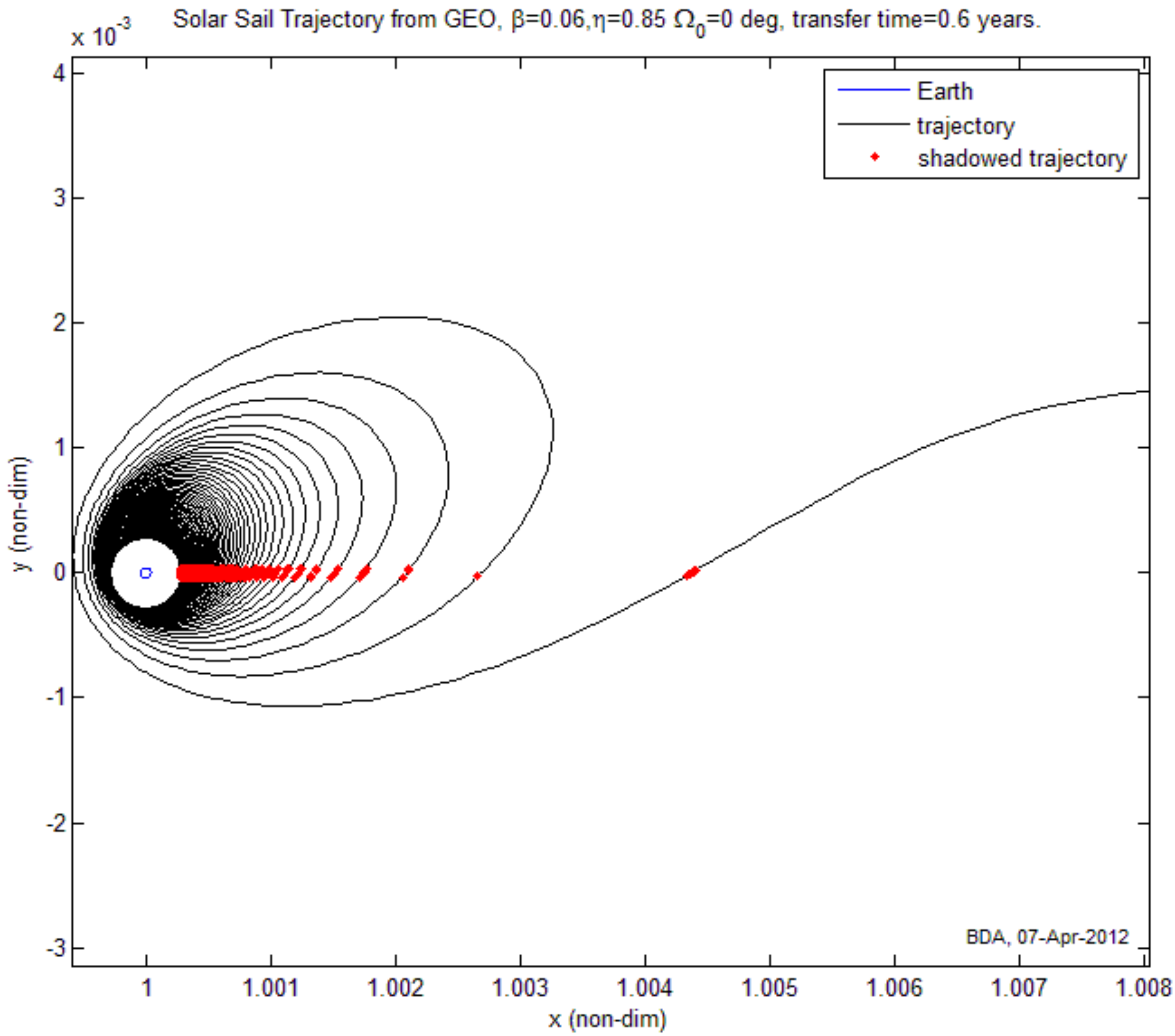
Earth Escape 10m Solar Sail, 2.35 Yrs



Brian Anderson (USC) and Martin Lo

Pre-decisional – for planning and discussion purposes only

Earth Escape 20m Solar Sail, 0.6 Yrs.



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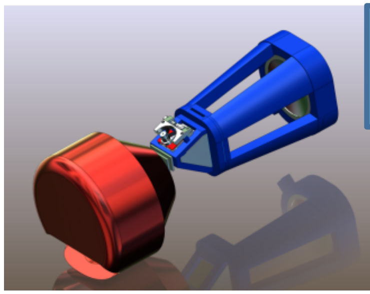
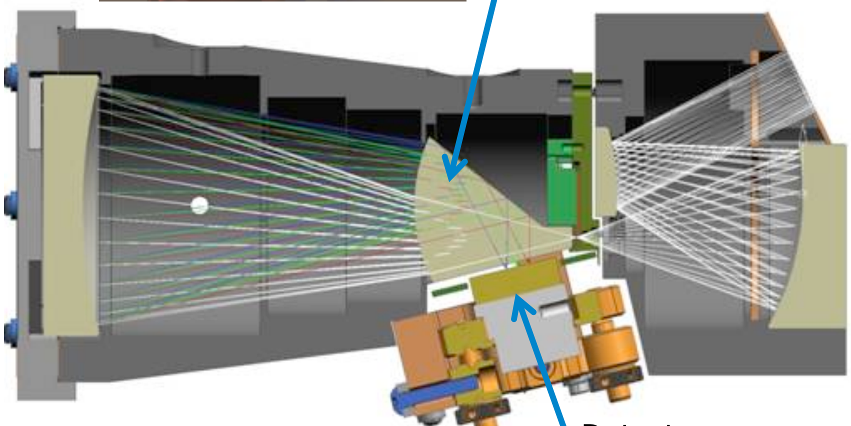


5.Instruments



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%

6. Maximizing downlink info content

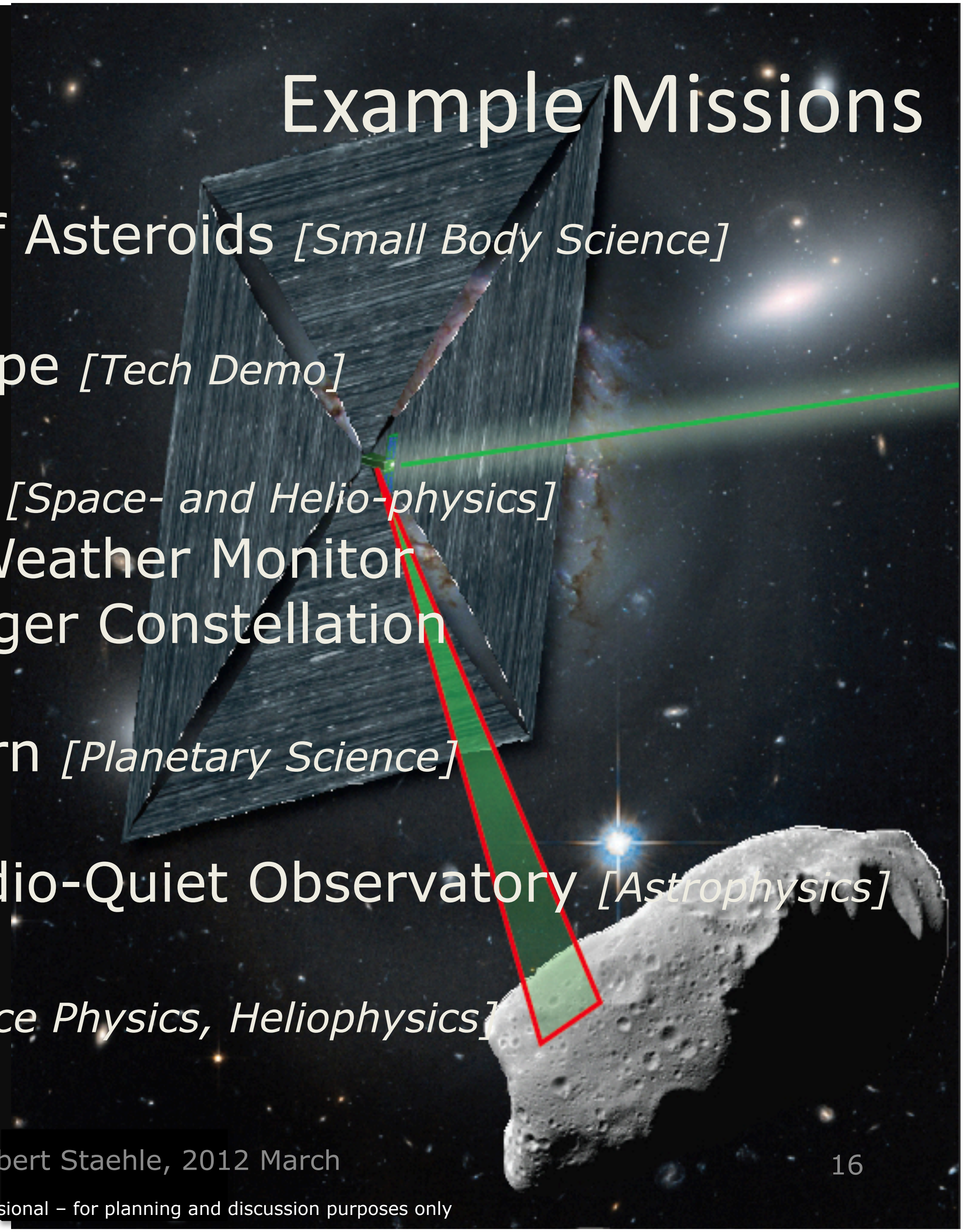
CubeSat Onboard processing Validation Experiment (COVE)*

- 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.

Example Missions



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

B. Solar System Escape *[Tech Demo]*

C. Earth-Sun System *[Space- and Helio-physics]*
   1) Sub-L1 Space Weather Monitor
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D. Mars Sample Return *[Planetary Science]*

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

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

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 C3>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

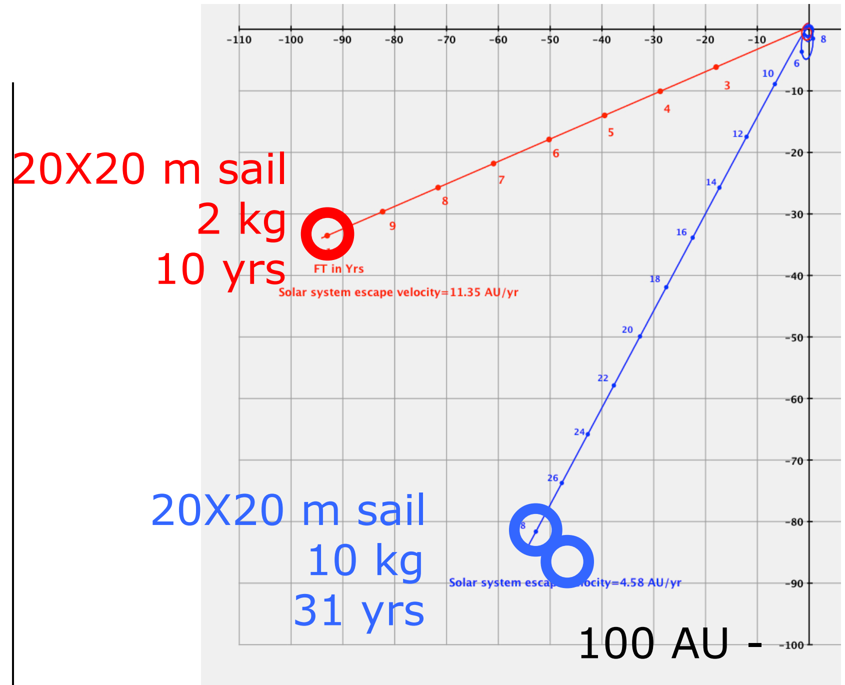
<u>6U</u> CubeSat:
2U imaging spectrometer instrument
2U solar sail
1U optical communications
1U satellite bus subsystems

Diana Blaney, Pantazis Mouroulis, Thor Wilson, 2012 March

*Proposed Mission

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

*Proposed Mission

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
<u>6U</u> 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

Solar Polar Imager CubeSat Constellation*

Proposed Mission Overview

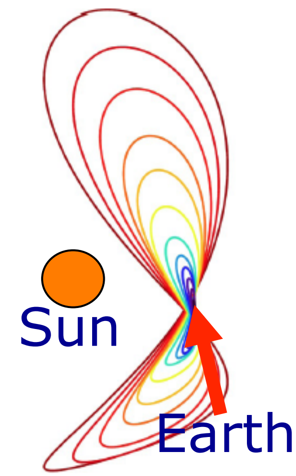
6 S/C in highly inclined constellation.
Out-of-Ecliptic Vertical Orbit, ~0.99 AU.
Use solar sail to reach high inclination.

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

Enabling Technology

Solar Sail
Miniaturized Instruments
New Vertical Orbit Trajectory Technology

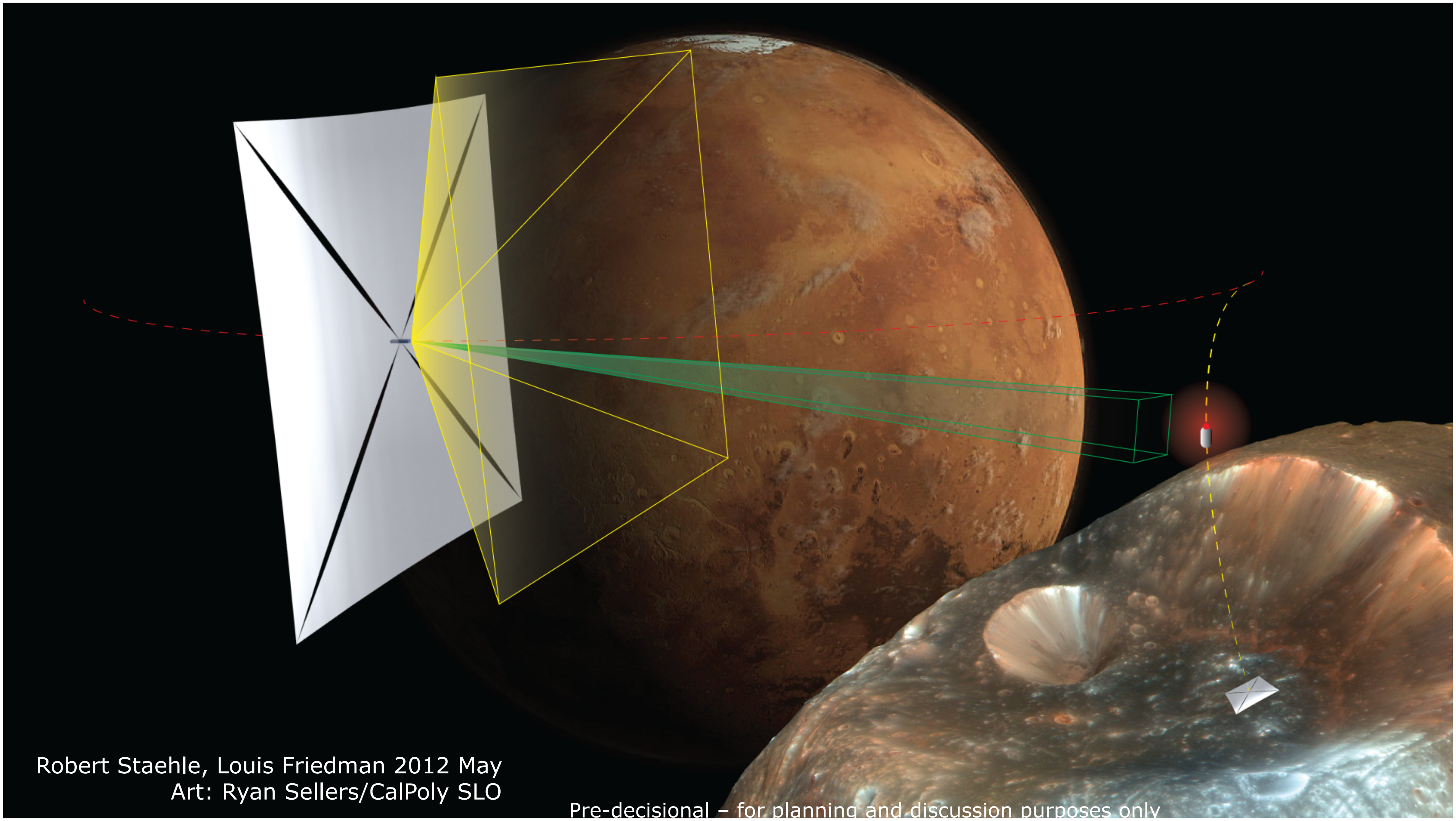
CubeSat Bus Concept
6 CubeSat Constellation:

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

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



Radio Quiet Lunar CubeSat: RAQL*

Proposed Mission Overview

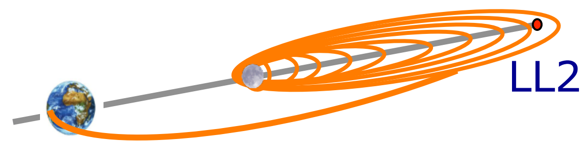
Assess radio quiet volume in shielded zone behind the Moon for future 21 cm cosmology missions.

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.

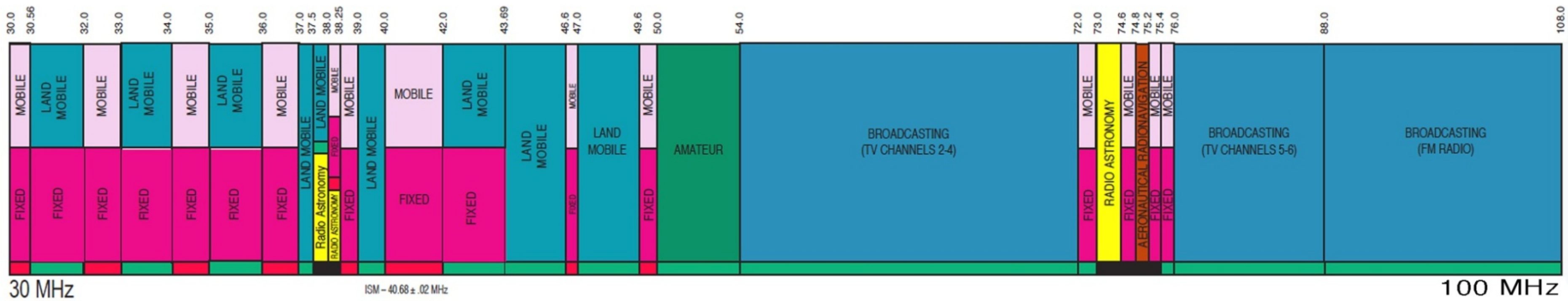
Other Features

- Data Rate < 10 Mbps
- Onboard processing?

Joseph Lazio, Dayton Jones, Martin Lo, 2012 March

*Proposed Mission

Mission Rationale



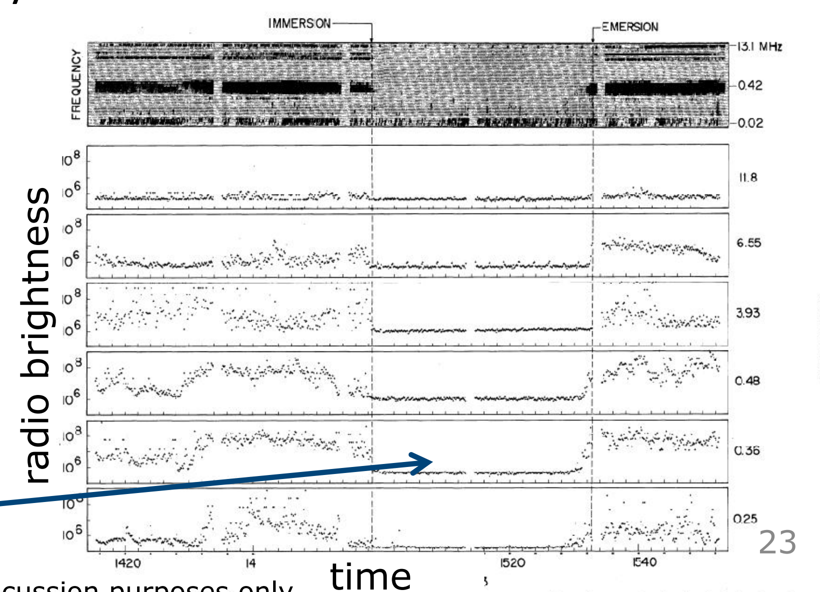
50 Myr since Big Bang	Portion of radio spectrum relevant for 21 cm observations of Cosmic Dawn and Dark Ages	330 Myr since Big Bang

- Yellow = reserved for radio astronomy

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**

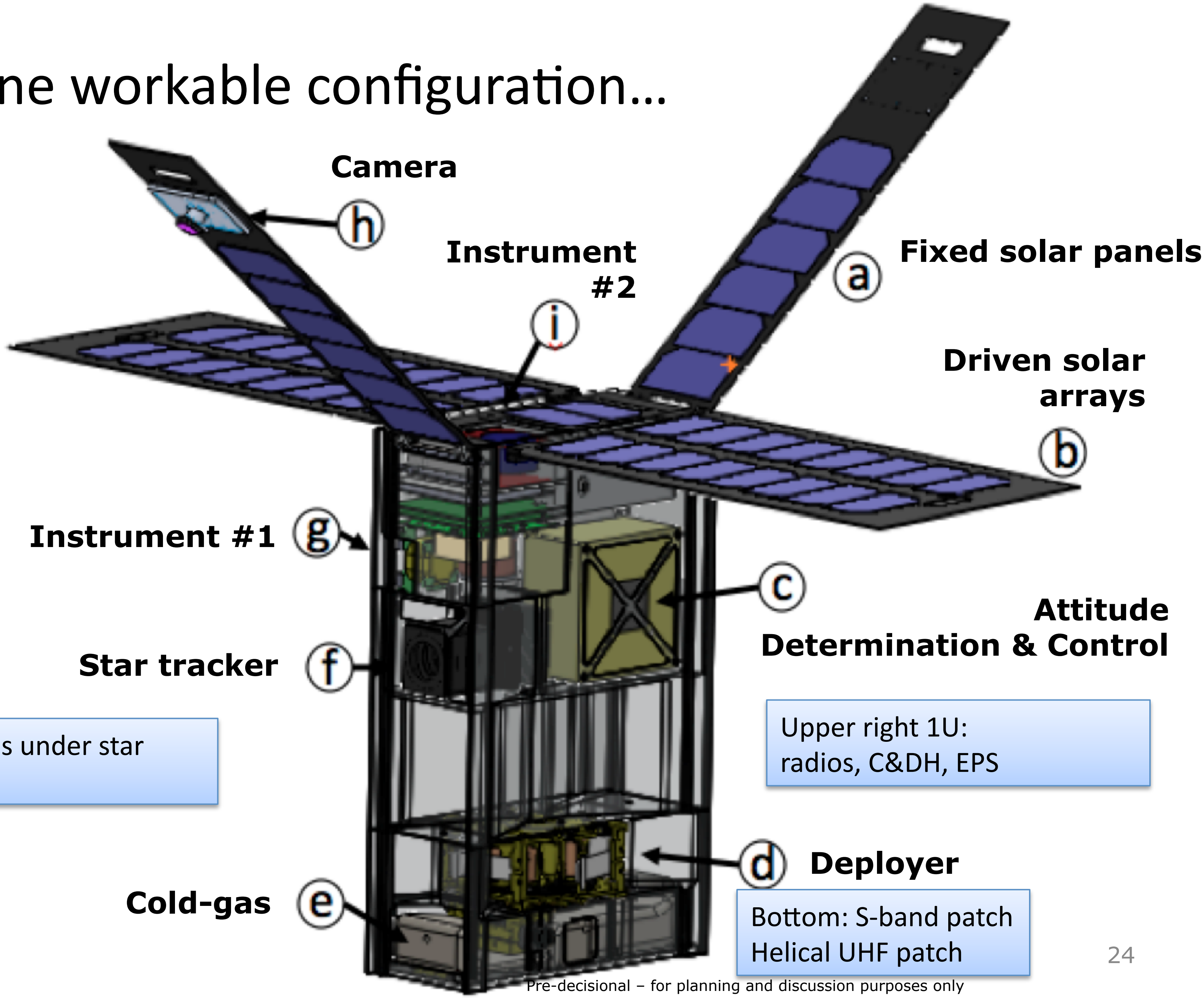


RAE-2 behind Moon

Joseph Lazio, Dayton Jones 2012 April

Pre-decisional – for planning and discussion purposes only

One workable configuration…



Batteries under star tracker

Upper right 1U: radios, C&DH, EPS

Bottom: S-band patch
Helical UHF patch

Preliminary Conclusions

- Interplanetary CubeSats could plausibly 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 could be developed to enable educational institutions and small businesses to lead them.

- Ongoing technology leaps and improvements continuously open new opportunities.

- 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 C3 >~0, and as hosted riders aboard some fraction of geostationary satellites.