Missions Enabled by an Interplanetary CubeSat Architecture

CubeSat Spring Workshop
2012 April 18
California Polytechnic University, San Luis Obispo

Robert L. Staehle, Diana Blaney, Hamid Hemmati, Dayton Jones, Andrew Klesh, Joseph Lazio, Paulett Liewer, Martin Wen-Yu Lo, Pantazis Mouroulis, Neil Murphy, Paula J. Pingree, Thor Wilson, Chen-Wan Yen
Jet Propulsion Laboratory, California Institute of Technology

Jordi Puig-Suari, Austin Williams
California Polytechnic University, San Luis Obispo

Bruce Betts, Louis Friedman
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

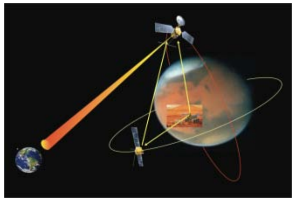
Six Technology Challenges

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*

1. Interplanetary environment

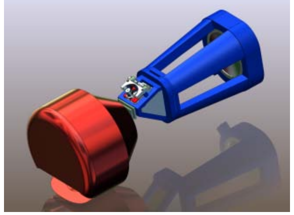


2. Telecommunications

3. Propulsion (where needed)

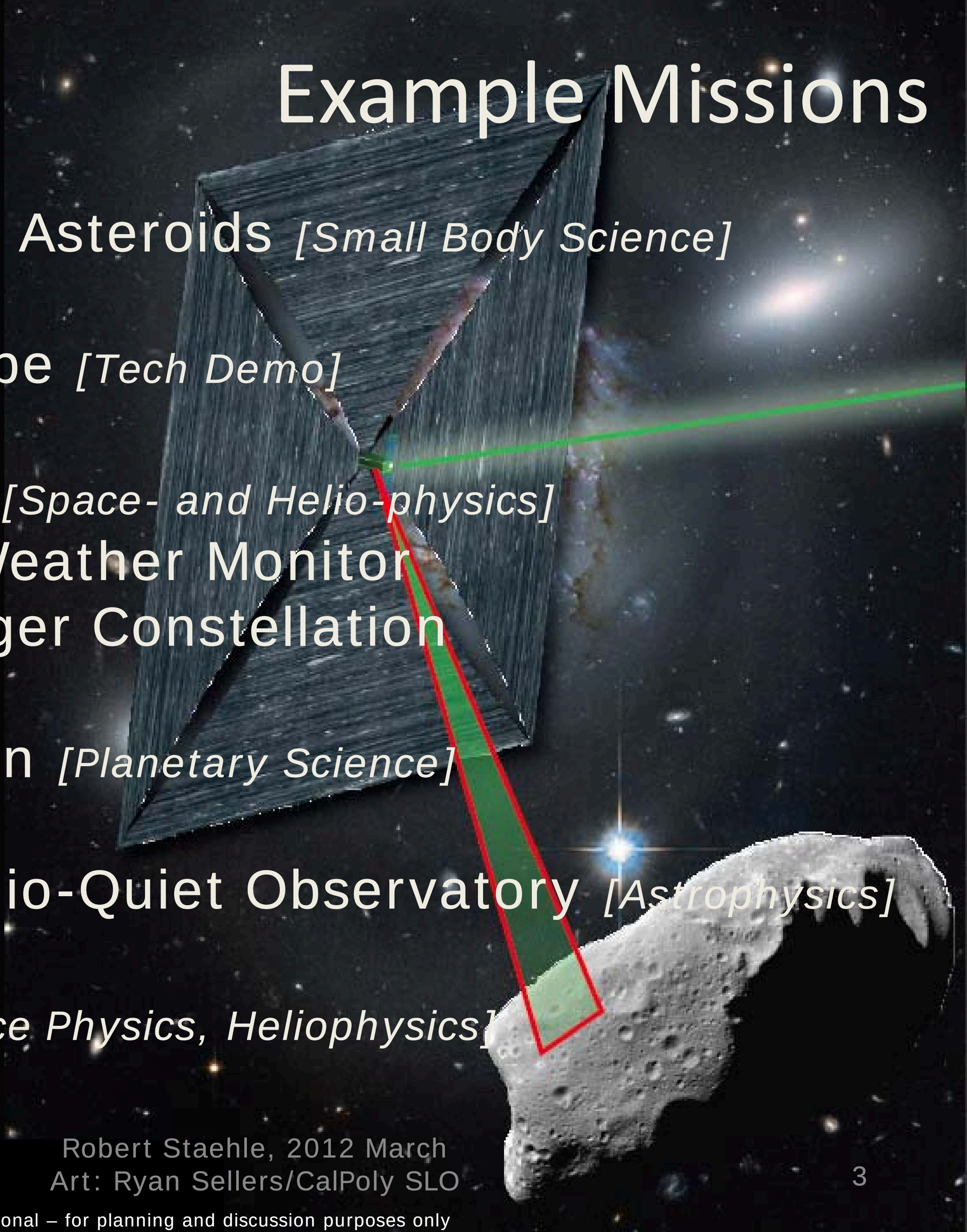
4. Navigation

5.Instruments



6. Maximizing downlink info content

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

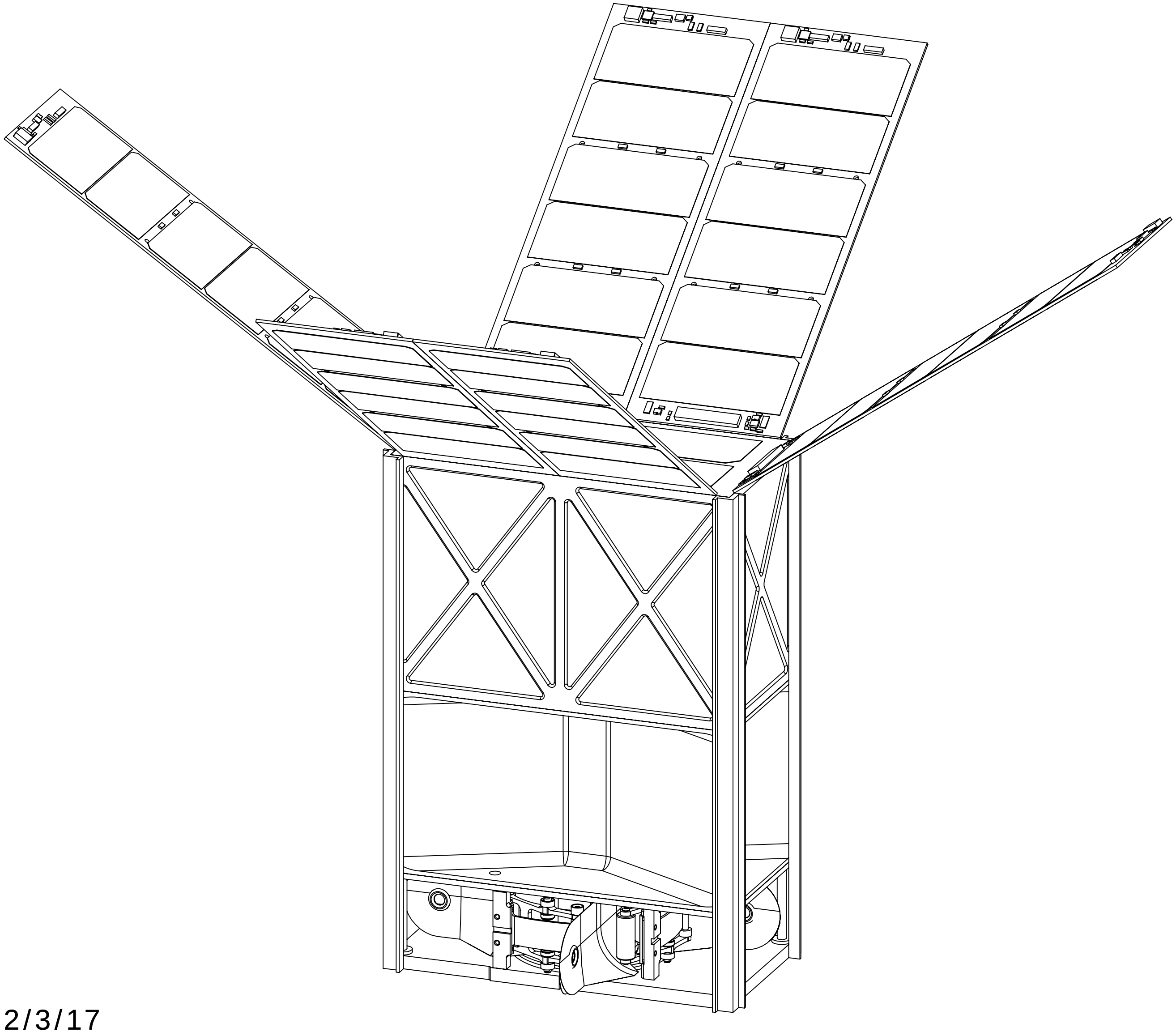
D. Mars Sample Return *[Planetary Science]*

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

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

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

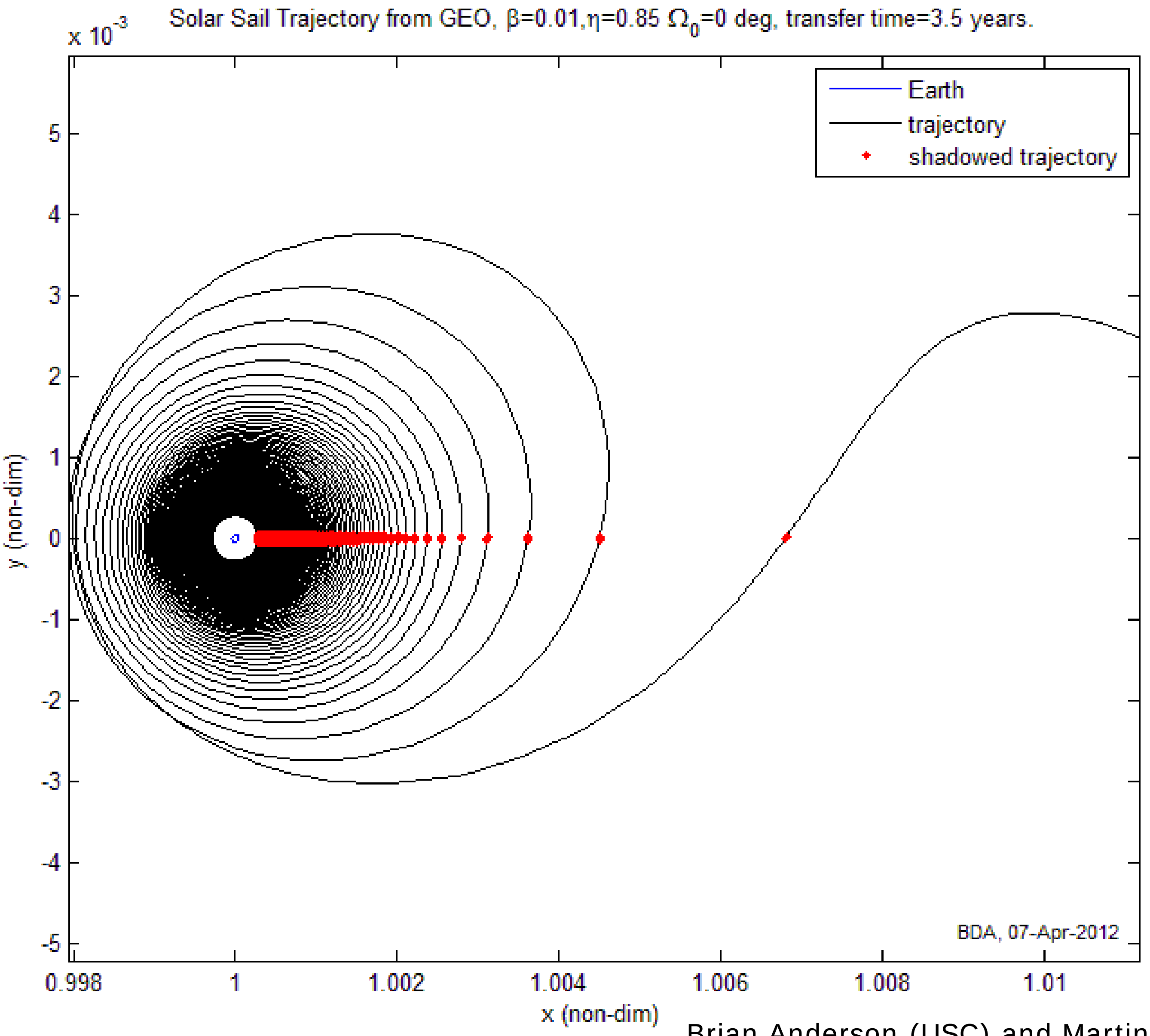
One Preliminary Configuration



Earth Escape Solar Sail Trajectories

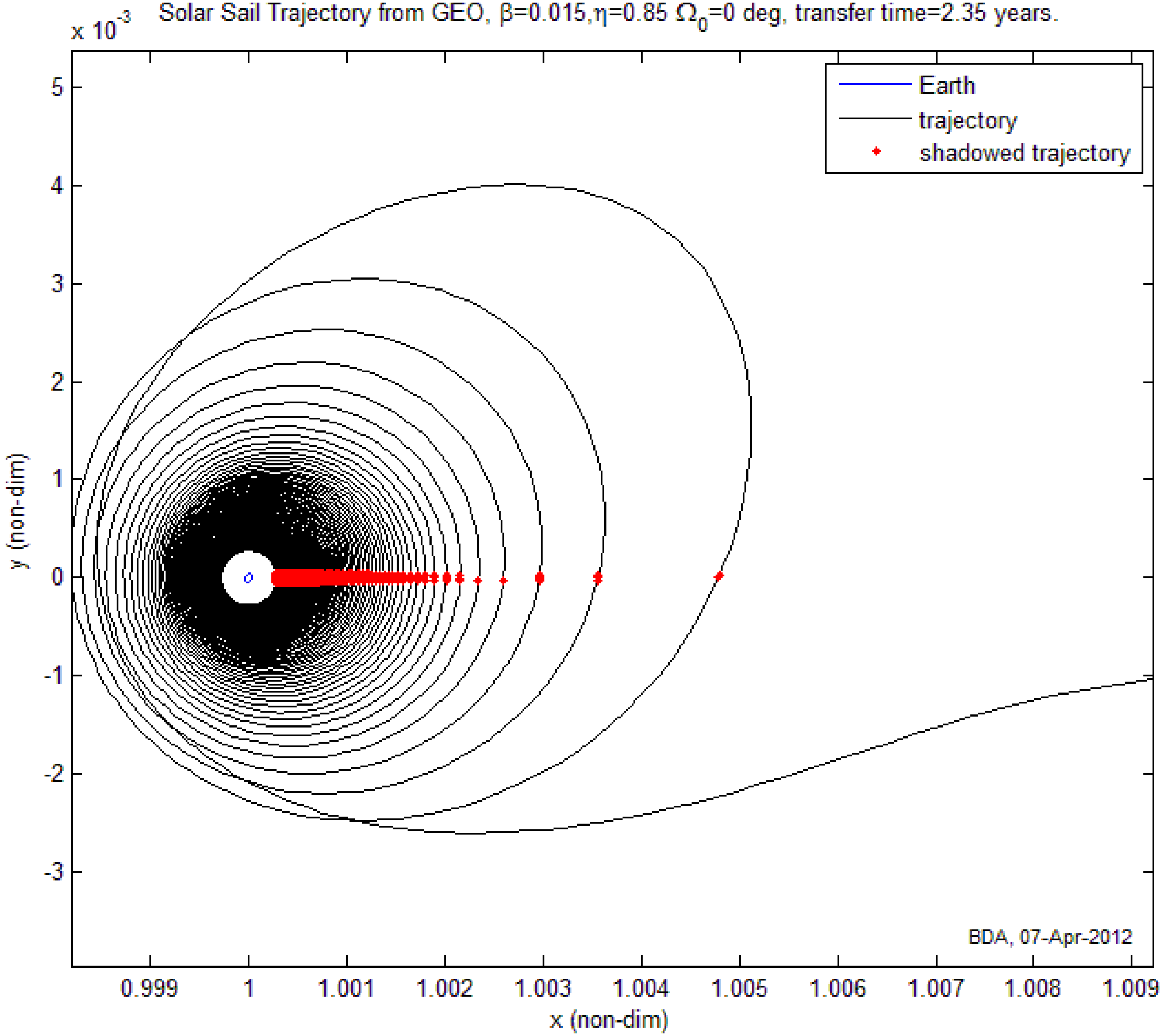
- Sail at 85% Efficiency
- 5.6m sail at 4.6 kg
- 10m & 20m sail at 10 kg
- Benefits of lunar gravity assist not accounted

Earth Escape 5.6m Solar Sail, 3.5 Yrs.



Brian Anderson (USC) and Martin Lo

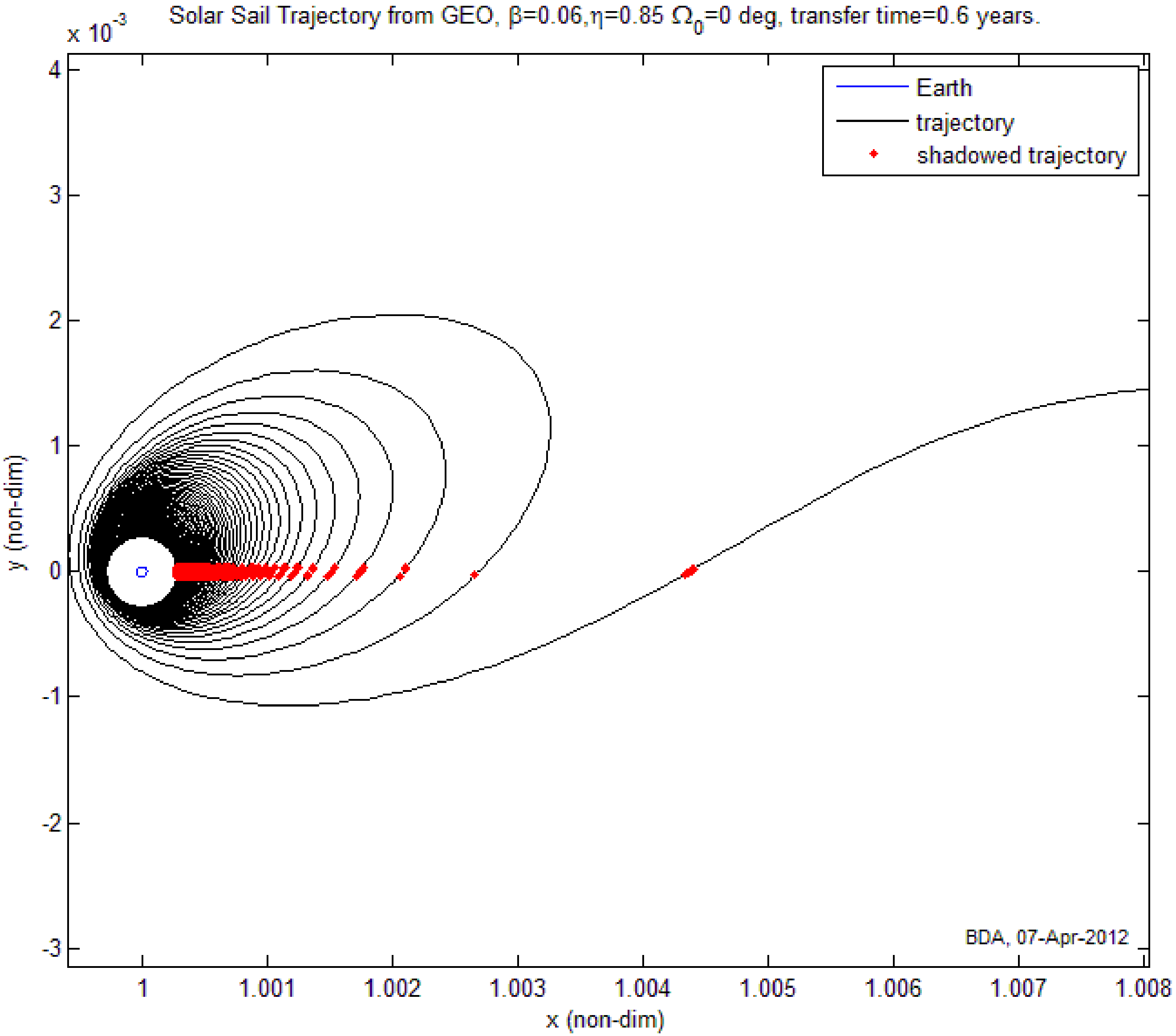
Earth Escape 10m Solar Sail, 2.35 Yrs



Brian Anderson (USC) and Martin Lo

Pre-decisional – for planning and discussion purposes only

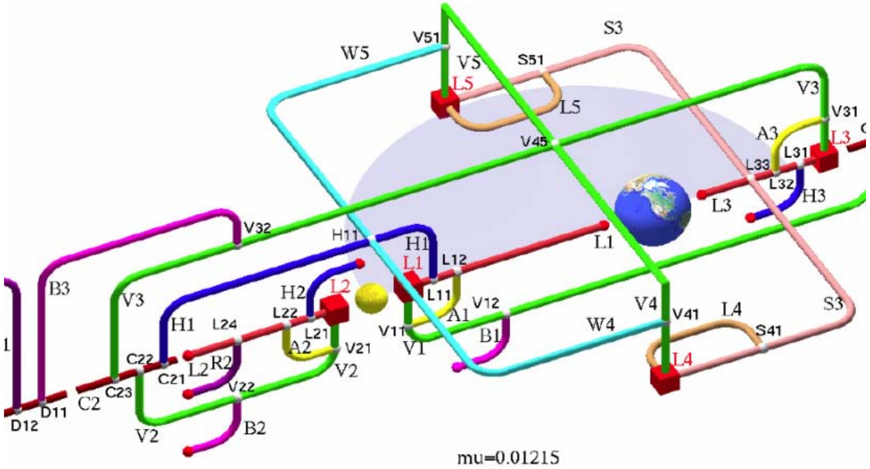
Earth Escape 20m Solar Sail, 0.6 Yrs.



Brian Anderson (USC) and Martin Lo

Interplanetary Superhighway Trajectory Technology Roadmap

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



- 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

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]*

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.

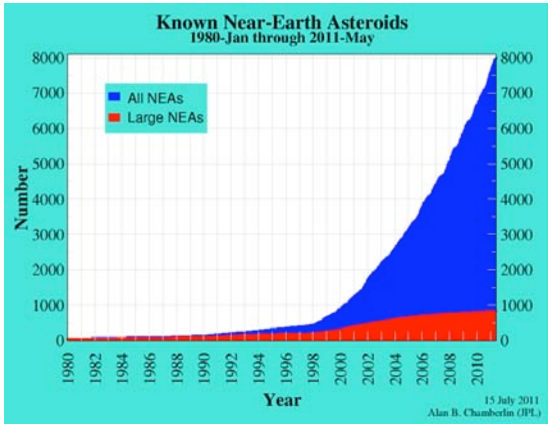
CubeSat bus

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

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.

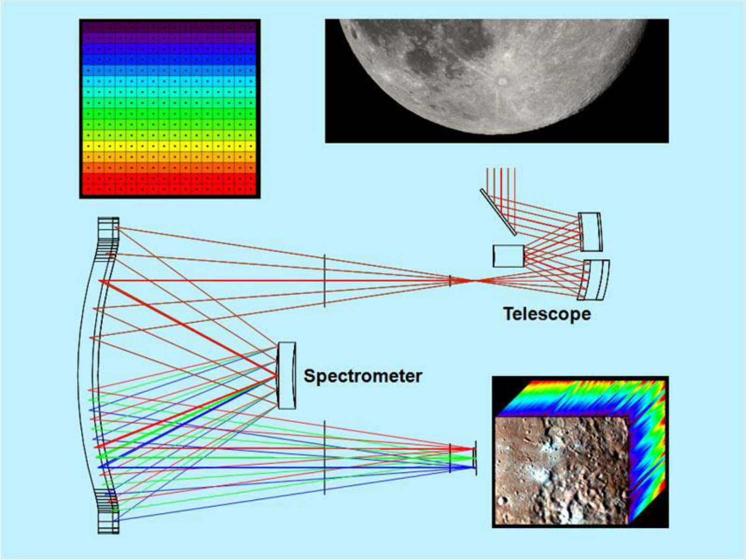
Targets of interest for future human exploration

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

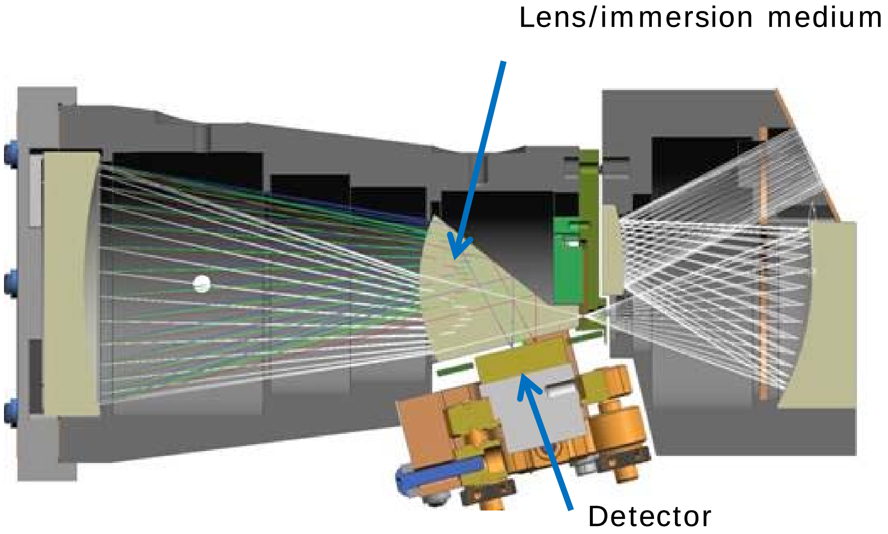
Close flybys of Near Earth Asteroid (NEA) with spacecraft imaging spectrometer to map surface mineralogy at geologic scales. Data collected then stored on board and returned to Earth post-encounter.



Building an Image Cube: Moon Mineralogy Mapper Example

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

Instrument



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.

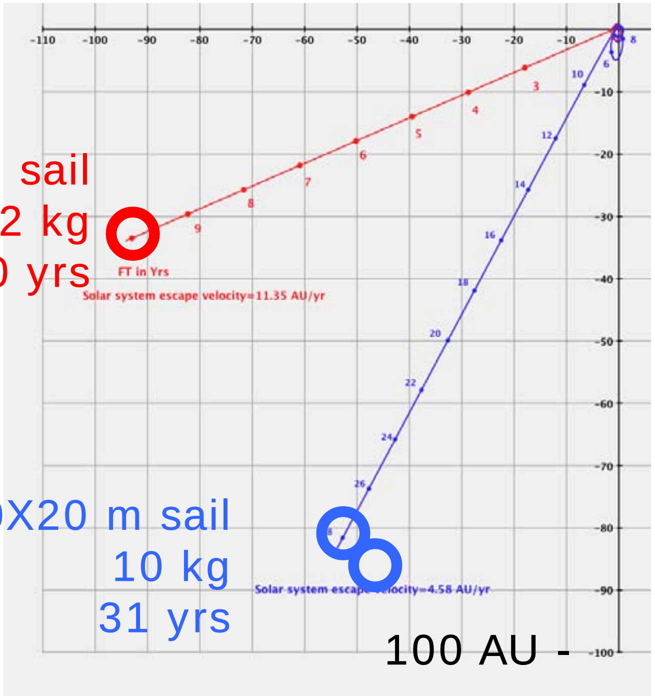
Instrument Electronics

- 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%

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



20X20 m sail
2 kg
10 yrs

20X20 m sail
10 kg
31 yrs

100 AU -

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*

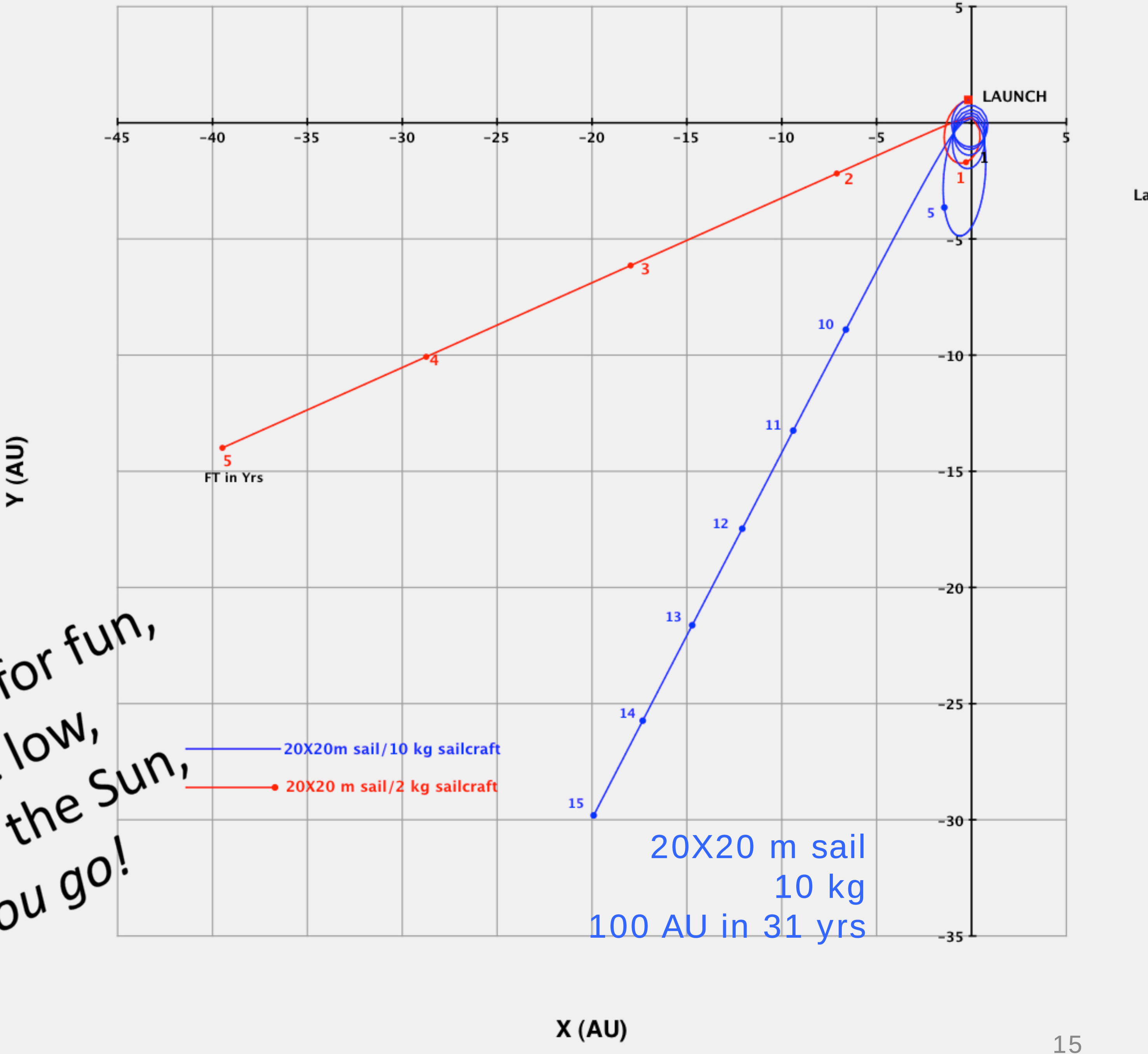
Louis Friedman, Paulett Liewer, Chen-Wan Yen, Robert Staehle 2012 April

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?

*Proposed Mission

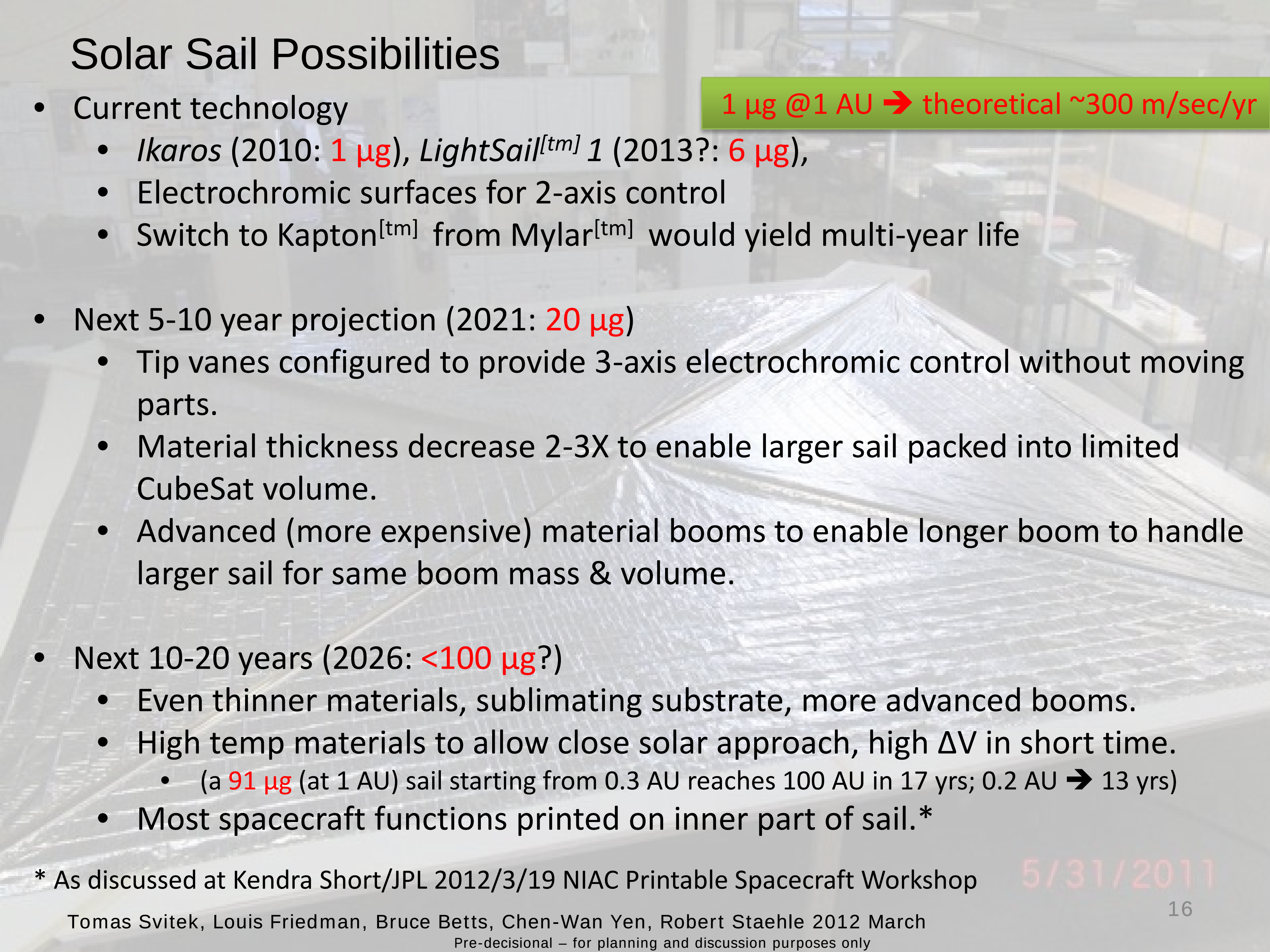
20X20 m sail
2 kg
100AU in 10 yrs



20X20 m sail
10 kg
100 AU in 31 yrs

Big sail makes for fun,
Mass make it low,
Sail close to the Sun,
and Fast you go!

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

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

Solar Polar Imager CubeSat Constellation*

Proposed Mission Overview

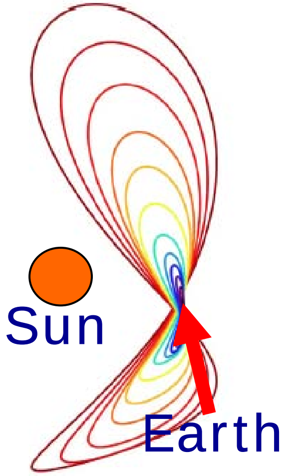
6 S/C in highly inclined constellation.
Out-of-Ecliptic Vertical Orbit, ~0.99 AU.
Use solar sail to reach high inclination.

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:

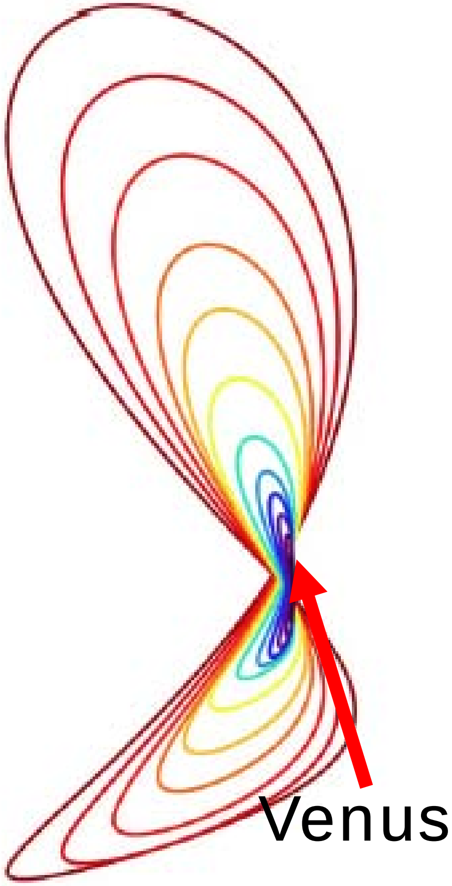
<u>6U</u> CubeSat:
1U for bus
2U for instruments
2U for solar sail
1U for optical communications

Paulett Llewer, Neil Murphy, Martin Lo, 2012 March

*Proposed Mission

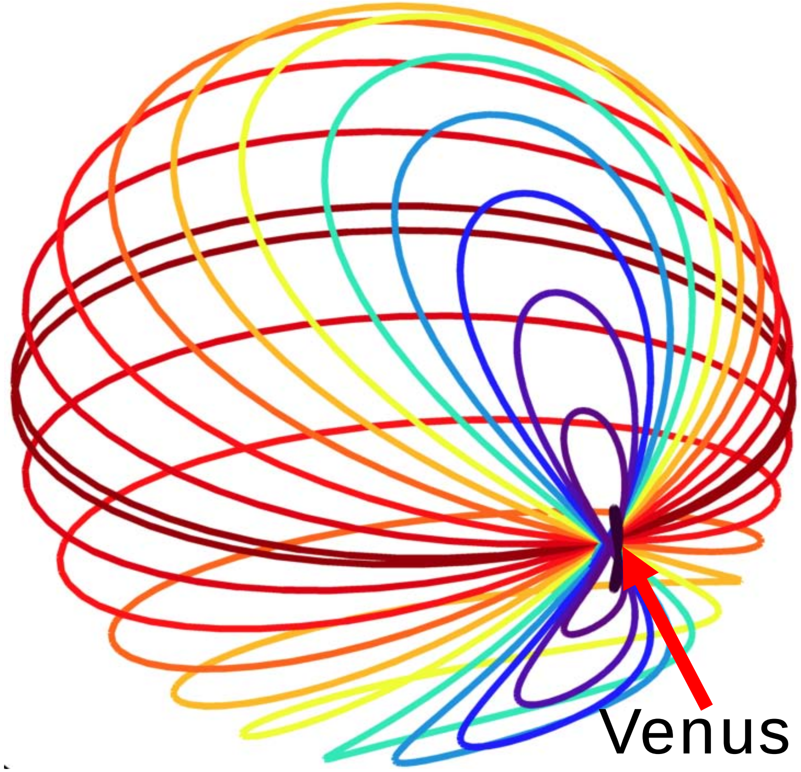
Possible Alternative Trajectory: go to Venus first

- 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



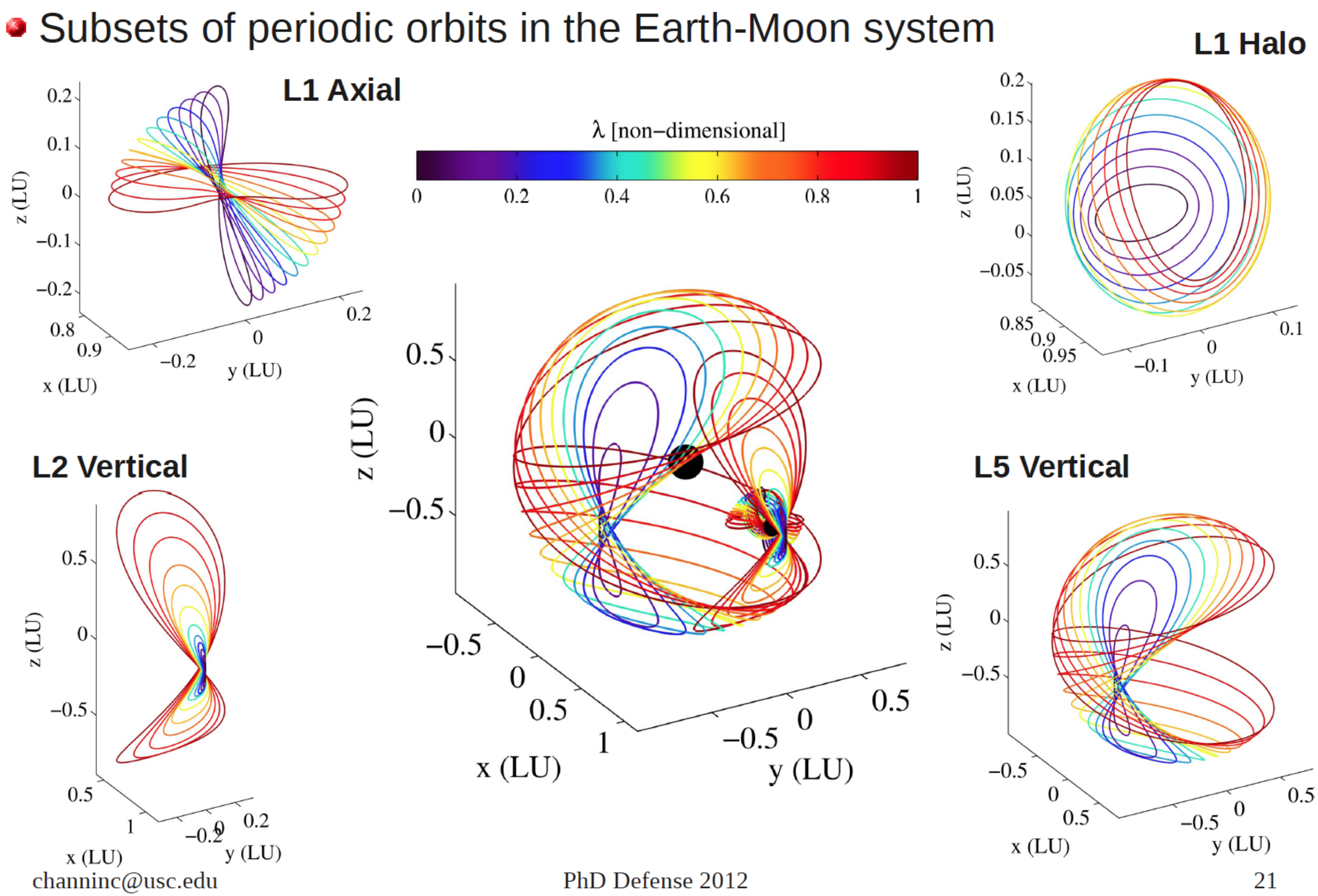
Trajectory Background

- Vertical L1/L2 Family Exists At All Inclinations.
  - Exist at all 5 libration points with different properties.
  - Sun Centered, Sun-Venus Rotating Frame



Trajectory Background:

Orbits in a 3-body system



- Subsets of periodic orbits in the Earth-Moon system

L1 Axial

L1 Halo

L2 Vertical

L5 Vertical

channinc@usc.edu PhD Defense 2012 21

Channing Chow 2012 March

Pre-decisional – for planning and discussion purposes only

Conceptual Phobos Sample Return*

Proposed Mission overview/ Science objectives

- Two 6U CubeSats launched to GEO or > C3.
- 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 < 100 cm/sec
- Return: 2U rendezvous sensor, precision thrusters, capture mechanism

*Proposed Mission

Radio Quiet Lunar CubeSat: RAQL*

Proposed Mission Overview

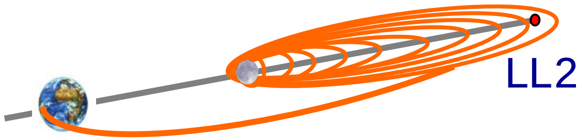
Assess radio quiet volume in shielded zone behind the Moon for future 21 cm cosmology missions.

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

<u>6U</u> 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

Science Background

- Universe undergoes transition from largely neutral state (**no** stars, *Dark Ages*) to largely ionized state (stars, black holes, galaxies) in the first billion years of its history.
- Prior to formation of first stars, evolution of the Universe is linear.
- Prior to formation of the first stars, intergalactic medium is dominated by neutral hydrogen, the raw material from which stars form.
- Neutral hydrogen has a spin-flip transition (1420 MHz)

➢ Spin-flip transition provides tracer for evolution of the Universe, vastly improved constraints on cosmological parameters.

➢ Deviations from predicted evolution indicate new physics, e.g., dark matter decay.

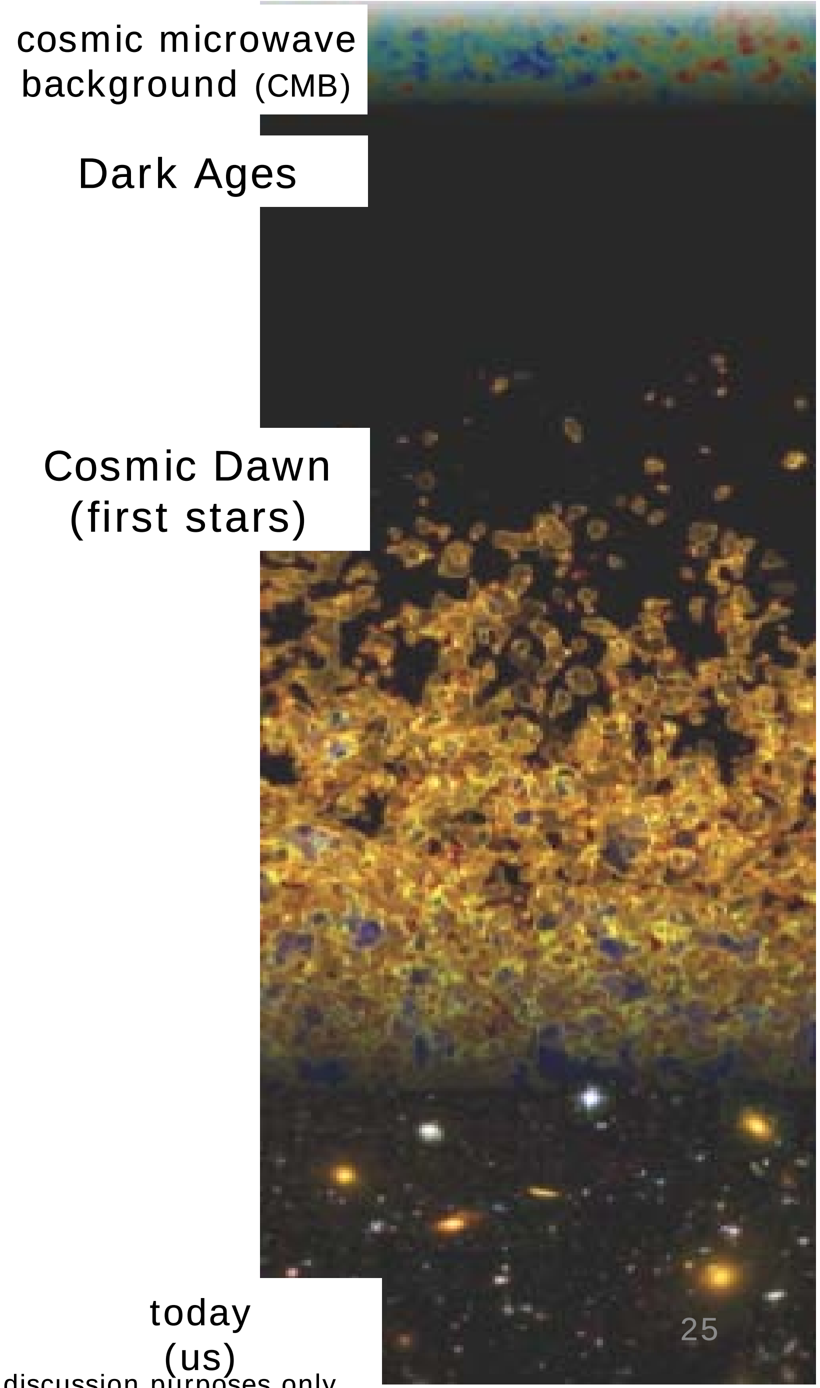
"What were the first objects to light up the Universe and when did they do?"

"Why is the Universe accelerating [nature of inflation]?"

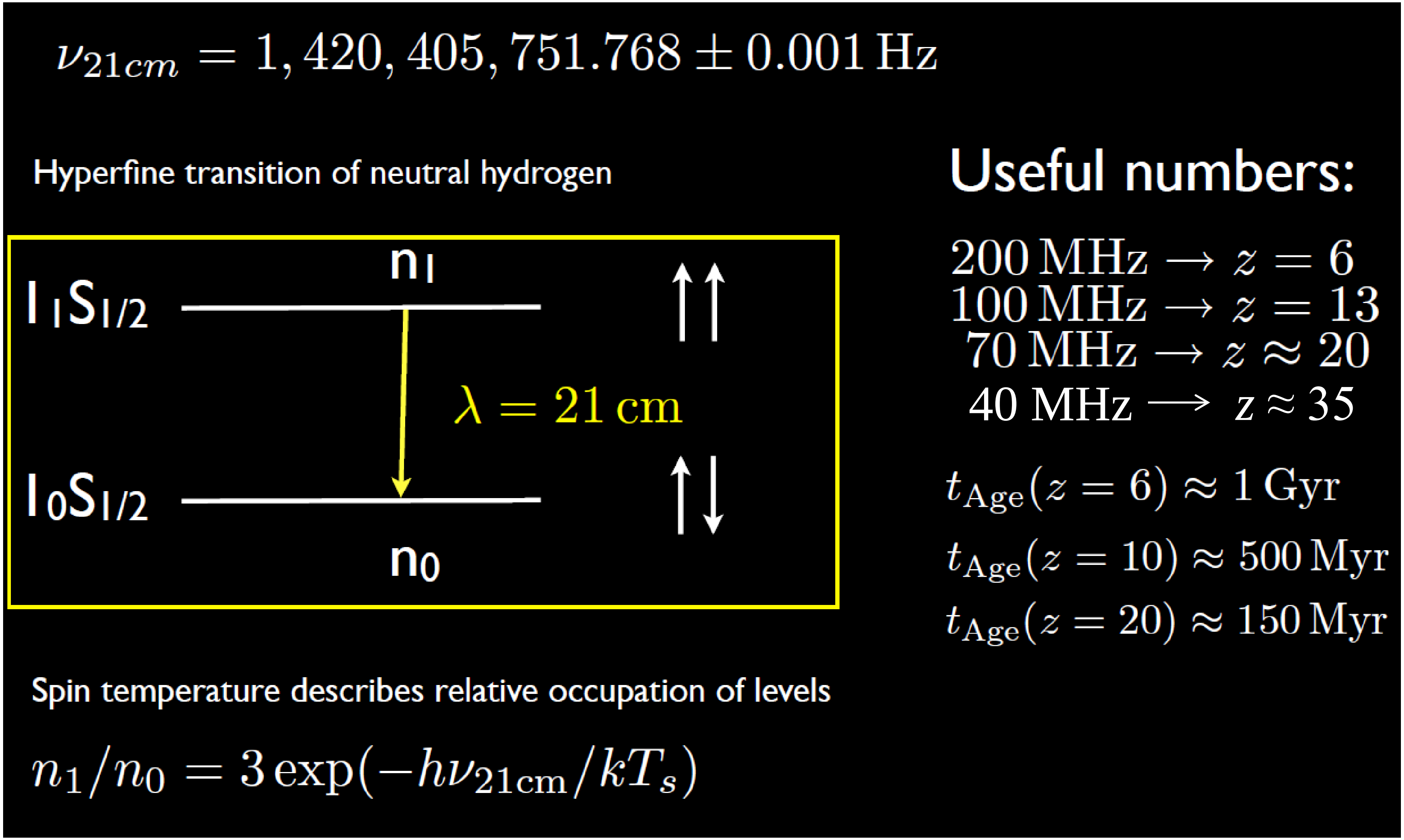
Science Background

The First Billion Years

- Cosmic microwave background forms ~ 300,000 yr after Big Bang.
- During Dark Ages, Universe dominated by neutral hydrogen.
- High precision constraints on cosmological parameters, and their evolution with time, can be obtained.
- Deviation from expected evolution is indication of new physics, e.g., dark matter decay.



21-cm Hyperfine Line of Neutral Hydrogen



$$\nu_{21cm} = 1,420,405,751.768 \pm 0.001\,\mathrm{Hz}$$

Hyperfine transition of neutral hydrogen

Spin temperature describes relative occupation of levels

$$n_1/n_0 = 3\exp(-h\nu_{21\mathrm{cm}}/kT_s)$$

Useful numbers:

$200\,\mathrm{MHz} \rightarrow z = 6$
$100\,\mathrm{MHz} \rightarrow z = 13$
$70\,\mathrm{MHz} \rightarrow z \approx 20$
$40\,\mathrm{MHz} \longrightarrow z \approx 35$

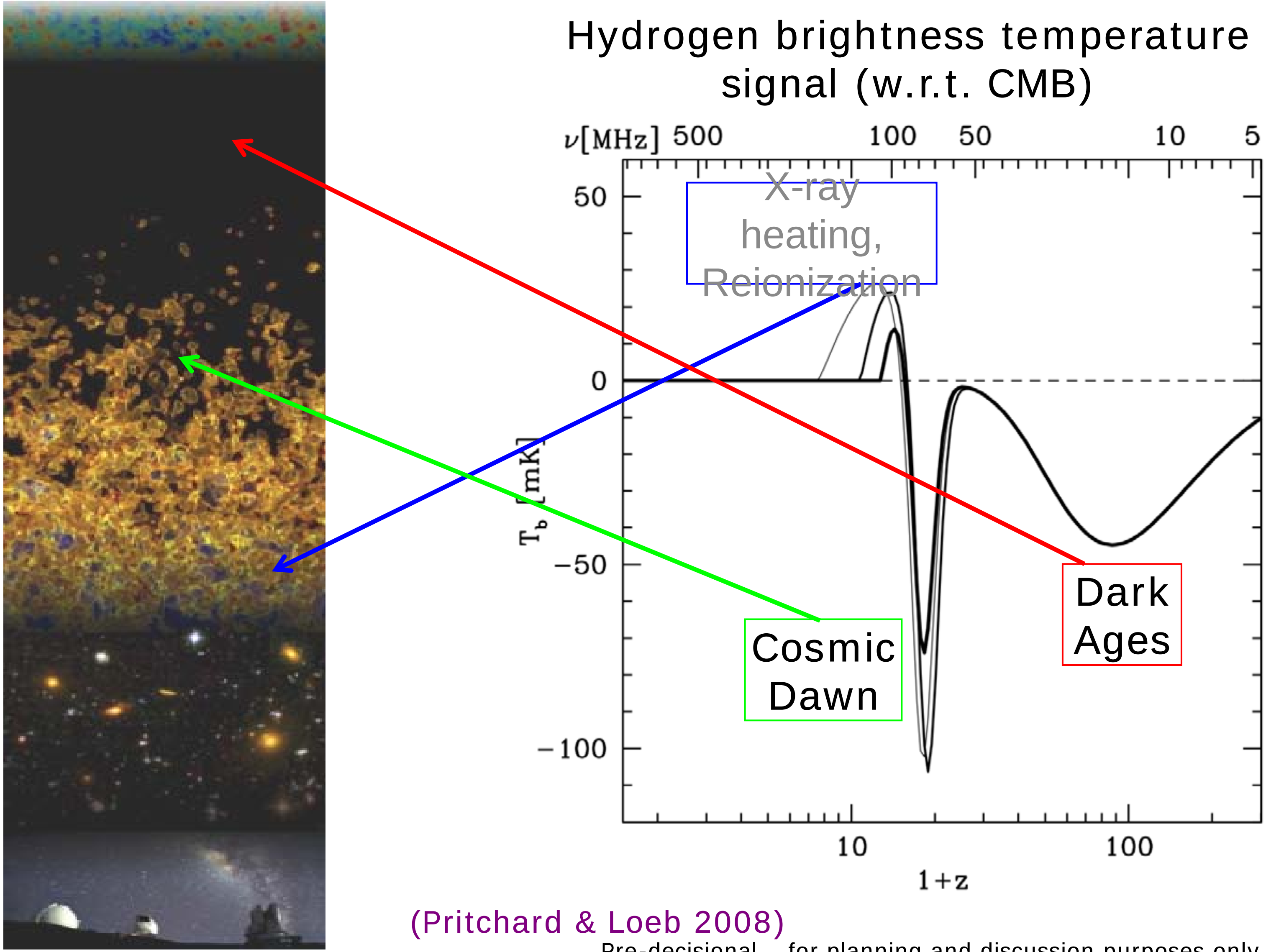
$t_{\mathrm{Age}}(z = 6) \approx 1\,\mathrm{Gyr}$

$t_{\mathrm{Age}}(z = 10) \approx 500\,\mathrm{Myr}$

$t_{\mathrm{Age}}(z = 20) \approx 150\,\mathrm{Myr}$

Courtesy of J. Pritchard

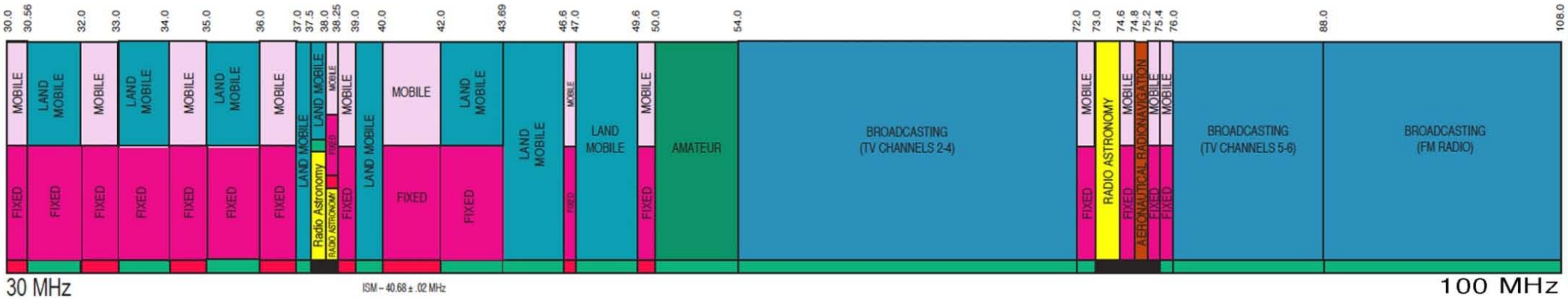
21 cm Signals from Cosmic Dawn & Dark Ages



Hydrogen brightness temperature signal (w.r.t. CMB)

(Pritchard & Loeb 2008)

Mission Rationale



50 Myr since Big Bang

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

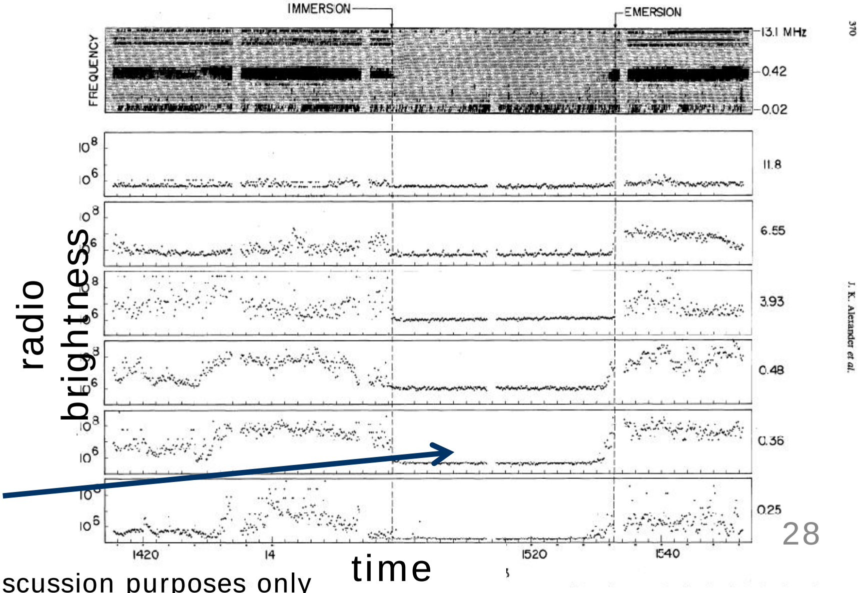
- Yellow = reserved for radio astronomy

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

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.

Missions Enabled by an Interplanetary CubeSat Architecture

?Questions?

Corresponding author:
robert.l.staehle@jpl.nasa.gov
818 354-1176

Robert L. Staehle, Diana Blaney, Hamid Hemmati, Dayton Jones, Andrew Klesh, Joseph Lazio, Paulett Liewer, Martin Wen-Yu Lo, Pantazis Mouroulis, Neil Murphy, Paula J. Pingree, Thor Wilson, Chen-Wan Yen
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