Interplanetary CubeSats:

Progress* toward Opening the Solar System to a Broad Community at Lower Cost

Third bi-monthly report*
2012 March 28

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The Planetary Society

Tomas Svitek
Stellar Exploration

*Preliminary progress report:
much of this material is incomplete, and all figures subject to revision

NIAC funds status as of 2012/3/18: Obligated = $61.2K: Costed = $47.7K; Available = $37.8K

Some NIAC Task Events

2011 August

- Presented at *JPL Student CubeSat Symposium*.

2012 March

- *Lunar & Planetary Science Conference* Poster*, Diana Blaney, *et al.*, focus on Asteroid Mineral Mapping example mission.
- Participated in *Printable Spacecraft Mission-focused Workshop*.

April

- Presenting at *CubeSat Spring Workshop*, CalPoly San Luis Obispo

June

- Presenting at *First Interplanetary CubeSat Workshop* (initiated by Cornell & MIT)

~July

- NIAC Step 1 Final Report

September

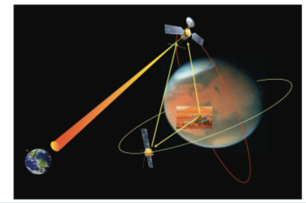
- AIAA Space 2012 Conference (abstract submitted, selection pending)

*D. L. Blaney, R. L. Staehle, B. Betts, L. Friedman, H. Hemmati, M. Lo, P. Mouroulis, P. Pingree, J. Puig-Sauri, .T Svítek, T. Wilson, and A. Williams, "Interplanetary CubeSats: Small, low cost missions beyond low Earth Orbit." Poster at *43rd Lunar and Planetary Science Conference*, (Abstract 1868), Houston, TX, March 2012.

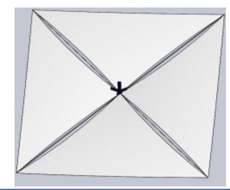
Getting to Interplanetary CubeSats

Six Technology Challenges

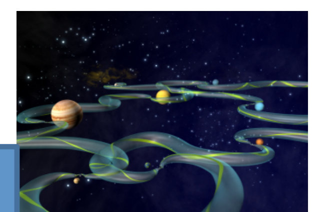
1. Interplanetary environment



2. Telecommunications

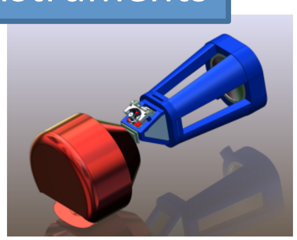


3. Propulsion (where needed)



4. Navigation

5.Instruments



6. Maximizing downlink info content

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*

Example Missions

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

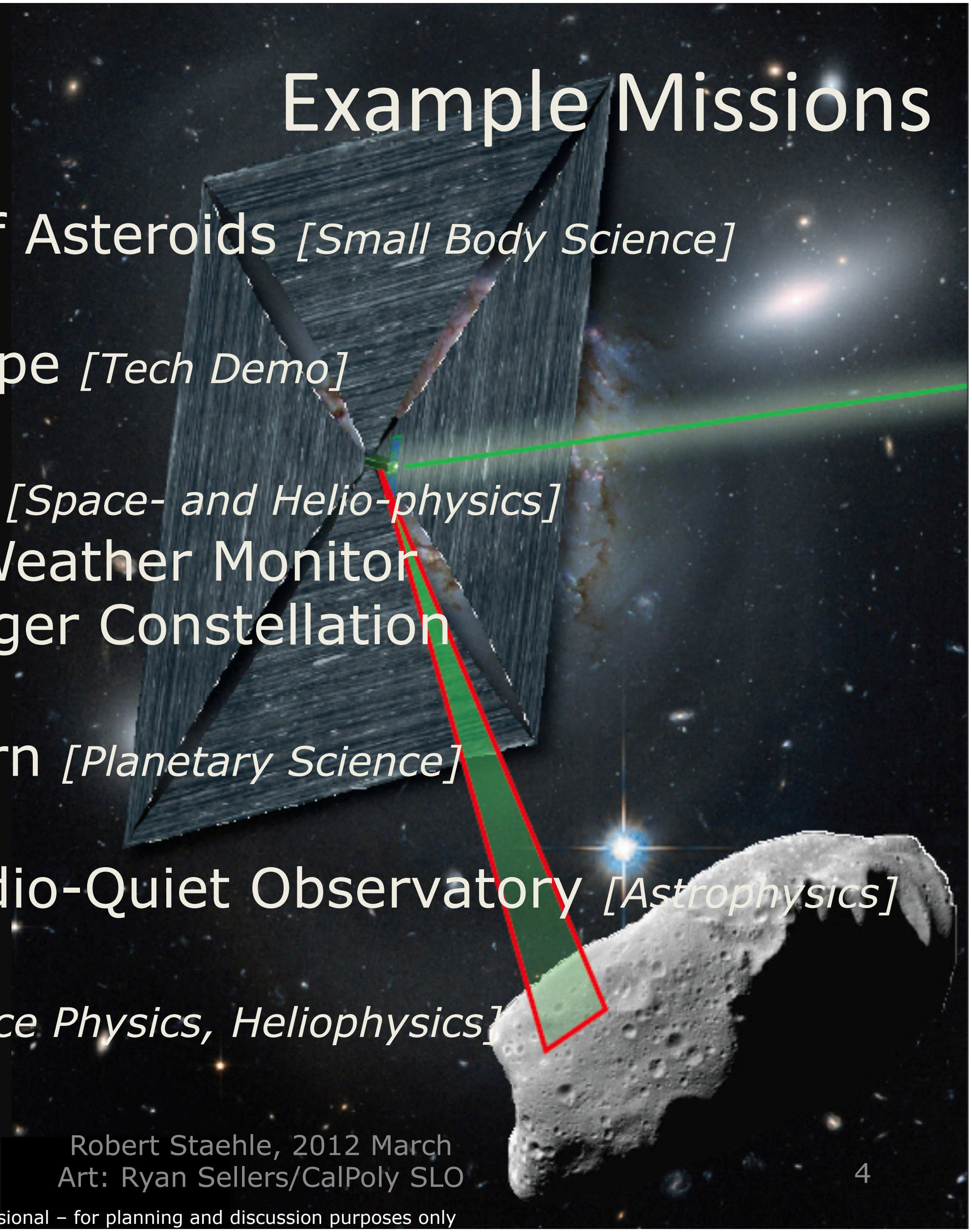
B. Solar System Escape *[Tech Demo]*

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]*

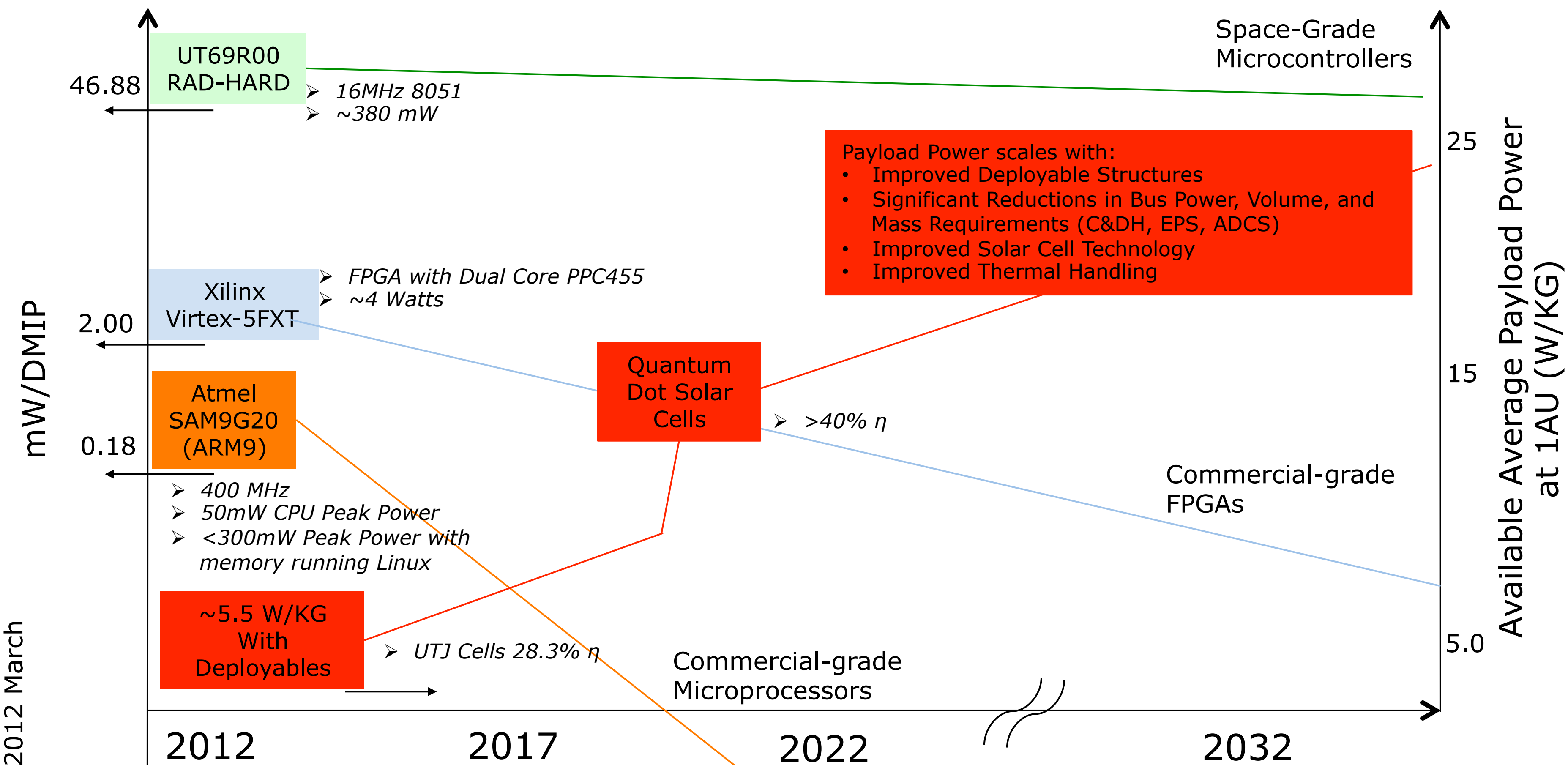
F. Out-of-Ecliptic *[Space Physics, Heliophysics]*



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

CubeSat Bus Power

(from partner CalPoly San Luis Obispo)



Austin Williams, 2012 March

RAD-HARD mW/DMIP won't scale appropriately

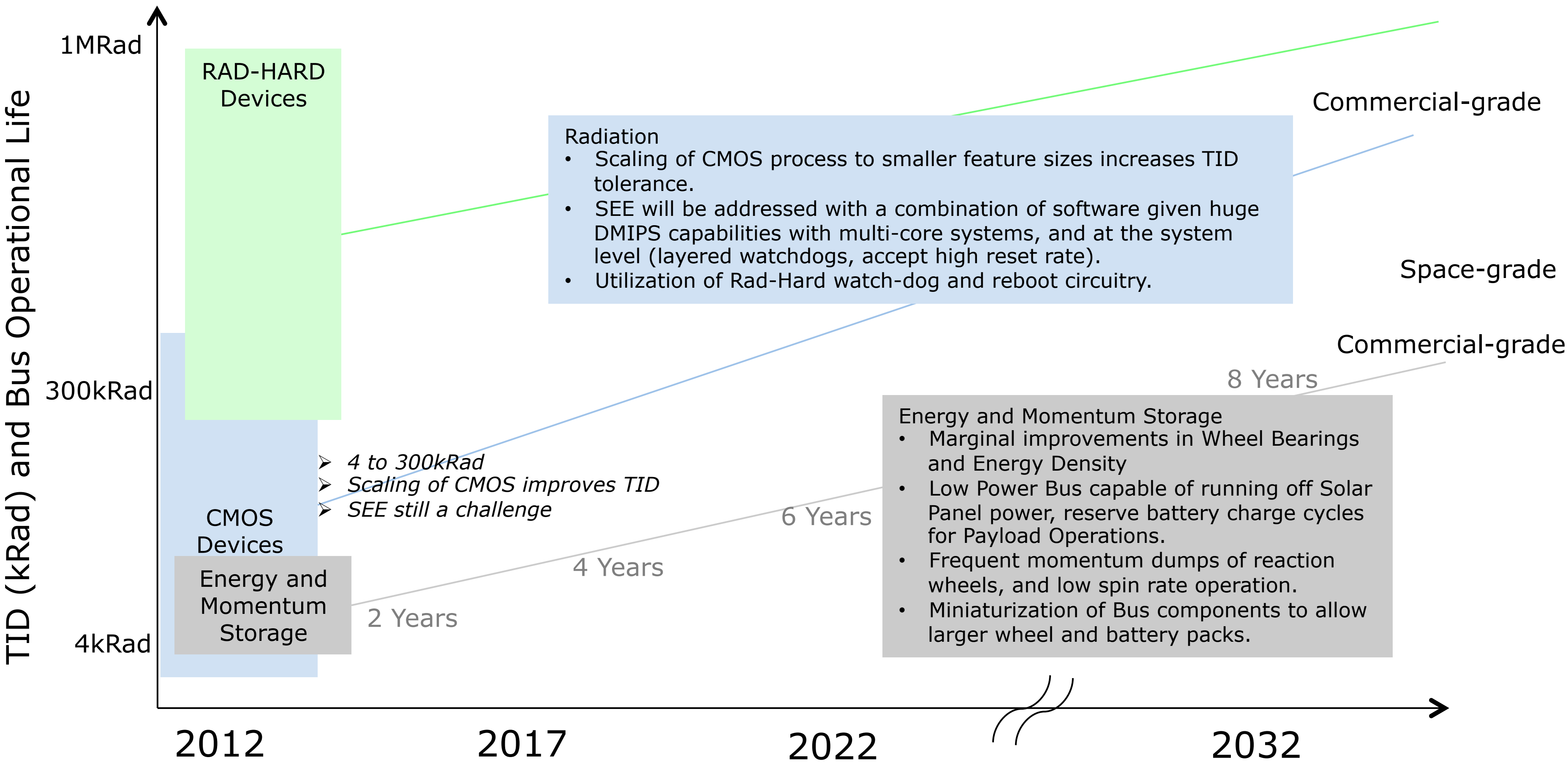
Xilinx W/DMIP will scale, but processing and FPGA capability is over-kill for Bus functionality.

ARM based processors (or it's competitors) will scale fastest in a mW/DMIP department, with aggressive power saving modes, and multi-core capabilities.

- Tyvak Intrepid SystemBoard developed at Cal Poly for LightSail-1 (The Planetary Society and Stellar Exploration)
- C&DH and EPS designed around the Atmel SAM9G20

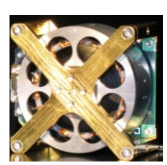
CubeSat Bus Longevity

(from partners CalPoly San Luis Obispo and JPL)



LG 18650 Li-Ion Cells
10.36Wh Each

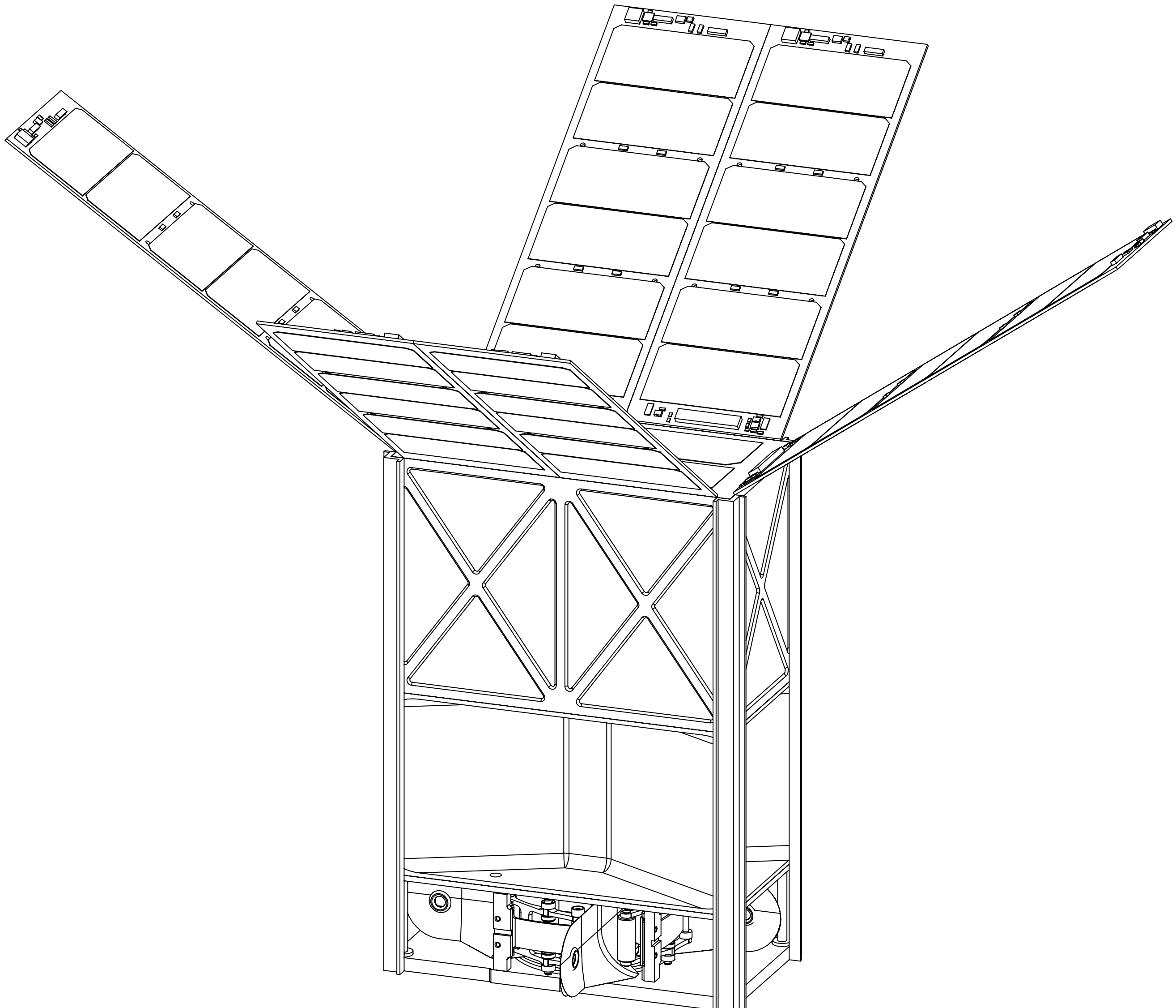
207.2 Wh/kg



Sinclair Interplanetary
60mNm-sec @ 6500 RPM

Austin Williams, 2012 March

One Preliminary Configuration

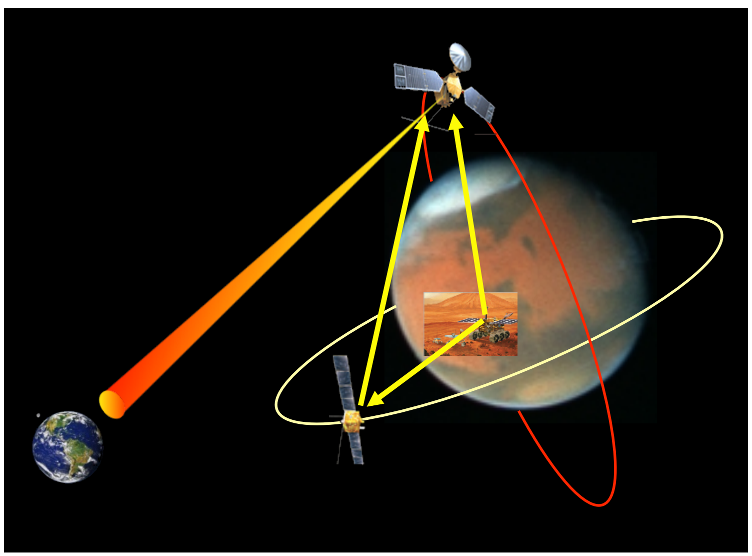


Tomas Svitek, 2012/3/17

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**

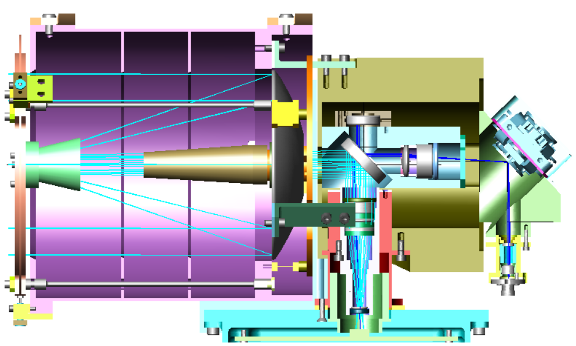
*Substantially higher data-rates may be achieved by using the LBT (11.8 m) telescope in Arizona

Hamid Hemmati, 2012 March

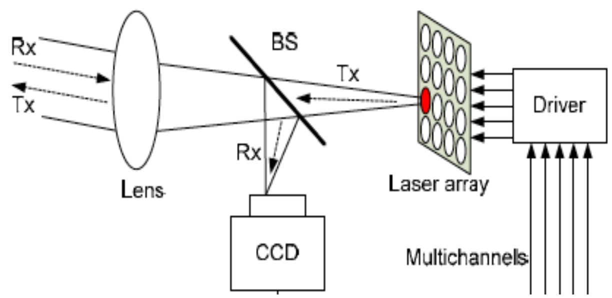
OPTICAL ASSEMBLY CONFIGURATION CONCEPTS

Several options are being traded:

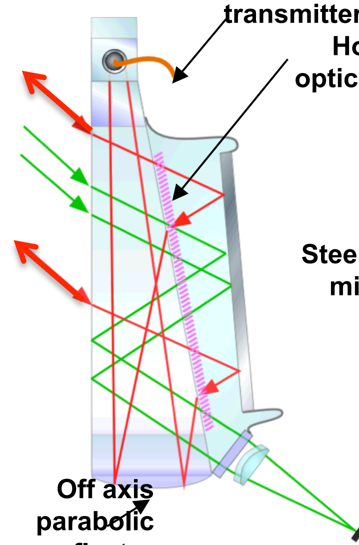
- **Conventional optical design, reduced in dimensions as much as possible**
  - Beam-pointing would be accomplished with the aid of a two-axis fast steering mirror
- **An array of laser transmitters and receivers behind a transmit/receive aperture**
  - Beam pointing would be accomplished by activating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



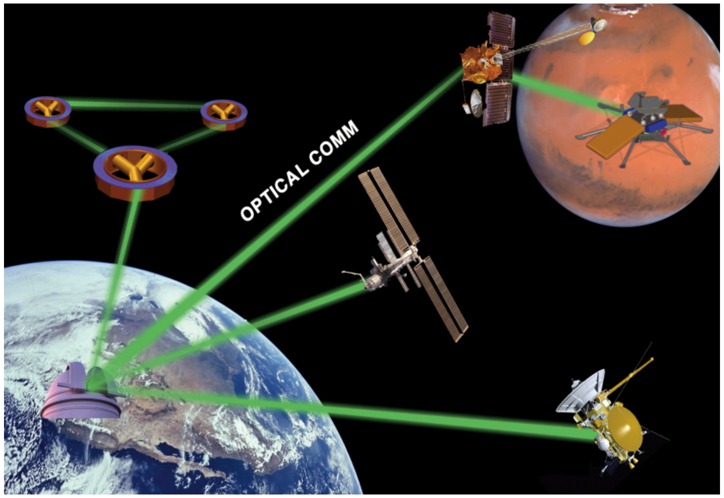
Laser array
transmission/reception
6-cm diameter aperture
(Ref.: Toyoshima et al,
www.intechopen.com/download/pdf/9003)



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

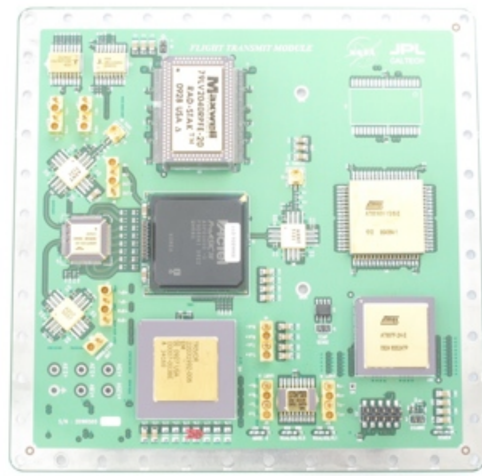
Beam Pointing Assembly Concept For Lasercom

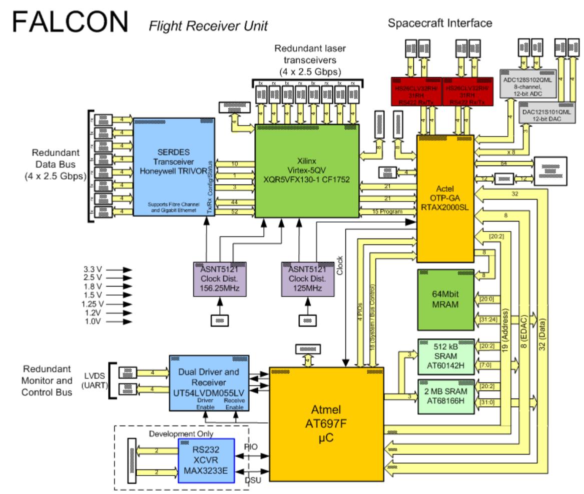
- **Assumed to be body-mounted**
  - No coarse pointing gimbal
  - Spacecraft would coarse point the terminal to about 3 to 9 mrad (for telecom, deep-space spacecraft typically point the RF antenna to <3 mrad) (9 mrad ~0.5°)
- **Incorporates a 1° (17.5 mrad) class field-of-view (FOV) camera** that could 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)



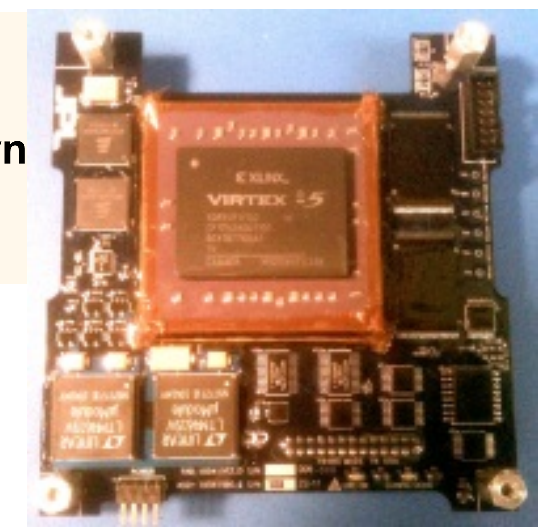
Electronics Concept for Lasercom

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



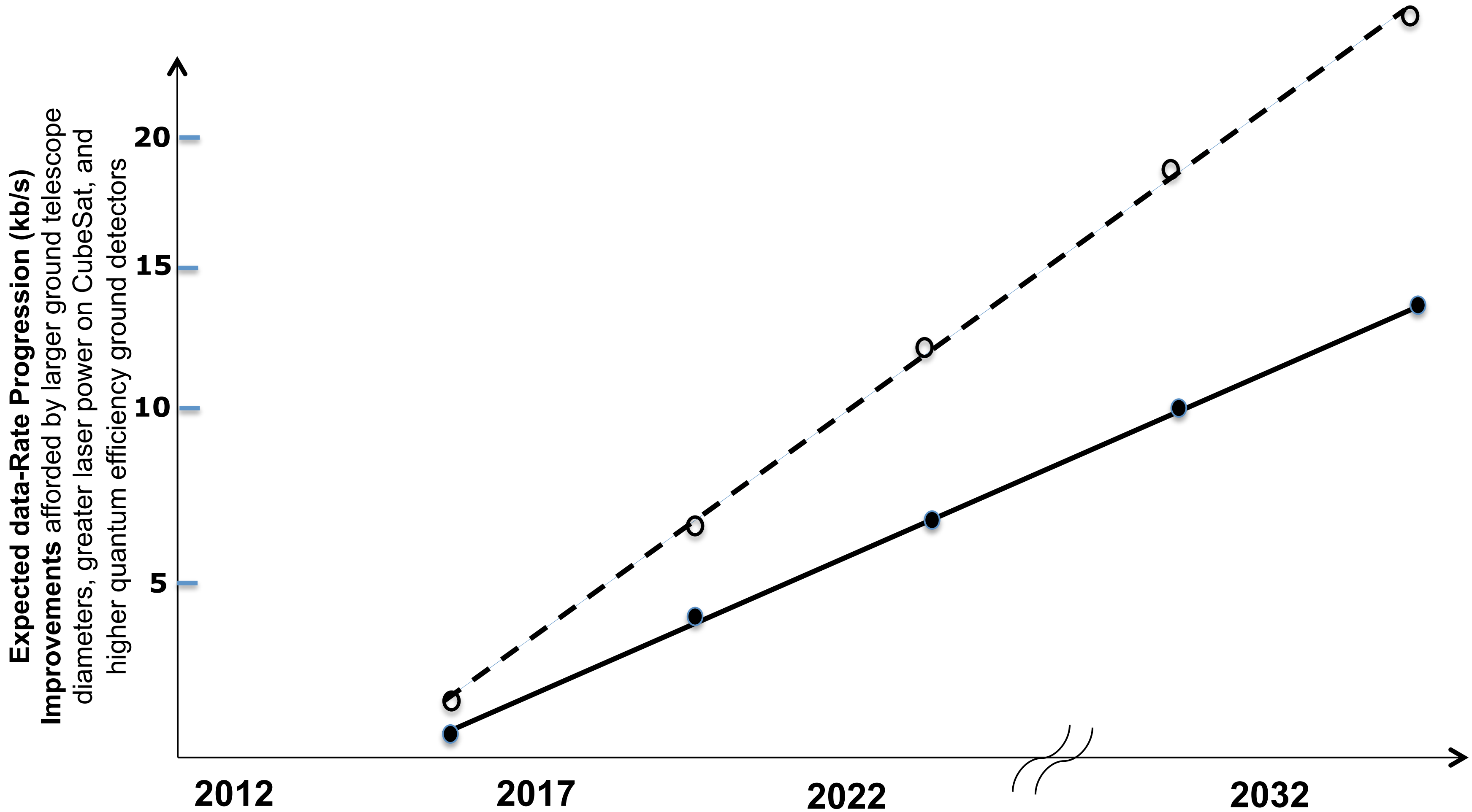


JPL-developed processor board developed and flown on CubeSat



Hamid Hemmati, 2012 March

Expected Lasercom Data Rate Progress with Time



Hamid Hemmati, 2012 March

Solar Sail (from partners Stellar Exploration & Planetary Society)

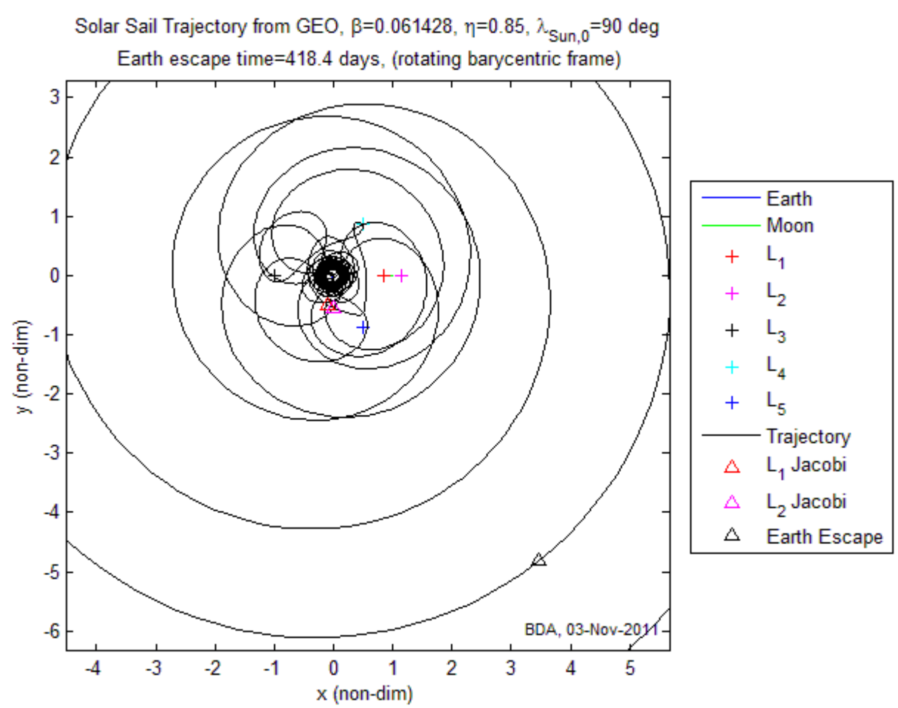
1 µg @1 AU ➔ theoretical ~300 m/sec/yr

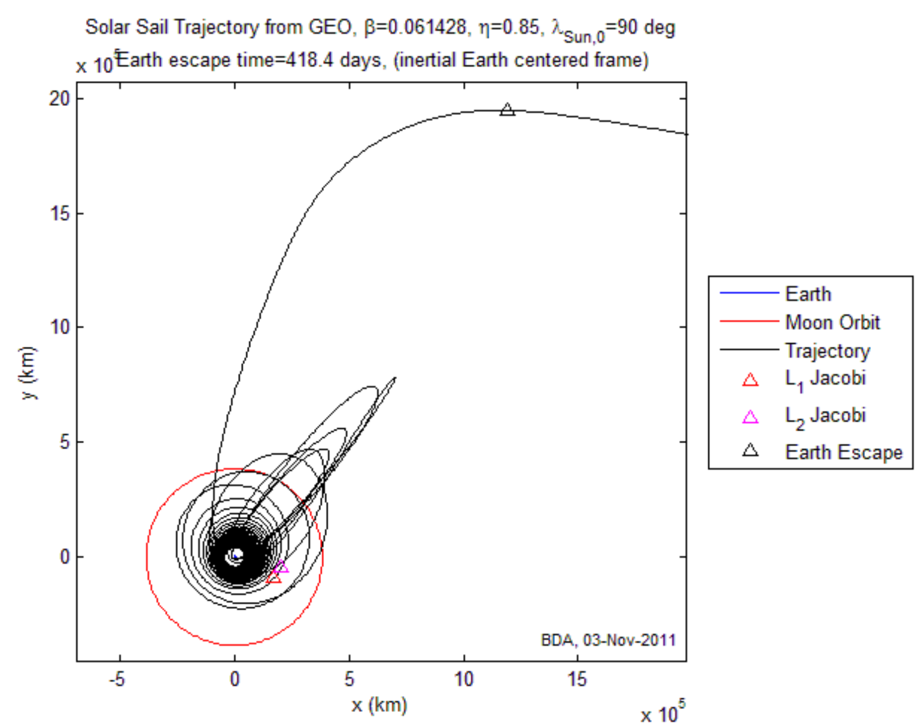
- Current technology
  - *Ikaros* (2010: 1 µg), *LightSail[tm] 1* (2013?: 6 µg),
  - Electrochromic surfaces for 2-axis control
  - Switch to Kapton[tm] from Mylar[tm] would yield multi-year life
- Next 5-10 years (2021: 20 µg)
  - Tip vanes would be configured to provide 3-axis electrochromic control without moving parts.
  - Material thickness decrease 2-3X would enable larger sail packed into limited CubeSat volume.
  - Advanced (more expensive) material booms would 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 would 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; <u>0.2 AU even better</u>)
  - Most spacecraft functions would be printed on inner part of sail.*

* As discussed at Kendra Short's 2012/3/19 Printable Spacecraft Workshop

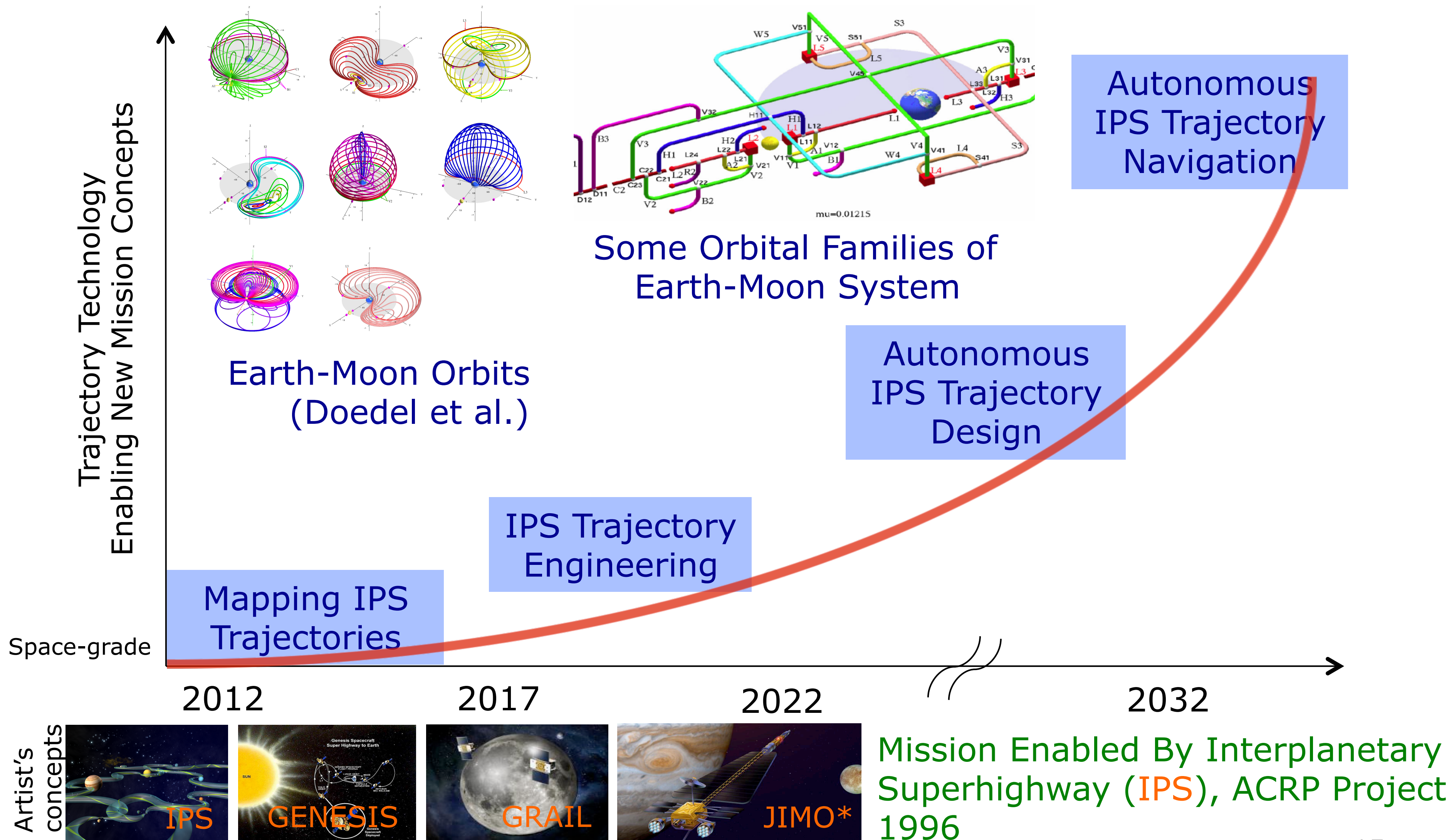
5/31/2011

Far Future Lightsail: Earth Escape, 20m/10kg, β=0.0614, T_{escape}=418 days





Interplanetary Superhighway Navigation



Martin Lo, 2012 March

All figures are Artists' Concepts – *JIMO was a proposed mission only.

Pre-decisional – for planning and discussion purposes only

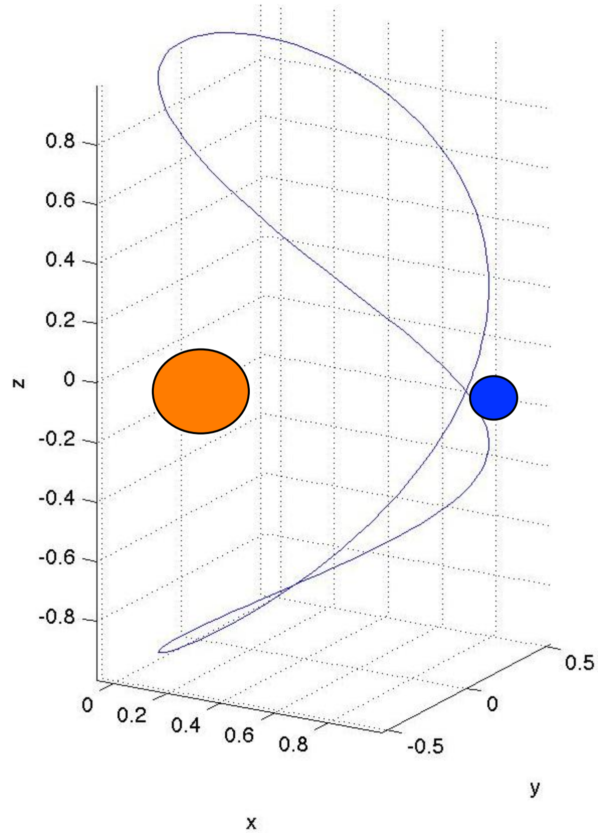
IPS Trajectory Technology Roadmap

- Mapping the Interplanetary Superhighway
  - Periodic Orbit Families
  - Invariant Manifolds & Connection Orbits
  - Low Energy Capture & Escape Orbits
  - For All Planets & Moons
- IPS Trajectory Engineering
  - Gluing Trajectory Segments from Maps
  - Optimize Glued Intermediate Trajectories
  - Move Orbits From Design to Operational Models
- Autonomous IPS Trajectory Design & Optimization
  - IPS Map On-Board for Autonomous Trajectory Generation
- Autonomous IPS Trajectory Navigation
  - On-Board OD, Error Analysis, Maneuver Design & Execution

"Vertical Orbits"* to Achieve Out-of-Ecliptic Perspective for Solar Mapping

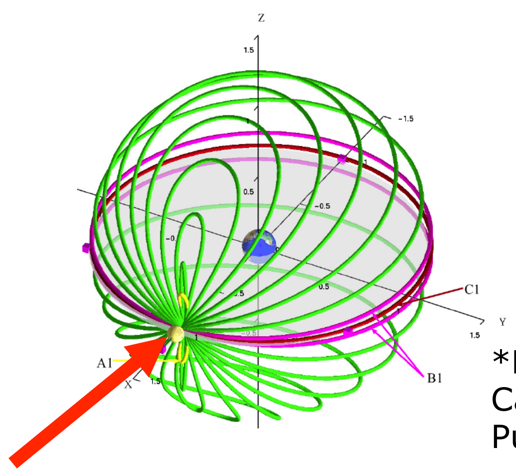
- Solar Polar Constellation Concept
  - Multiple CubeSats, Each would carry 1 or 2 Instruments.
  - Would use high inclination ~75° orbits

Would use Vertical Orbit Family (Out-of-Ecliptic) around Earth L1, exists at all inclinations



Earth-Sun Example ↖

Earth-Moon Example →



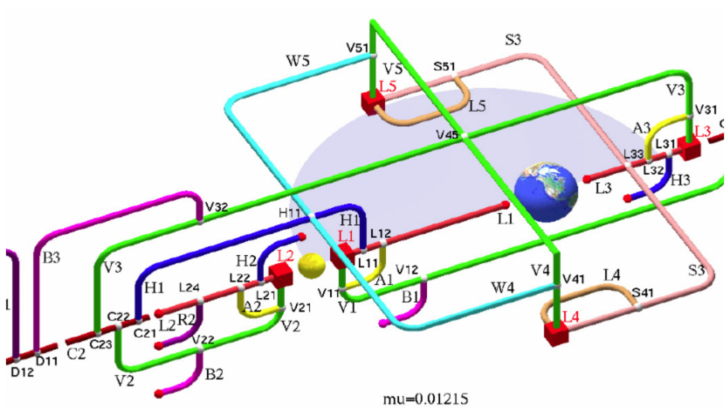
Moon

Martin Lo, , Rodney Anderson/JPL,
Channing Chow/USC, Benjamin Villac/UCI
2012 March

*Moulton, F. R., "Periodic Orbits", Carnegie Institution of Washington Publication, No. 161, Washington, 1920.

IPS Trajectory Technology Roadmap

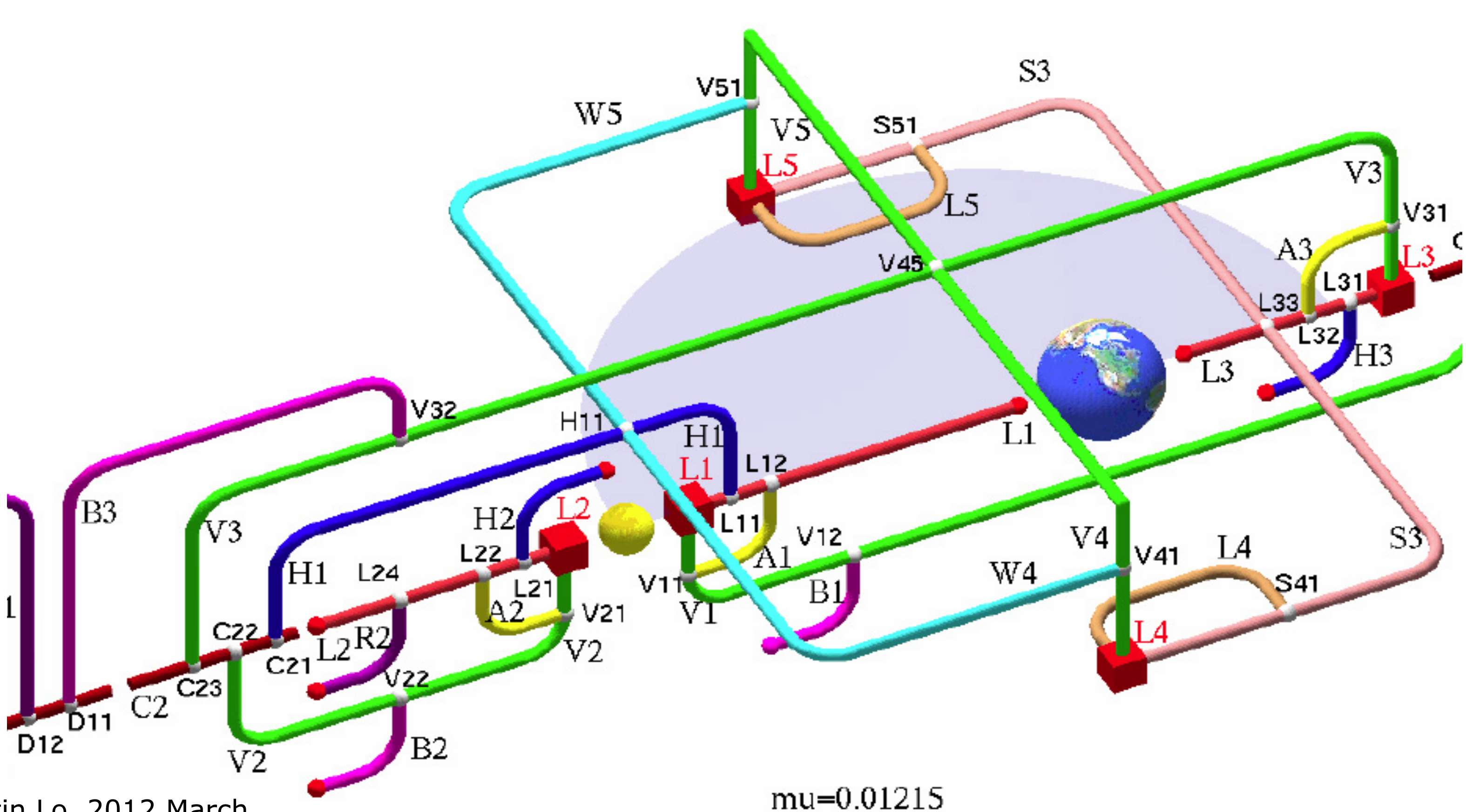
- Earth-Moon Example (Doedel et al.)
  - Orbit Families Around L1,L2,L3,L4,L5



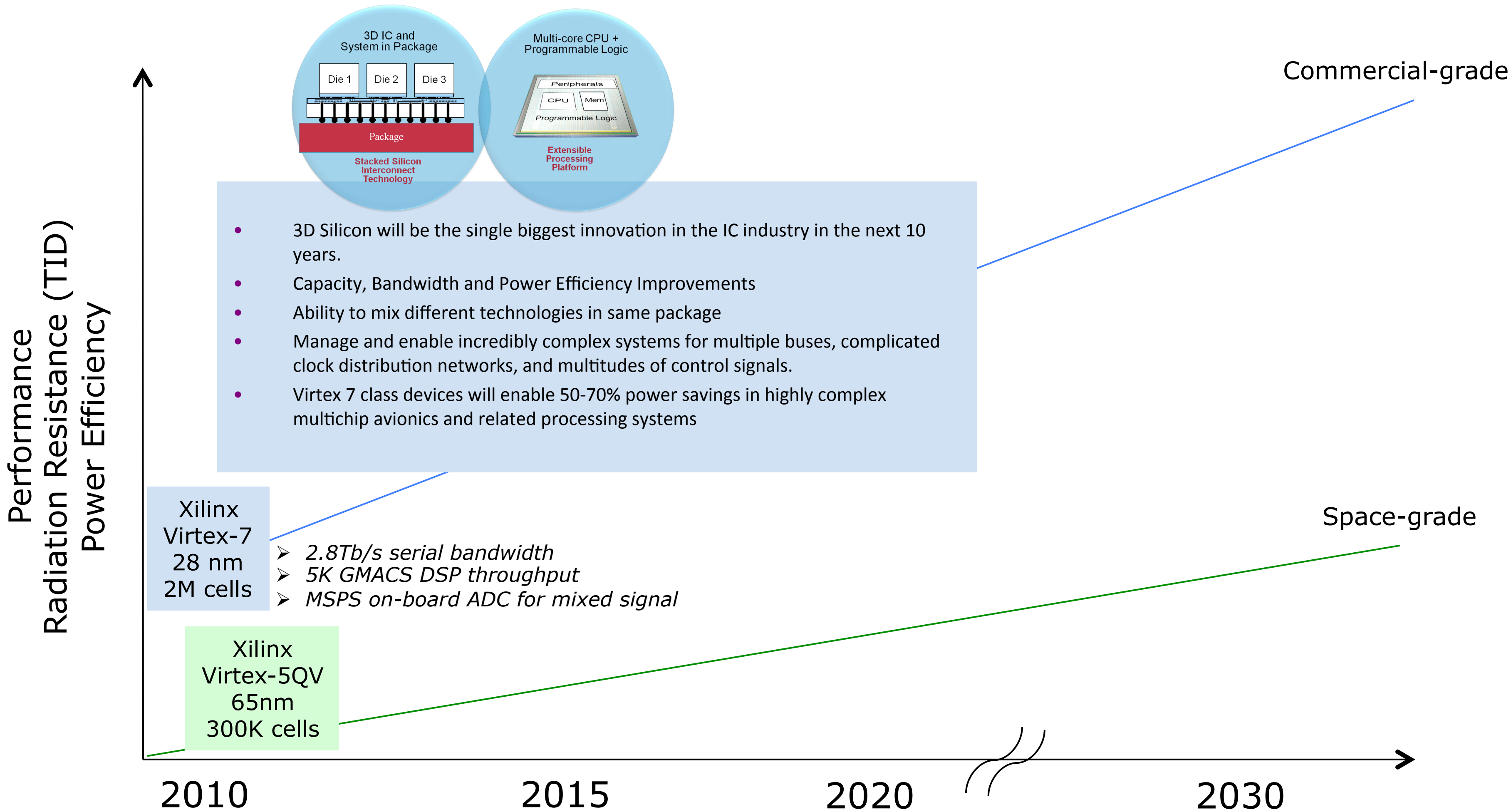
- Currently Only Halo Orbit Families Are Used
  - Only around Earth, Moon L1 and L2
- Many Identified Families Yet To Be Used
- Many Other Families Yet To Be Identified & Mapped
- Families for Other Planets and Moons To Be Mapped

Only Halo Orbits Have Been Used!

- Very Few Orbits Used To Date
  - Only Halo Orbits Have Been Used for Space Missions
  - The H1, H2 Blue Curves = Halo Orbit Families

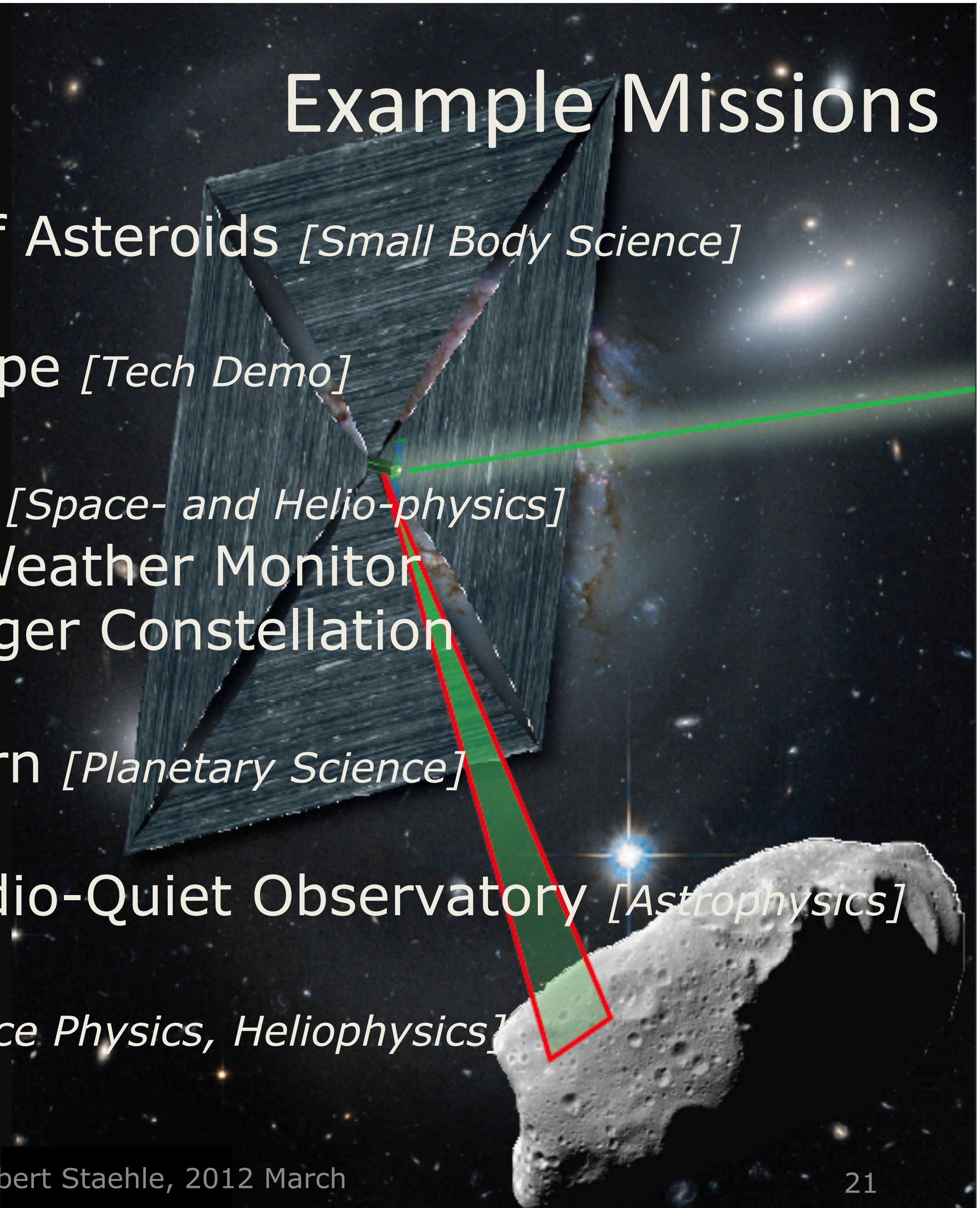


On-Board Data Processing



- COVE (CubeSat On-board processing Validation Experiment), V5QV tech demo
- JPL Payload on U. Michigan M-Cubed CubeSat
- Launched Oct. 28, 2011 as NPP Secondary Payload

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]*

Proposed Phobos Sample Return

Tomas Svitek, Robert Staehle, 2012 March

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.

Instrument details/enabling technology

- 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

Trajectory phases (all low thrust)

1) Would 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, rendez-vous, capture, spiral out of Mars orbit, to Earth.
7) Capture, retrieval near Earth-Moon L2 or tbd.

CubeSat bus details/other

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

Cost <$100M??; Readiness after 2020…

Radio Quiet Lunar CubeSat: RAQL*

Proposed Mission Overview

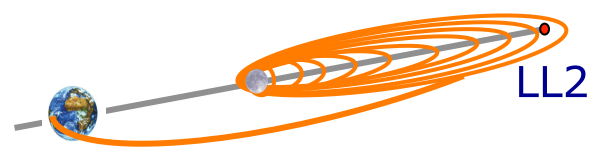
Assess radio quiet volume in shielded zone behind the Moon for future 21 cm cosmology missions.

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

- GTO/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

Solar Sail control and as radio antenna
Trajectory Technology

CubeSat Bus Details

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

Other Details

- Data Rate < 10 Mbps
- Onboard processing?

*Proposed Mission

Solar Polar Imager CubeSat Constellation*

Proposed Mission Overview

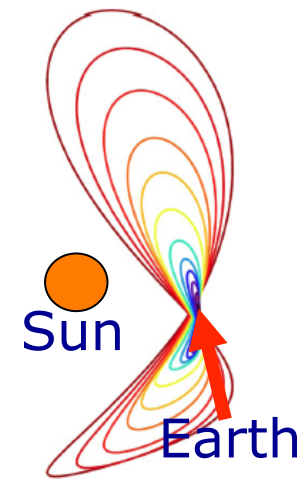
S/C in highly inclined ~75° Earth L_1, Out-of-Ecliptic Vertical Orbit, ~0.99 AU. Use solar sail to reach high inclination.

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

Vertical family of orbits at Earth L_1. Inclination ~75°. Reach by solar sail & Earth Moon flybys. Science would begin right after launch.
Near Future Lightsail: β=0.0154, 10m/10kg
Transfer: ~700 Days



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: Corograph

Enabling Technology

Solar Sail
Miniaturized Instruments
New Vertical Orbit Trajectory Technology

CubeSat Bus Details

6 CubeSat Constellation:

6U CubeSat Configuration (proposed):
1U for bus
2U for instruments
2U for solar sail
1U for optical communications

Paulett Llewer, Neil Murphy, Martin Lo, 2012 March

*Proposed Mission

Mineral Mapping of Asteroids*

Proposed Mission overview

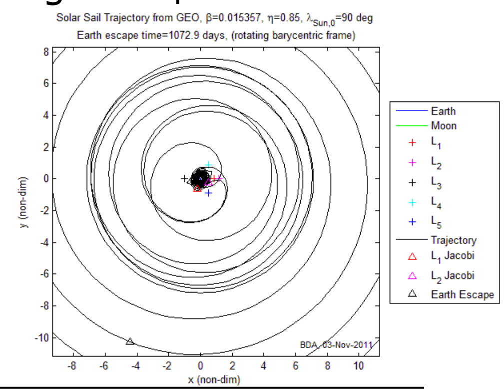
- 6U CubeSat launched on a GEO satellite or Mars-bound mission as a secondary payload.
- solar sail to reach near Earth asteroids.

Proposed Science objectives

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

Trajectory overview

- Use Moon, Mars & Earth flybys following Earth escape.
- Near Future Lightsail: Earth Escape, β=0.0154, 10m/10kg Tescape=1073 days.



Instrument details

- ~spatial IFOV of 0.5 mrad
- spatial sampling 0.5 m -10 m depending on the encounter range.
- imaging spectrometer, 0.4 – 1.7 µm, perhaps to 2.5 µm w/ HOT-BIRD detector and achievable cooling.

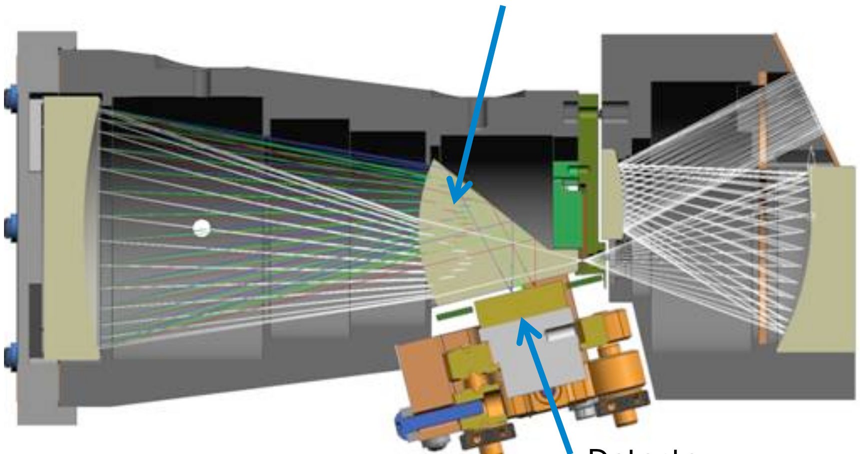
CubeSat bus

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

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 would extend our concept from the PRISM airborne spectrometer, due for tests in early 2012, and a fast, wide-field imaging spectrometer demonstrated as a laboratory breadboard through NASA's PIDDP33 program.

Instrument Electronics

- The detector would be similar to the one being flown on PRISM
- Data processing design is also based on a heritage design
- Consumes only ~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%

Preliminary Conclusions

- Interplanetary CubeSats would be able to 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 would be 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 would yield a broad and rapid increase in the community of institutions having the capability to perform affordable, independent science investigations from 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.