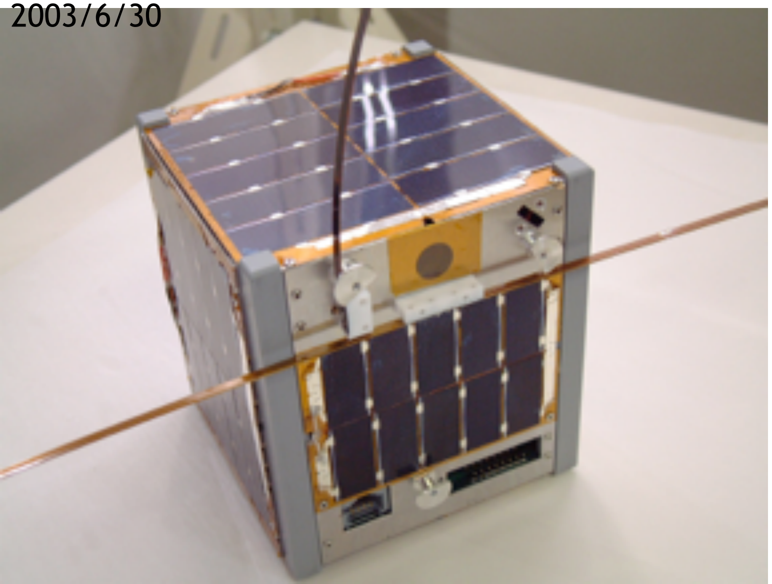
Jet Propulsion Laboratory
California Institute of Technology

Leaping CubeSats!
Enabling Beyond-Earth Missions in Small, Inexpensive Packages

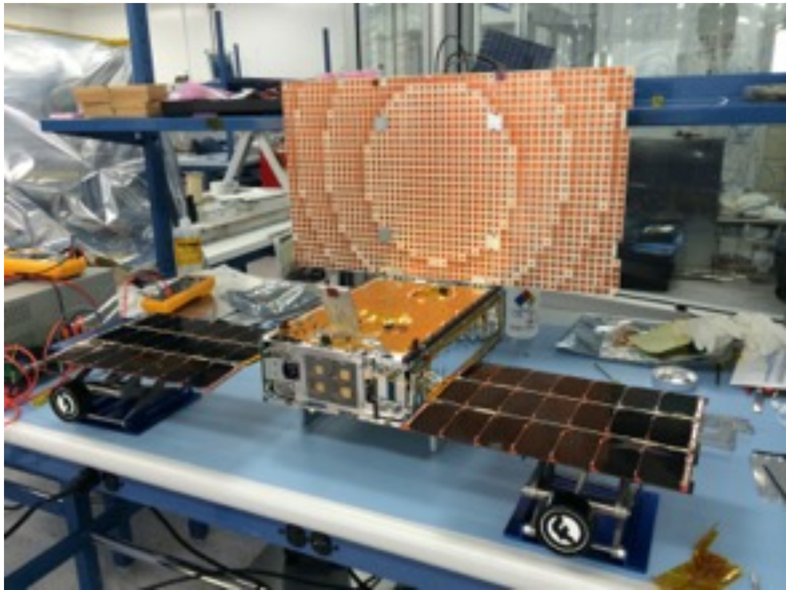
CubeSat Developers Spring Workshop; CalPoly-San Luis Obispo
2016 April 21
Robert L. Staehle, Instruments Division

XI-IV “sai-four”/Univ. of Tokyo, launched 2003/6/30



http://www.space.t.u-tokyo.ac.jp/cubesat/news/img/011231l.jpg

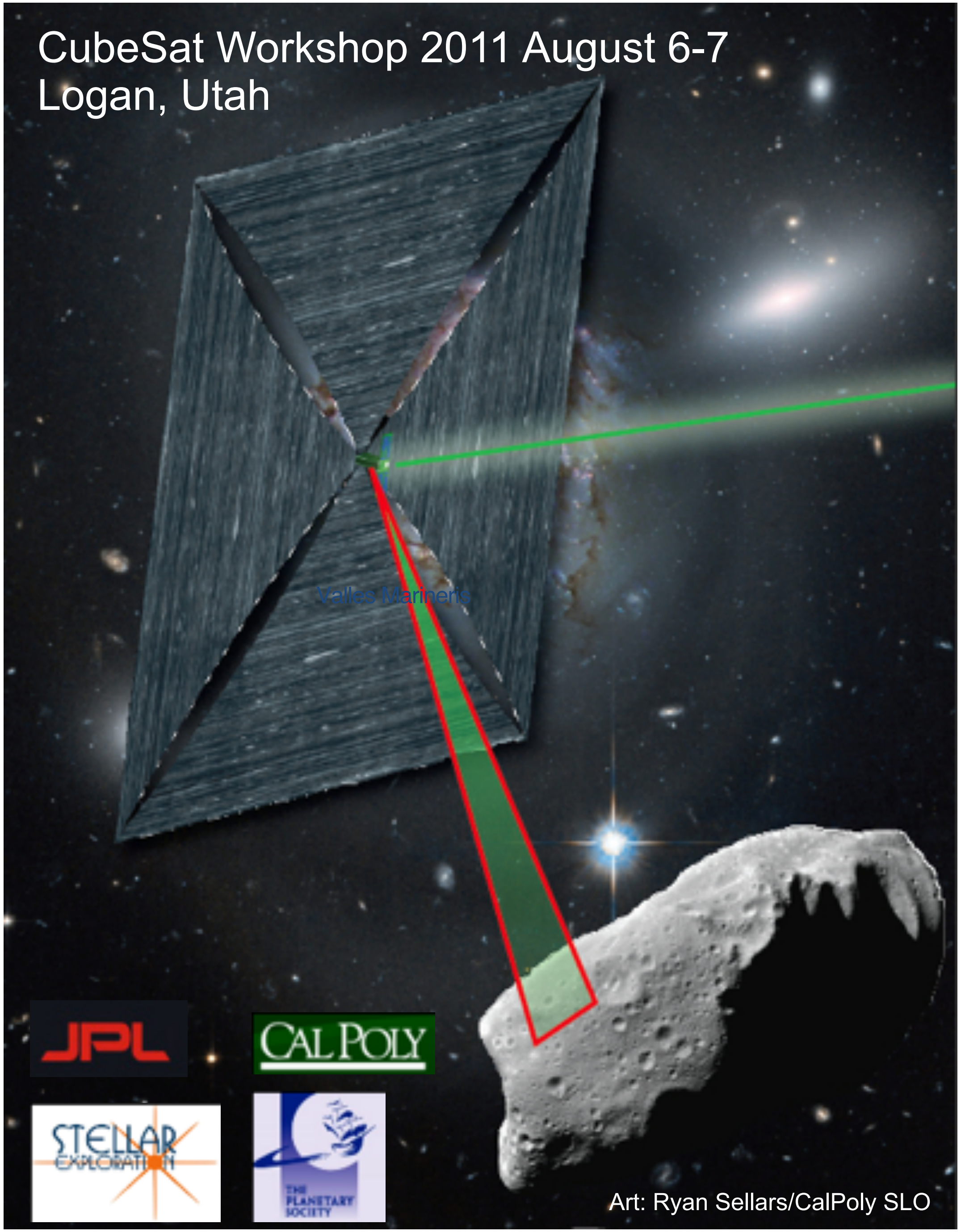
MarCO/JPL, 2015/12/6



Starting Small: moving out into the Solar System

1999	CubeSats conceived
2003	First CubeSats in orbit (Wikipedia definition)
2010./11	GAINSTAM Workshop
2010 end	70 total CubeSats launched to date (modified St. Louis Univ. count*)
2010./4, 9	NIAC proposal submitted, funded
2011./7	Interplanetary CubeSat capabilities briefed to AES/HEOMD
2012/9	NIAC Interplanetary CubeSat report
2012/11	*INSPIRE* funded
2013/9	HEOMD funds *BioSentinel*, *Lunar Flashlight*, *Near-Earth Asteroid Scout*
2014/6	*INSPIRE* complete, stored for launch
2015/12	*MarCO* complete
2015 end	428 total CubeSats launched to date (modified St. Louis Univ. count*)

Acronyms:
GAINSTAM = Government and Industry Nano-Satellite Technology and Mission, hosted at Boeing, Huntington Beach 2010/11/3.
NIAC = NASA Innovative Advanced Concepts
INSPIRE = Interplanetary NanoSpacecraft Pathfinder In a Relevant Environment
HEOMD = Human Exploration & Operations Mission Directorate (NASA HQ)
MarCO = Mars CubeSat One
*excludes 7 “CubeSats” launched before 2003, from https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database



CubeSat Workshop 2011 August 6-7
Logan, Utah

Art: Ryan Sellars/CalPoly SLO

Interplanetary CubeSats: Opening the Solar System to a Broad Community at Lower Cost

Robert Staehle*
Diana Blaney
Hamid Hemmati
Martin Lo
Pantazis Mouroulis
Paula J. Pingree
Thor Wilson
Jet Propulsion Laboratory/
California Institute of Technology

Jordi Puig-Suari
Austin Williams
CalPoly San Luis Obispo

Bruce Betts
Louis Friedman
The Planetary Society

Tomas Svitek
Stellar Exploration

**robert.l.staehle@jpl.nasa.gov*
+1 818 354-1176
MS 306-416
4800 Oak Grove Drive
Pasadena, California 91109 USA

?How does it fit?

6U Total (10 X 20 X 30 cm) ^

2U Miniature Imaging Spectrometer
visible/near-IR, $\Delta\lambda$= 10 nm
based on instruments currently being built at JPL

2U Solar sail: >6 X 6 m square → 5 m/sec/day @ 1 AU solar distance
based on Planetary Society/Stellar Exploration LightSail 1

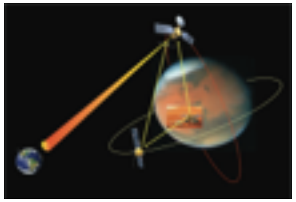
1U Optical telecom flight terminal: 1 kbps @ 2 AU Earth-s/c distance
NIR transmitting to existing facility
based on JPL Laser Telecommunications development

1U Satellite housekeeping
(C&DH, power, attitude determination & stabilization)
based on CalPoly CP7 and JPL/Univ of Michigan COVE

Getting to terplanetary CubeSats

Six Technology Challenges

1. Interplanetary environment

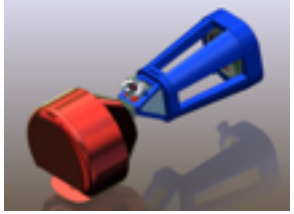


2. Telecommunications

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

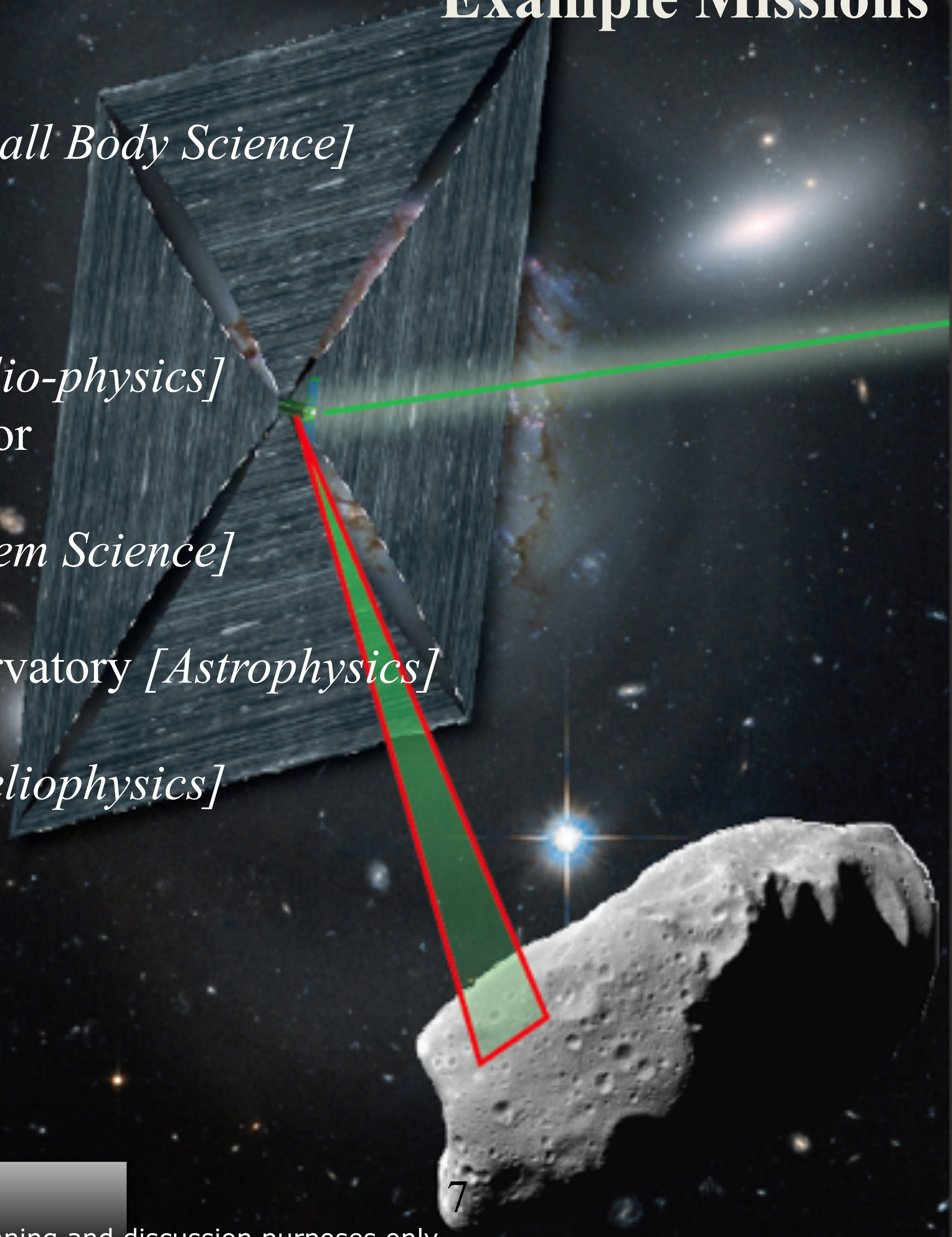
  1 – 10 km/sec/yr
  - *Electric*
  - *Solar Sail*

NIAC Results (our forecast)…

"Investigation during our Phase 1 work has demonstrated the feasibility of a new class of missions that can open Solar System exploration to a broader community of participants at lower cost. Looking ahead to the 2020s, the work proposed here will enable missions that depart Earth's vicinity several times a year—at one-tenth the cost of current Discovery missions—to a variety of destinations with focused goals of small body science, lunar and planetary investigations, space physics, heliophysics, and technology development. Interplanetary CubeSat missions will be mounted by NASA Centers, well-equipped universities, and small businesses in ways that were simply unattainable when mission costs were measured in multiples of $100M."

- New architecture → new mission class → broader community involvement
- Missions leave Earth a few times a year
- Focused objectives (<<Discovery) at < Discovery cost ÷ 10
- Variety of beyond-Earth destinations
  - Small body science
  - Lunar & planetary
  - Space- & Heliophysics
  - Technology development

Example Missions



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

B. Solar System Escape *[Tech Demo]*

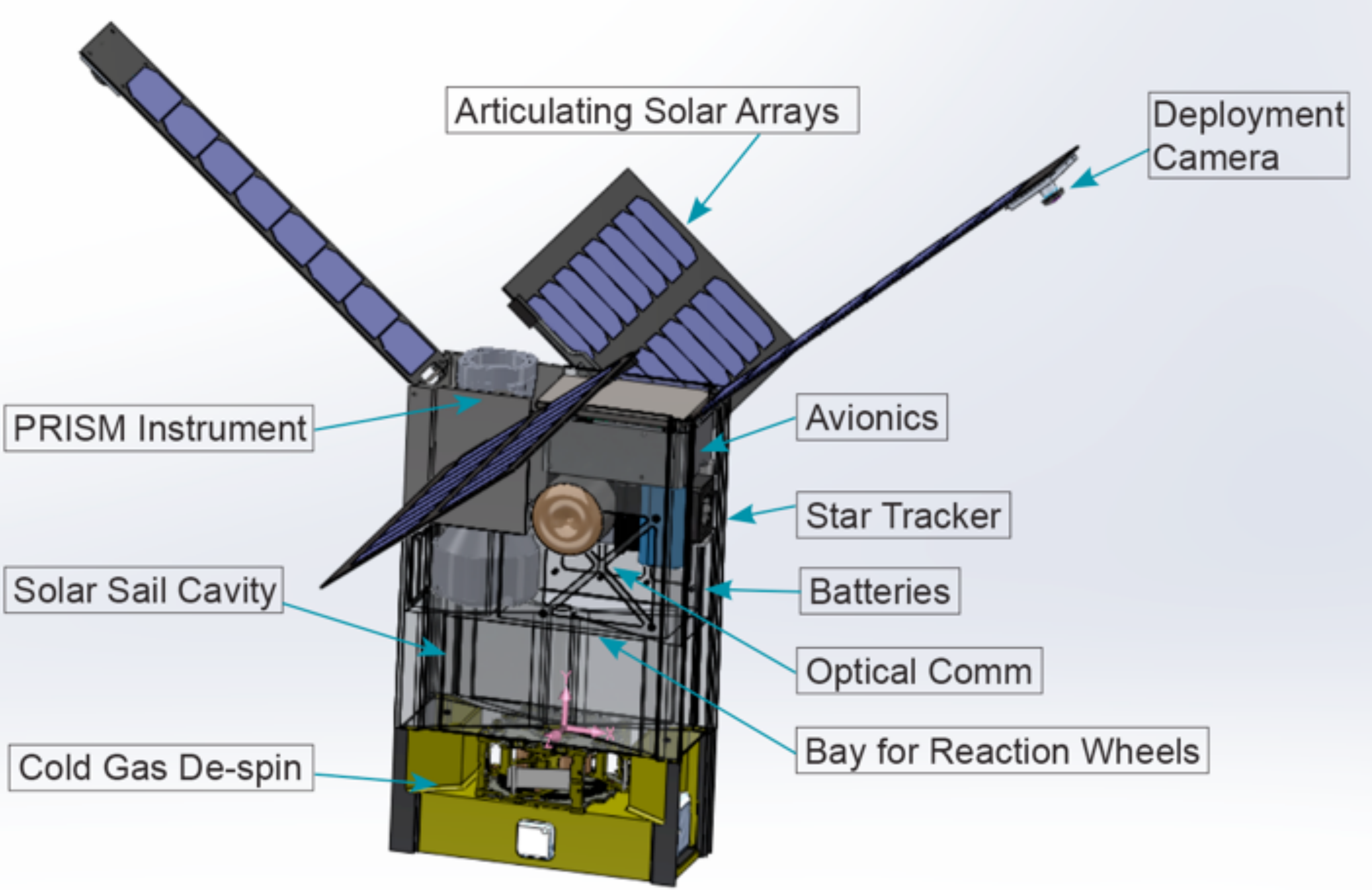
C. Earth-Sun System *[Space- and Helio-physics]*
e.g., Sub-L1 Space Weather Monitor

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

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

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

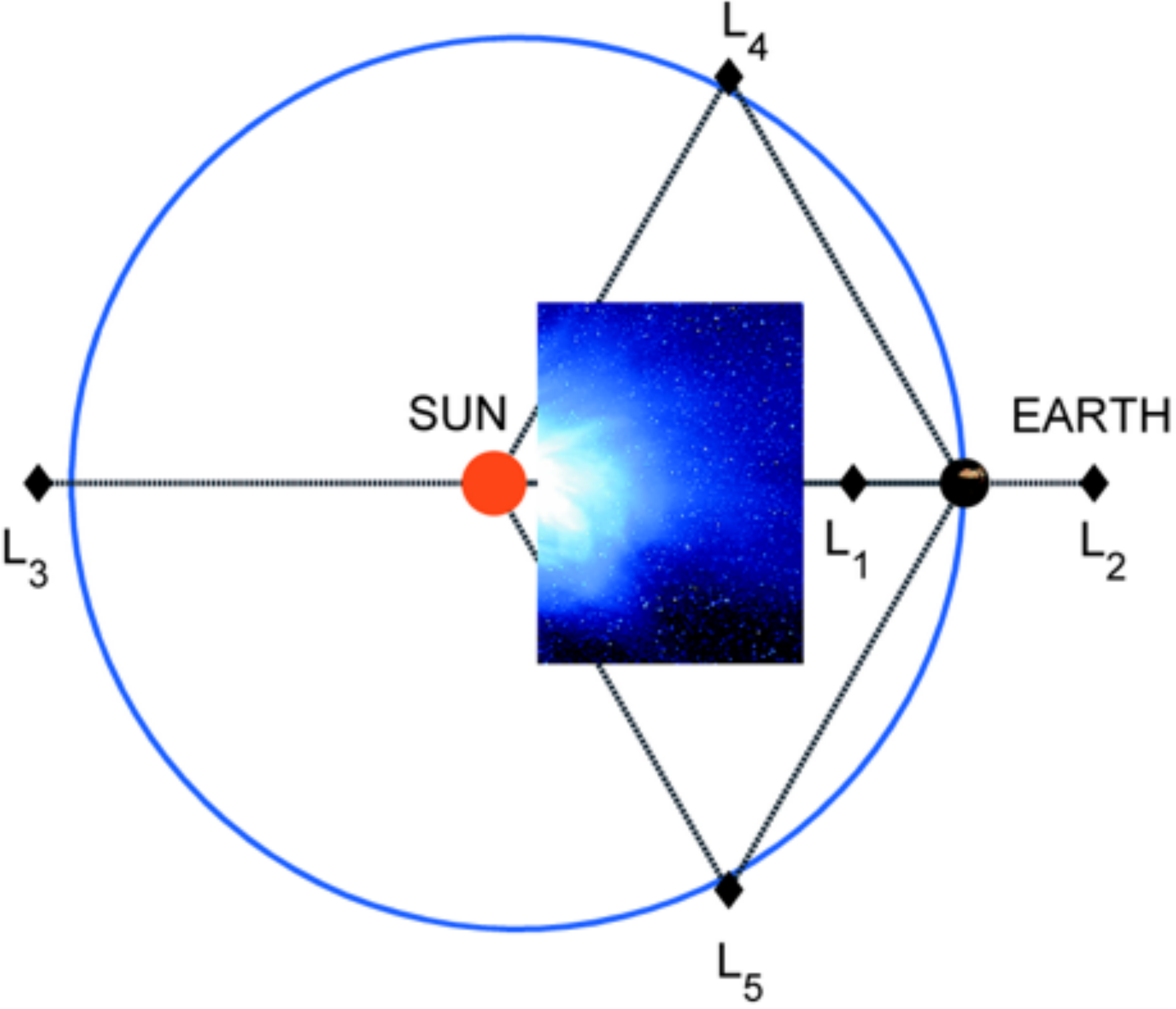
2012 Concept looks crude today…



From: Robert L. Staehle, Brian Anderson, Bruce Betts, Diana Blaney, Channing Chow, Louis Friedman, Hamid Hemmati, Dayton Jones, Andrew Klesh, Paulett Liewer, Joseph Lazio, Martin Wen-Yu Lo, Pantazis Mouroulis, Neil Murphy, Paula J. Pingree, Jordi Puig-Suari, Tomas Svitek, Austin Williams, Thor Wilson, “Interplanetary CubeSat Architecture and Missions”, *AIAA Space2012*, Pasadena, CA 2012 September 12

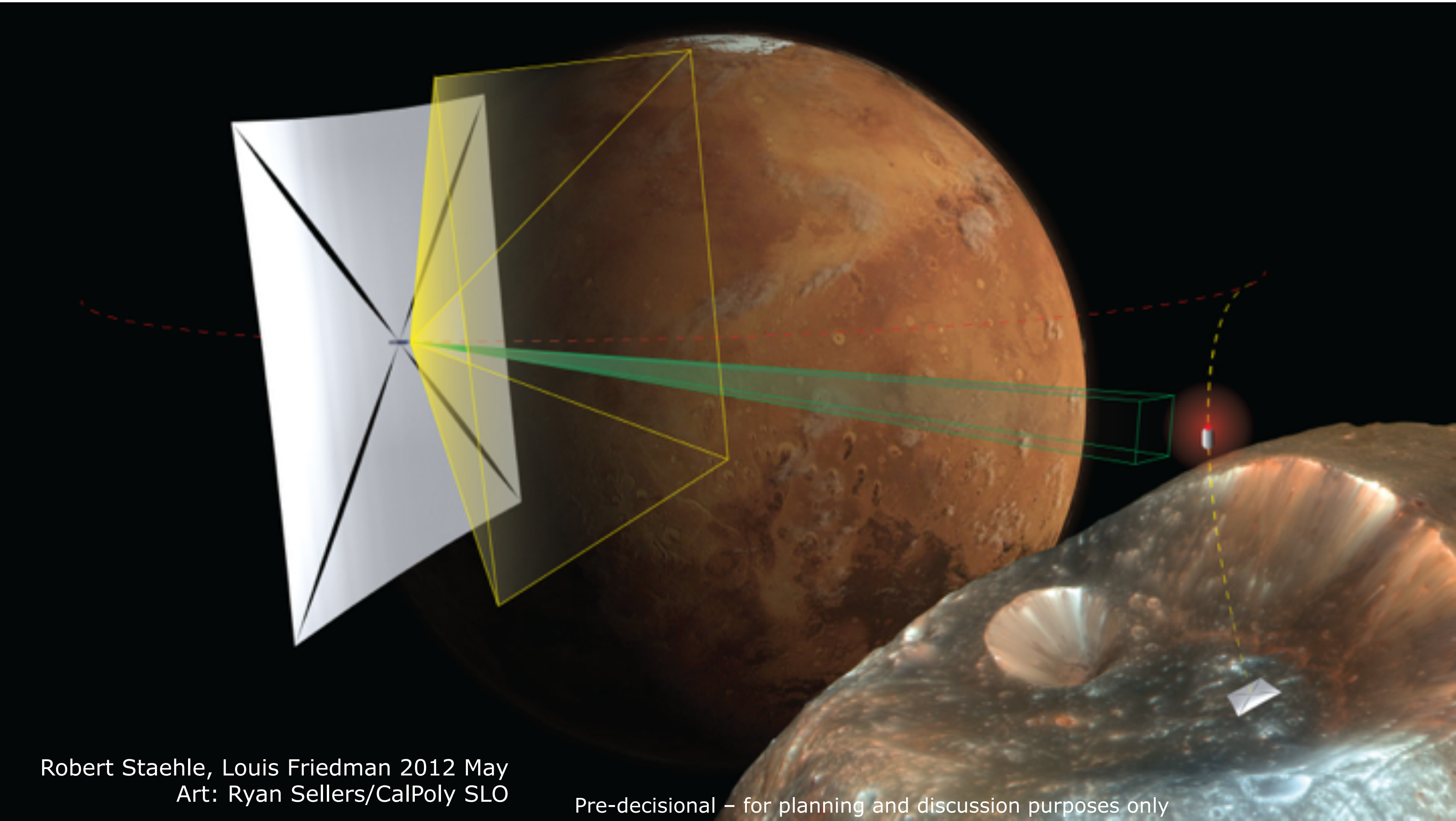
A Fractionated Space Weather Base at L_5 Using Solar Sails and CubeSats

Concept originated at *Small Satellites: A Revolution in Space Science* Workshop, 2012 July & October, Sponsored by Keck Institute of Space Studies (KISS) at Caltech, Pasadena, California.



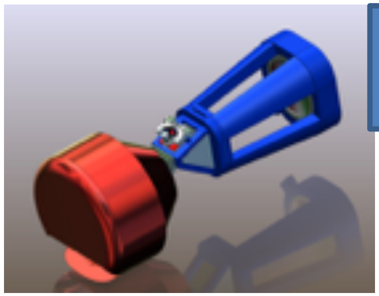
From: Paulett C. Liewer, Brian D. Anderson, Vassilis Angelopoulos, Manan Arya, James W. Cutler, Andrew T. Klesh, E. Glenn Lightsey, Martin W. Lo, Neil Murphy, Sergio Pellegrino, Robert L. Staehle and Angelos Vourlidas, "A Fractionated Space Weather Base at L_5 Using Solar Sails and CubeSats," Poster for American Astronomical Soc. *44th Solar Physics Division Meeting*, Bozeman, Montana, 2013 July 8-11

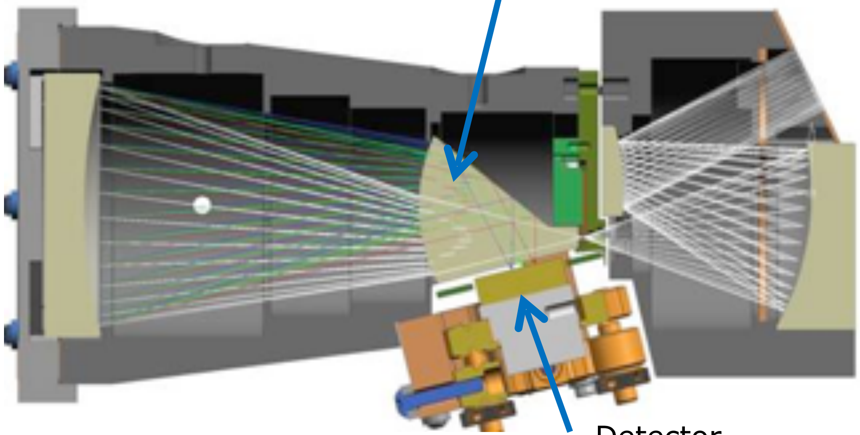
Far-out concept:
Can two Interplanetary CubeSats retrieve a sample from Phobos or Deimos?



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

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

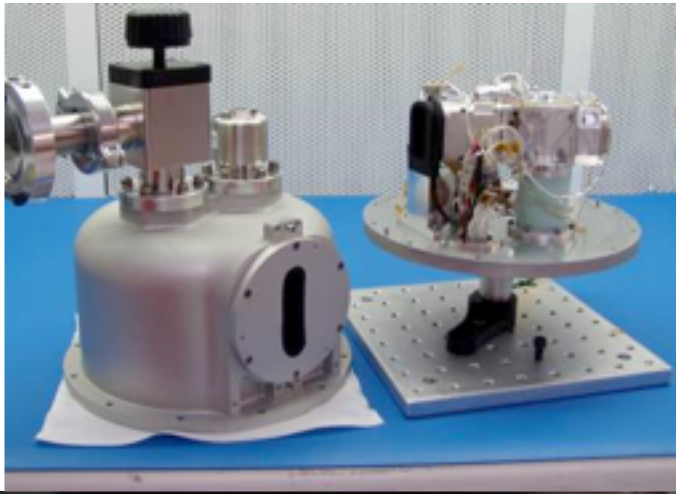
- Detector similar to the one flown on PRISM (Portable Remote Imaging Spectrometer)
- Data processing based on a heritage design
- Consumes ~1W of average power
- Detector interface and data storage would be a new design feature

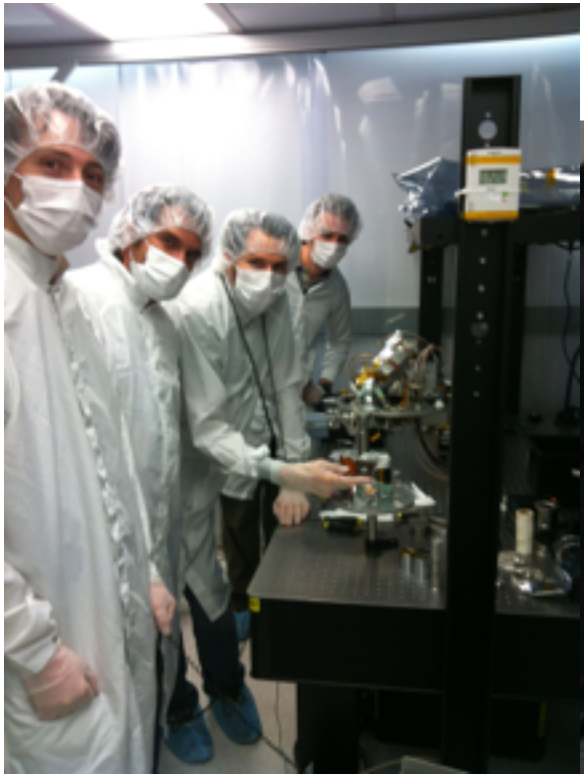
Parameter	Value
Wavelength Range	450-1650 nm
Wavelength Sampling	10 nm
Detector Type	Thinned InGaAs array
Pixel Pitch	25 μm typ.
Angular Resolution	0.5 mrad
Field of View	14°
Detector Operating Temp	270 K
Response Uniformity	'95%

Pantazis Mouroulis 2011

Among the instruments that have come to or are approaching fruition at CubeSat size…

- Imaging spectrometer (shown; Blaney, Mouroulis, et al.)
- Magnetometer
- Microwave radiometer
- Radar
- pick your favorite…





D. L. Blaney, P. Mouroulis, B. Van Gorp R. Green, J. Rodriguez, G. Sellar, B. Van Gorp, and D. Wilson., "The Ultra Compact Imaging Spectrometer (UCIS)," *International Workshop on Instrumentation for Planetary Missions* (2012), Presentation 1105.pdf

Design Overview

CubeSat Overview:

Volume: 3U (10x10x30cm)

Mass: 4.05 kg

Power Generation:

3 Axis Stabilized: 21 W

Tumbling: 13.7 W

Data Rate: 62-260000 bps

Software:

Developed in-house (protos)

I&T:

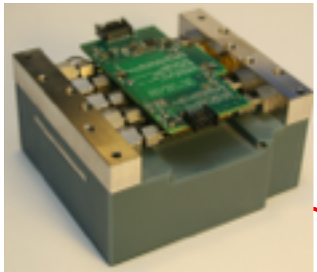
In-house S/C I&T, external environmental testing, NASA CLI P-Pod/Launch Integration

Operations:

Primary: DSN

Secondary (Receive only): DSS-28 (GAVRT), & Secondary Stations, ex: Peach Mountain

S/C components provide *the basis for future high-capability, lower-cost-risk missions* beyond Earth expanding and *provide NASA leadership in an emergent domain*



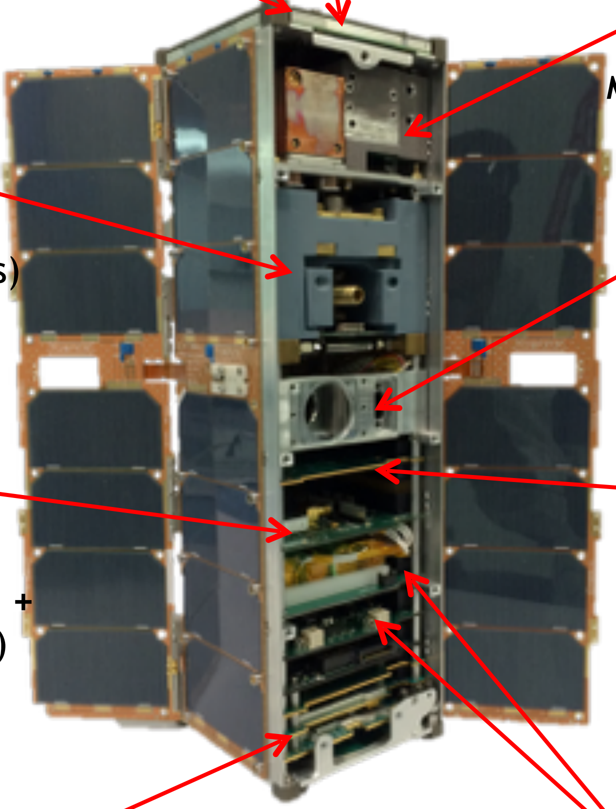
Cold-Gas ACS (U. Texas)

C&DH + Watchdog Board + Lithium UHF (AstroDev)

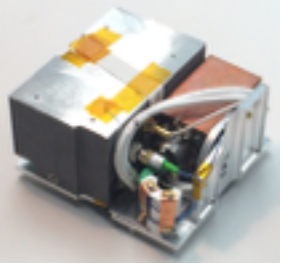
Nav/Comm X-Band Radio (JPL)

UHF Antenna (ISIS)

X-Band Patch Antennas (JPL) [two sets]



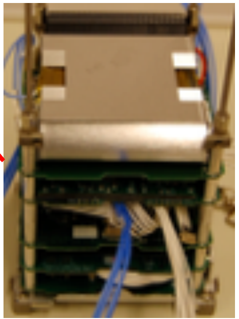
Deployable Solar Panels + Structure (Pumpkin)



Magnetometer (JPL/ UCL

Star Tracker (Blue Canyon)

Processing Board (CalPoly / Tyvak)



Electrical Power System + Battery Board (U. Michigan

Interplanetary NanoSpacecraft
Pathfinder In a Relevant Environment

INSPIRE Flight Spacecraft Completed On-Cost / On-Schedule

from: Andrew Klesh, Lauren Halatek, et al., INSPIRE: *Interplanetary NanoSpacecraft Pathfinder In a Relevant Environment*, International Astronautical Congress, Toronto, Canada 2014 October.

Multiplying Mars Lander Opportunities with MARS$_{\text{DROP}}$ Microlander

2015 June 11

IAA Low Cost Planetary Missions Conference
Berlin, Germany

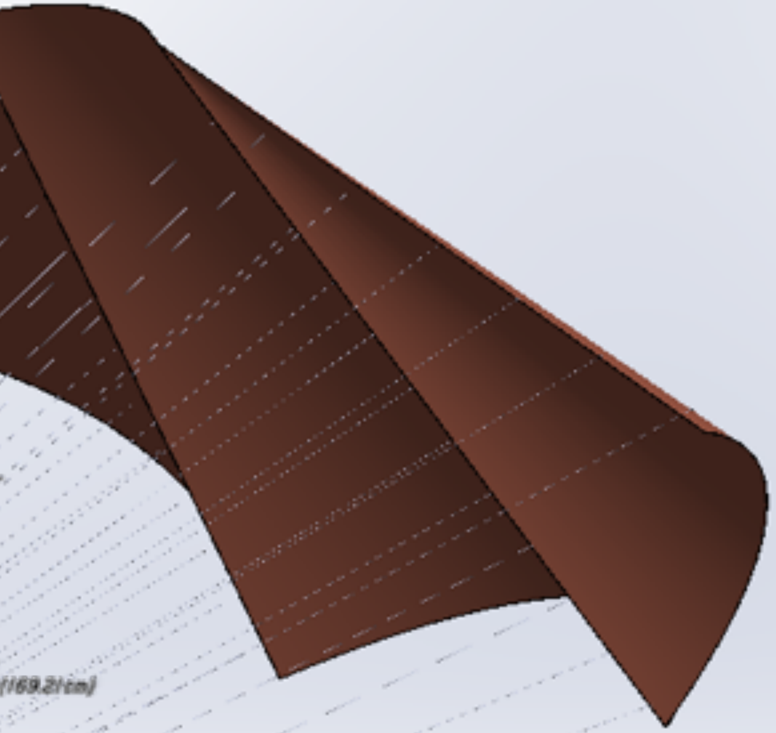
Robert L. Staehle/Jet Propulsion Laboratory-California Institute of Technology
Matthew A. Eby/Aerospace Corp., Rebecca M. E. Williams/Planetary Science Institute
Sara Spangelo, Kim Aaron, Rohit Bhartia, Justin Boland, Lance Christensen,
Siamak Forouhar, Marc Lane, Manuel de la Torre Juarez, Nikolas Trawny,
Chris Webster/JPL-Caltech
David Paige/University of California-Los Angeles

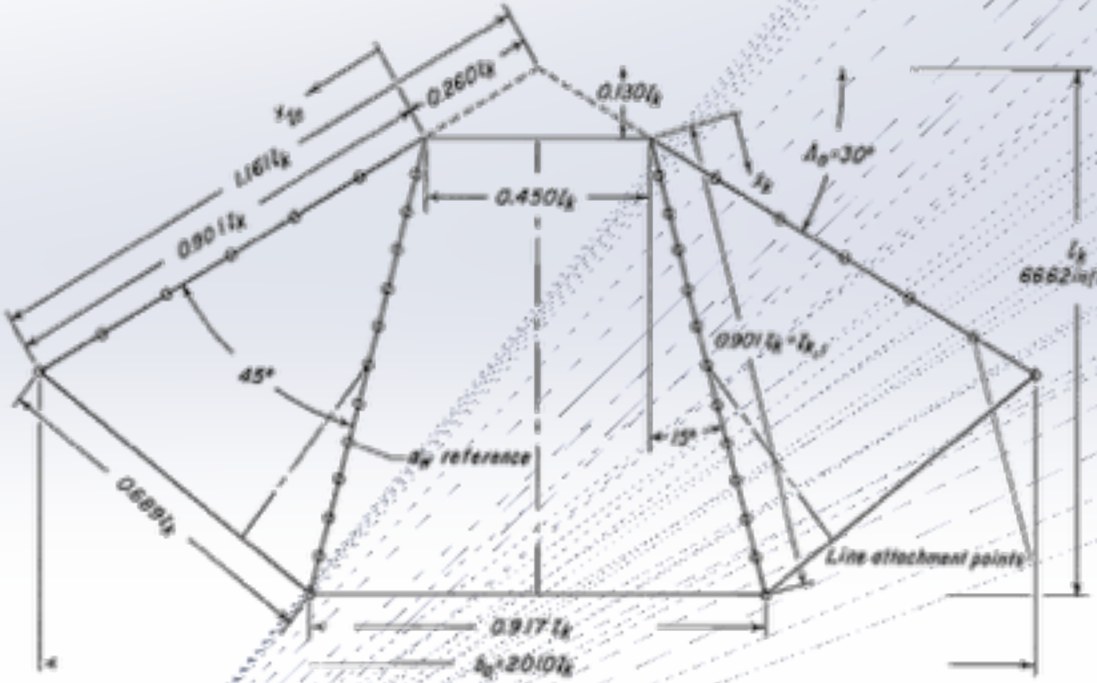
AEROSPACE

Planetary Science Institute

Parawing Deployment

Scaled Version of NASA's Twin-keel Parawing Model 21

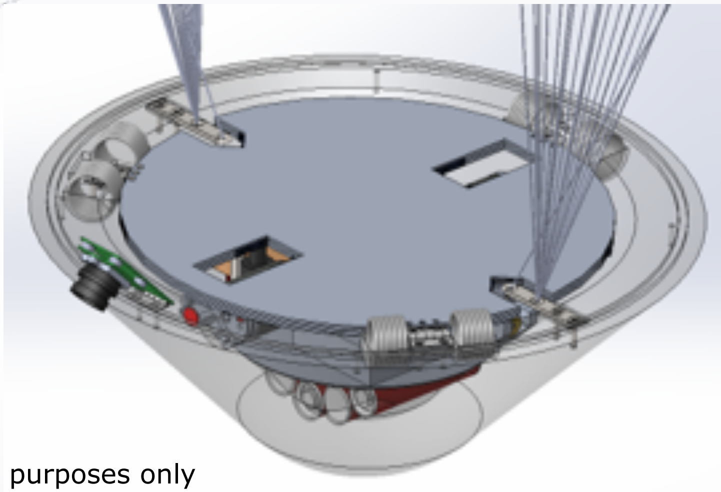




NASA Graph: Technical Note D-5965

Design Sizing Point

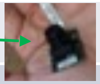
- *L/D = 3, CR=1.00*
- *Produces a 70° Glide Angle*

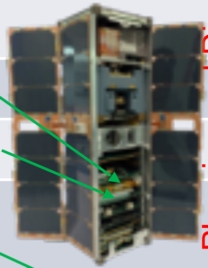


Master Equipment List

Suppliers shown only for proof-of-concept; no selection is represented.

Subsystem	Components	Mass	Power	Heritage / Supplier
Entry & Descent	Aeroshield (1,200 g), Parawing (400 g), Stepper motors (2 x 10 g)	1,620 g	-	REBR/Aerospace Corp.
Payload	Methane Detector (Tunable Laser Spectrom-TLS)	100 g	0.67 W	MSL/ JPL
	Pressure, Air Temperature, and Humidity Sensors	113 g	0.43 W	MSL/ JPL, various
Payload/Navigation	Descent/Geology Camera (2 x 40g)	80 g	1 W	None*/ Aptina
Navigation	IMU (Gyro & Accelerometer)	10 g	0.1 W	Variable/ Blue Canyon Tech.
Power	Body-Mounted Solar Panels (20 x UJT Cells)	40 g	-	Variable/ Spectrolab
	Batteries (6x18650 Li Ions, ~16 W-hr each max)	270 g	-	INSPIRE/ Panasonic
	Electric Power System & Battery Board	80 g	-	RAX & INSPIRE/ JPL
Computing & Data Handling	Gumstix Flight Computer & Storage	10 g	0.5 W	IPEX/ Gumstix
Telecom	UHF Proxy-1 Radio	50 g	2 W	Variable/ JPL
	UHF Low Gain Antenna (Whip)	5 g	-	Variable/ JPL
Mechanical & Others	Shelf (68 g), Brackets (26 g), Wing Actuator (19 g), Springs (48 g), Hinges (7 g), Fasteners (20 g), Harnessing (50 g), and others (20 g)	256 g	-	Variable/ JPL
Thermal	Heaters (3 x 50 g), Aerogel (10 g)	160 g	2 W	Variable/ JPL
Sterilization	Sterilization Bag	100 g	-	Variable/ JPL
TOTAL	Total No Margin/ With 20% Margin	**2.9 kg/ 3.5 kg**	~3 W (avg)	-

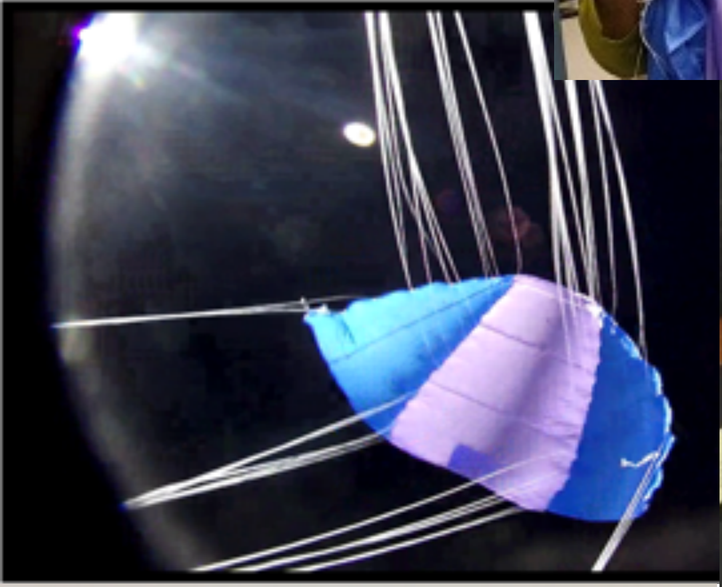


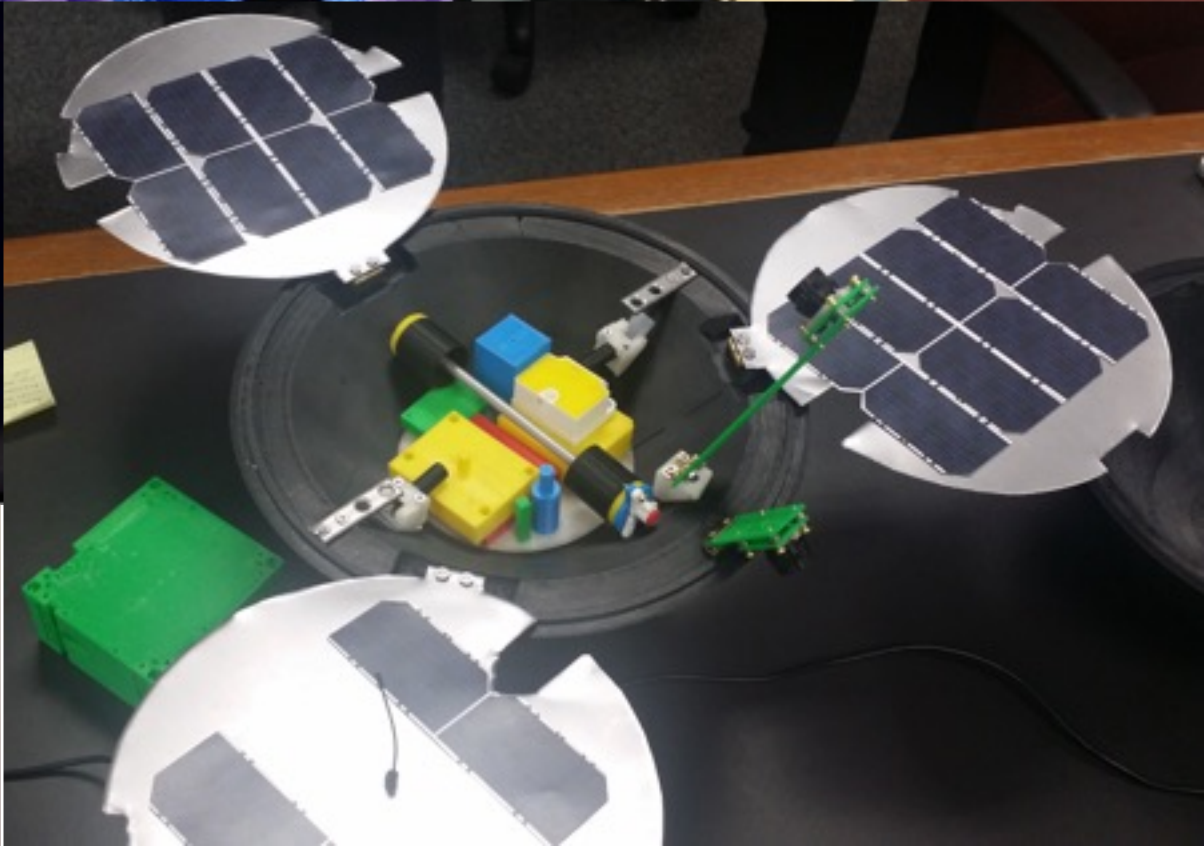


*Radiation and thermal testing will be performed to ensure reliability

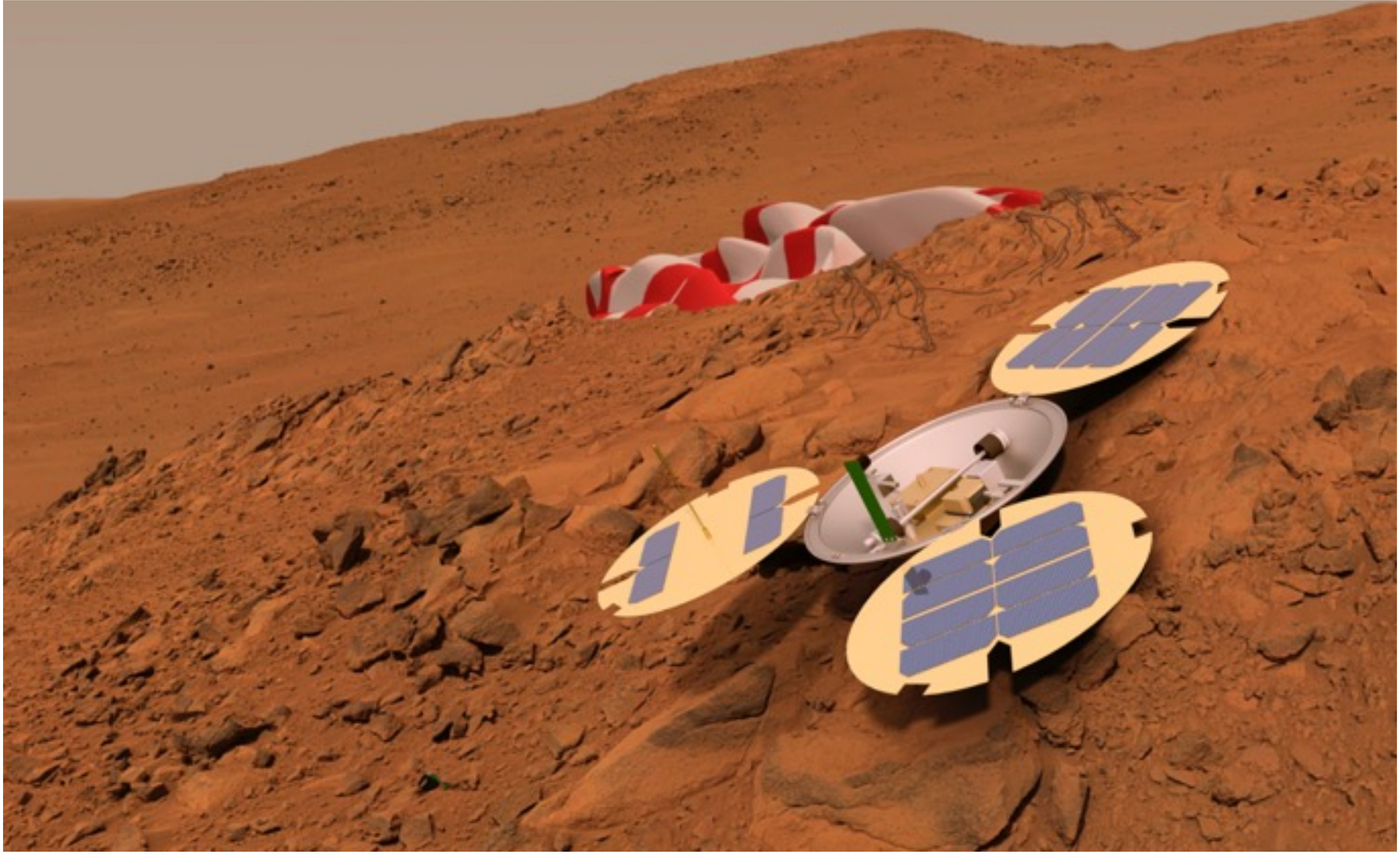
Entry mass (3.5 kg) consistent w/ mass from Aerospace Corp. REBR flights from Earth orbit.

Note: the Backpack (ACS & mechanical interfaces, spring for jettison) is an additional 0.7 kg/ 0.9 kg (30% margin).





Mars$_{\text{Drop}}$: Out-of-form-factor Mars MicroLander could be enabled by CubeSat/smallsat thinking, cost approach, and componentry.



Artist's concept of the JPL/Aerospace/PSI jointly developed MarsDrop concept (Image courtesy of and reprinted by permission of The Aerospace Corporation).

First Interplanetary CubeSat Session, at the 13th Annual CubeSat Developer's Workshop

***MarCO* – Ready for Launch** Andrew Klesh, et al., JPL

***BioSentinel*: Mission Development of a Radiation Biosensor to Gauge DNA Damage and Repair Beyond Low Earth Orbit on a 6U Nanosatellite** Matthew D'Ortenzio, NASA Ames

Payload Developments on the *Lunar Flashlight* Mission Travis Imken, et al., JPL

***Lunar Ice Cube*: Lunar Water Dynamics via a First Generation Deep Space CubeSat**
Pamela E. Clark, et al., JPL, Morehead State Univ., NASA/GSFC, Busek, Vermont Technical College

The Lunar Polar Hydrogen Mapper (*LunaH-Map*) CubeSat Mission Craig Hardgrove, et al., ASU, and others

A 6U CubeSat Designed for Lunar Orbit and Beyond in the NASA CubeQuest Challenge
Kathleen Morse, Yosemite Space, Inc.

***DustCube*, a 3U Cubesat to Characterize the natural dust environment and microscopic ejecta due to DART high speed impact on the Binary asteroid 65803 Didymos**
Diego Nodar, et al., Universitario de Vigo (Spain)

The *CuSP* interplanetary CubeSat mission Don George, et al., SwRI, JPL, NASA/GSFC

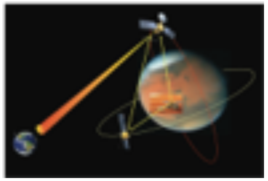
Architectural Flexibility of the Iris Deep-Space Transponder Masatoshi M. Kobayashi, et al., JPL

Backup information.

6 New Technologies → 1 New Architecture

CubeSat electronics and subsystems

- extended to operate in the interplanetary environment
- radiation and duration of operation



Optical telecommunications

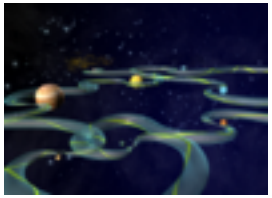
- very small, low power uplink/downlink over 2 AU distances

  [rf also discussed]

Solar sail propulsion

- rendezvous with multiple targets using no propellant

  [other propulsion techniques also discussed]



Navigation of the Interplanetary Superhighway

- multiple destinations over reasonable mission durations
- achievable ΔV

Small, highly capable instrumentation

- (miniature imaging spectrometer example)
- acquire high-quality scientific and exploration information

Onboard storage and processing

- maximum utility of uplink and downlink telecom capacity
- minimal operations staffing