JPL’s Advanced CubeSat Concepts for Interplanetary Science and Exploration Missions

Sara Spangelo, Julie Castillo-Rogez, Andy Frick, Andy Klesh, Brent Sherwood, NASA JPL/Caltech
CubeSat Workshop, Logan, Utah, August 2015

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JPL Interplanetary CubeSat Roadmap

CubeSat Workshop 2015

http://www.jpl.nasa.gov/cubesat/
Overview of Interplanetary Small Spacecraft

Planetary small spacecraft (e.g. CubeSats) that fly as secondaries and are deployed at destinations to perform missions and communicate via mothership or direct to Earth:

- Planetary Science and Exploration Value:
  - Enhance primary’s science objectives
  - Enable new science and exploration in new, potentially dangerous environments

- Novel Technology Demonstrations:
  - Mature technology (TRL) of new instruments or measurements
  - Accept higher risk by exploring dangerous/unknown environments
  - Relatively low cost ($10-$25M, < 5-10% of primary mission costs)
  - Low additive mass (5-20 kg with deployer, <10% of primary mission)

- Interplanetary CubeSats leverage:
  - CubeSat community hardware/software heritage, experience
  - Miniaturized instrumentation (imagers, sensors, etc.) at << 1 kg
  - Autonomous operations and telecommunication technologies

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Active Interplanetary CubeSat Projects Provide Heritage

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**INSPIRE** - Navigation demonstration with Iris beyond Moon
- I&T Complete, Awaiting Launch

**MarCO** - InSight
- Insertion real-time Mars relay
- Launch March 2016 to Mars

**NEAScout** - Asteroid Detection Mission & Lunar Flashlight
- Lunar Orbiter to search for ice
- Launch ~2018 to NEA/Moon

- **DSN Telecom**
- **Cold Gas ACS**
- **Star Tracker**
- **C&DH w/Watchdog**
- **VHM Magnetometer**

- **High Data Rate DSN Telecom**
- **Cold Gas TCMs**
- **Reaction Wheels + Star Tracker**
- **Upgraded Electrical Power**
- **C&DH Upgrades**

- **High Resolution Imaging**
- **Agile Science Image Processing**
- **Optical Navigation**
- **High Performance, Rad Tolerant C&DH**
Unique Challenges Faced by Interplanetary CubeSats

Conventional spacecraft design approaches are not applicable to small sats
- Cannot increase size, more propellant, thicker structure walls, etc.
- Multi-functional component/ subsystems (Iris, cold gas thrusters, imagers)

<table>
<thead>
<tr>
<th>Areas</th>
<th>New Challenges in Deep Space</th>
<th>Solutions</th>
</tr>
</thead>
</table>
| Power                         | • Solar collection low a >1 AU  
• High power requirements (telecom, propulsion)                                                 | • Low-power modes  
• Power cycling  
• Higher energy storage capacity                                                           |
| Telecom                       | • Direct-to-Earth (DTE) challenging at large distances  
• Mothership relay cooperation                                                              | • On-board data compression  
• Dedicated deployer telecom  
• Disruption tolerant networking (DTN)                                                     |
| Orbit & Attitude Control      | • Limited mass, volume, power  
• Reaction wheel e-sats outside Earth’s geomagnetic field                                     | • Off-the-shelf, ACS  
• Cold gas thrusters (propulsion and de-sats)                                               |
| Autonomy                      | • No direct link for long times                                                                | • Onboard autonomous operations  
• Agile science algorithms                                                                  |
| Lifetime/Environment          | • Long duration cruises  
• High radiation, severe thermal                                                              | • Rad-tolerant C&DH; shielding  
• Short mission durations                                                                   |
| Programmatic                  | • Potential risk to primary                                                                    | • Aligning with strategic goals of PI  
• Standard deployer, ΔV tip-off                                                              |

Conventional spacecraft design approaches are not applicable to small sats
- Cannot increase size, more propellant, thicker structure walls, etc.
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Deep Space Deployable Payloads Architecture & Disruption Tolerant Network
Provides common housing (heating, power, data), telecom relay at target

IntelliCam
Modular intelligent camera that supports optical navigation (Justin Boland)

Standard Deployment (PDCS)
Payload Data and Communications System provides common housing (data, power, thermal), telecom relay at target

New Miniaturized SrI2 Gamma Ray Spectrometer
(PSI/Fisk U/ JPL)
Agile Science Software enables autonomously maximizing science return

On-board autonomous rapid feature detection, adaptive sampling rate, data analysis

Dynamic Gain Setting, Autonomous Dust Detection, Data Downlink Prioritization

As demonstrated on TextureCam, NASA ASTID, EO-1

Disruption Tolerant Network (DTN)

Maximizes chance of successful data return and minimizes scheduling burden for networks without continuous connectivity

To enable autonomous navigation, trajectory planning, descent and landing, in unknown/poorly understood gravitational environments.
**Mission Architectures:** short-lived single free-flyers, small body hoverer, pair of CubeSats flying in coordination, two landers/penetrators at small bodies, and two independent, long-lived CubeSat missions

**Technology Demonstrations:** mothership-daughtership telecommunication architectures, autonomous navigation and operations, miniaturized instrumentation, and software for on-board processing of science data.

**Science Applications/Instruments:**
- Measuring magnetic fields, high-resolution images at low altitudes
- Searching for volatiles and water ice (mini spectrometer)
- Acquiring acceleration profile optimized with agile science algorithms
- Performing controlled dust adhesion investigation (SKGs)

**Parameter range for secondary CubeSats**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dormant Cruise Duration</td>
<td>100-2200 days</td>
</tr>
<tr>
<td>CubeSat Mission Duration</td>
<td>Most 1-7 days, one 30 days, one 3 years</td>
</tr>
<tr>
<td>Sun Range</td>
<td>0.75-3 AU at destination</td>
</tr>
</tbody>
</table>
## Designs Leveraged CubeSat Component “Library”

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Design Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computing</td>
<td>Rad-hard LEON processor (dual core, 200 MIPS), which supports on-board autonomy and agile science algorithms</td>
</tr>
<tr>
<td>Telecommunication</td>
<td>UHF radio or Iris transponder (DTE); low, medium, or high gain antennas; reflect-array antennas</td>
</tr>
<tr>
<td>Attitude Control</td>
<td>XACT BCT attitude control unit (star trackers, reaction wheels, IMU)</td>
</tr>
<tr>
<td>Orbit Control</td>
<td>VACCO cold gas thrusters (0.25-0.5U; ΔV≤80 m/sec)</td>
</tr>
<tr>
<td>Power Systems</td>
<td>Solar arrays, primary/secondary batteries (average consumption: 1-5 W)</td>
</tr>
<tr>
<td>Structure</td>
<td>3U-6U Al CubeSat structure</td>
</tr>
<tr>
<td>Carrier/ Deployer</td>
<td>PDCS and avionics (5-10 kg for 3U-6U)</td>
</tr>
</tbody>
</table>

*Designs leverage components and design from MarCO and other JPL CubeSats*
Planetary CubeSat Portfolio “Family Portrait”

**Secondary Orbiter/Flyby Pairs**
~48-72 hour operations with (semi-)autonomous operations and Mothership relay

**High Resolution Proximity Imaging**

**Distributed, Simultaneous Particles & Fields Measurements**

**Ice Prospecting Infrared Spectrometer**

**Impactors/Landers**
~48-72 hour surface science operations with mothership localization and relay support

**Asteroid/Comet Instrumented Surface Penetrator**

**Phobos Surface Landing w/ Gamma Ray Spectrometer**

**Hitchhiking Deep Space Nano-Satellite**
Mothership-deployed s/c to other interplanetary destinations

**Deep Space Navigation & Radio Science Demonstrations**
Representative Mission Concept: Kuiper Tech Demo

CubeSat (6U) AutoNav Demonstration

- Hitches ride to Earth-Sun L1 on Discovery-class mission
- Demonstrates orbit determination on 6U CubeSat to avoid expensive (time, power) tracking to the DSN.
- Paves the way to operations cost reduction for future small interplanetary CubeSats.
- Introduces the IntelliCam, tailored to reference target acquisition.
- JPL’s new CubeSat C&DH supplies processing performance needed for orbit determination and autonomous maneuver planning and execution.

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Target: L5; Solar Distance ~1 AU; Transfer time ~2.3 years

L1: 100 kbps

L5: 100 bps

Image Credit: Lucy Burton
Future Impact of Science-Driven Small Spacecraft

- **Performing significant ΔV and high-precision attitude control enables:**
  - Hovering, landing, large orbit transfers to Moon, Mars, asteroids
  - Creating and maintaining swarms, constellations, formation flight
- **Autonomous Operations enabling:**
  - Autonomous navigation: orbit determination and trajectory planning
  - Agile Science for on-board autonomy to locate Earth, detect objects (e.g. plumes)
  - Dynamic observation planning, disruption-tolerant networking (DTN)
- **Future potential to accomplish high-priority (Explorer, Discovery-class) science:**
  - Multi-spacecraft architectures: constellations, mother-daughtership, swarms
  - Pre-cursor missions to explore dirty/dangerous/unknown environments

Comet 46P Wirtanen Orbital Transfer
Image Credit: Lucy Burton

Mars DROP to deliver excess payload to Mars

Mars DROP enters, steers, and targets locations to deliver science payloads to Mars surface. Credit: Aerospace Corp. & JPL

Robotichedgehogs for Phobos Exploration; Credit: Stanford University & JPL
Acknowledgments

• Partners: Blue Canyon Technologies, Aerospace Corp. PSI, KSC, Ames, universities
• Ross Jones, Susan Jones, Kim Reh for study definition and management
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• Shyam Bhaskaran for AutoNav support
• JPL scientists and PIs for their support

Previous Presentations on Deep Space CubeSats:
• JPL Missions in Implementation: MarCO, NEAS, LF (Frick et al.)*
• NanoSpacecraft as secondary payload on planetary mission (Discovery TDO CubeSat Portfolio) – (Frick, et al.)*
• OCCAM: A flexible, responsive architecture for comet/NEA reconnaissance (Castillo, et al.)*
• Hybrid Spacecraft/Rover for Small Body Exploration (Pavone, et al.)*
• Asteroid Kinetic Impactor Missions (Chesley et al.)
• A system of technologies for future robust deep space spacecraft (Beauchamp et al.)
• NanoSats and MicroSats in Deep Space – on track for exponential growth (Freeman et al.)
• Multiplying Mars Lander Opportunities with MARSdrop Microlander (Staehle et al.)
Questions?

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Active Low Earth Orbit (LEO) CubeSat Projects

M-Cubed/COVE-2 (NASA ESTO)
High data-rate on-board processing
P. Pingree: JPL, U. Michigan
Launched VAFB: Dec. 5, 2013 (NASA CLI)

IPEX/CP-8 (NASA ESTO)
Autonomous low-latency product generation
S. Chien: JPL, GSFC, Cal Poly SLO, Tyvak
Launched VAFB: Dec. 5, 2013 (NASA CLI)

GRIFEX (NASA ESTO)
Unprecedented frame-rate ROIC/FPA
D: Rider JPL, U. Michigan
Launched VAFB: Jan. 31, 2015 (NASA CLI)

RACE
Hydrometric Atmospheric Radiometer
B. Lim: JPL, UT Austin
Launch Failure WFF: Oct. 2014 (NASA CLI)

ISARA (EDISON)
Integrated Solar Array & Reflectarray Antenna
R. Hodges: JPL, Aerospace Corp., Pumpkin Inc.
Launch Manifest: Aug. 2015 (NASA CLI)

LMRST
Low Mass Radio Transponder
C. Duncan: JPL, Stanford
Launch Manifest: 2015 (NASA CLI)

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Emerging & Enabling Technologies

- Telecommunication and Navigation systems
  - Iris Transponder (JPL) and high gain antennas
  - High-rate S/Ka-Band radios (50+ Mbps dld from LEO)
- CubeSat Propulsion systems ($\Delta V$>3 km/sec in 3U)
  - VACCO Cold Gas Systems (low $\Delta V$ for TCMs/ de-sats)
  - NASA-funded MEP (MIT- S-iEPS, JPL- MEP, Busek- HARP)3
  - CubeSat Ambipolar Thruster (CAT), Busek CHAMP, Chemical Thruster
- High-accuracy attitude control technology
  - Blue Canyon’s XB1: 7.2 arcsec accuracy, 1 arcsec stability, <2.5 kg, ~1 U, <2.5 W
- Solar arrays that are deployed and are gimbaled for Sun-tracking
  - Deployable Solar Arrays (Clyde Space, MMA up to 130 W/kg)
- Integrated bus architectures and radiation-tolerant components
  - Blue Canyon XB1 Bus (GNC, C&DH, Telecom, Power, ACS)
  - Companies offering buses like Tyvak, Blue Canyon, etc.
- Standard deployers (JPL’s PDCS, Planetary System’s CSD, Tyvak’s Deployers)
Active Interplanetary CubeSat Projects Provide Heritage

**INSPIRE (JPL)**
Navigation demonstration with the IRIS radio beyond the Moon

**NEA Scout (MSFC/JPL)**
Asteroid characterization mission [EM-1]

**Lunar Flashlight (JPL/MSFC)**
Lunar orbiter to search for ice in lunar craters [EM-1]

**MarCO (JPL)**
InSight insertion real-time Mars relay

**BioSentinel (Ames)**
Biosensor to study impact of radiation on living organisms [EM-1]

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Psyche

The Psyche TDO paves the way for future investigations that are best addressed with mother–daughter architectures and automated science data handling (e.g., multi-site magnetic field measurements in Europa’s system).

**Target:** 16 Psyche; **Solar Distance** ~3 AU; **CubeSat Lifetime** ~48 hours

---

**Objectives**

**Technology Demonstrations**
* Demonstrate a mother-daughter architecture leveraging the form factor, subsystems, and standards introduced by the CubeSat community but upgraded to withstand the environment and constraints specific to a mission in the main belt of asteroids
* Implement Agile Science algorithms for automated feature detection, adaptive data collection and disruptive tolerant networking.

**Science Enhancements**
* Acquire magnetic field measurements at high spatial resolution complementary to the low-degree harmonics acquired by the mothership
* Acquire images with a resolution better than 1m/pix at an altitude lower than 30 km
The TDO is a CubeSat-based investigation of the surface composition of 24 Themis, which Proteus will fly by on Oct. 4 2025. It infuses a new miniaturized spectrometer enhanced with intelligent software for rapid extraction of spectral signatures.

**Target:** 24 Themis; **Solar Distance** ~2.9 AU; **CubeSat Lifetime** ~24 hours

**Objectives:**

**Technology Demonstrations:**
- Implement Agile Science algorithms for surface feature detection and prioritization and disruption-tolerant networking.
- Demonstrate a new miniaturized spectrometer

**Science Enhancement:**
- This TDO enhances Proteus’ science by searching for volatiles, and especially water ice, at the putative parent of 238P/Read.
The BASiX TDO will demonstrate hovering in close proximity (<500 m) to a micro-g body using Autonomous Navigation and primitive body navigation technology developed at JPL under NASA sponsorship and implemented with a deep space CubeSat. This demonstration will lower the risk of close proximity operations at small bodies for future NASA missions.

Technology Demonstrations:
• Implement AutoNav algorithms to enable autonomous close proximity operations and controlled hovering at targeted sites near a micro gravity body.
• Implement Agile Science algorithms for: 1) autonomous plume detection, 2) adaptive data collection, 3) adaptive gain/framing and 4) disruption-tolerant networking.

Science Enhancement:
• Acquire high-resolution imaging of the crater created by the explosion.
CoRE’s TDO will demonstrate NASA sponsored primitive body navigation technology for controlled impact and survival of an instrumented penetrator at a small body **Target:** Tempel 2; **Solar Distance** ~3 AU; **CubeSat Lifetime** ~48 hours

### Objectives

#### Technology Demonstrations
Perform close proximity operations and controlled targeted impact on a low-gravity body
Implement agile science algorithms for: 1) multi-asset coordination, 2) adaptive gain/framing and 3) disruption-tolerant networking (DTN)
This TDO infuses primitive body navigation (PBN) software sponsored by NASA’s NEO program and agile science algorithms, which will expand NASA’s core competencies in deep space navigation and science data handling.

### Science Enhancements
Measure the surface strength of Tempel 2 via acceleration profile upon impact
Acquire stereo imaging during descent, optimized with Agile Science algorithms
Pyxis (aka PANDORA’s “box”) will demonstrate autonomous soft landing of a CubeSat on a milli-g body. The CubeSat carries a new miniaturized, low power gamma ray spectrometer (JPL/PSI/Fisk U) and electrodynamics shielding technology (NASA/KSC) for demonstrating dust mitigation on spacecraft surfaces and mother-daughter system architecture for future NASA missions.

Objectives:
Technology Demonstration
- Implement AutoNav algorithms for autonomous targeted soft landing on a milli-g body.
- Implement Agile Science algorithms for disruption-tolerant networking (DTN).

Science Enhancements
- Measure the elemental composition of a landing site on Phobos and the galactic cosmic ray environment
- Perform a controlled dust adhesion investigation that helps retire key SKGs related to charging in low gravity environment
- PANDORA’s observation of Pyxis’ interaction with the surface yields direct insight on Phobos’ geotechnical properties.

Target: Phobos
Solar Distance ~1.5 AU
CubeSat Lifetime ~7 d
Our TDO (Cupid’s Arrow) is a high value investigation to sample the noble gases in Venus’ atmosphere at low cost using a nanosat. Inventorying the noble gases is the highest-priority investigation for Goal I/Objective A identified by the VEXAG.

**Target**: Venus; **Solar Distance** ~0.75 AU; **CubeSat Lifetime** ~30 d

**Objectives**

**Technology Demonstration**: a new ultracompact quadrupole ion-trap mass spectrometer (QITMS) hosted on a nanosat.

**Science Enhancement**: Sample the Venus atmosphere and measure the noble gases ($^4$He, $^{20}$Ne, $^{36}$Ar, $^{40}$Ar, $^{84}$Kr, $^{130}$Xe) abundances and their isotopic ratios with precision <1-5%.
MarCO: CubeSats to Mars

The “Mars CubeSat One” Mission consists of two 6U CubeSats launching with InSight in March 2016.

MarCO provides an 8kbps real-time relay for InSight’s Entry, Descent and Landing at Mars.
MarCO
Concept of Operations

TCM 1
TCM 2
TCM 3
TCM 4
TCM 5

6.5 Month Cruise

Mar 2016

Earth

Sept 28, 2016

InSight Entry, Descent, and Landing

Mars

TCM 5
Concept of Operations

2 CubeSats, ~6 months cruise

CCAM

InSight Deploy

X-Band Tx to Earth

UHF Rx from InSight

MarCO* would provide a real-time communication relay for InSight EDL

*Mission Concept - Pre-Decisional – for Planning and Discussion Purposes Only
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**MarCO**
Flight System Overview

- Solar Arrays (MMA)
- Cold Gas Thrusters (Vacco)
- X-Band Transponder (JPL)
- SSPA & LNA (JPL)
- High Gain Reflectarray (JPL)
- MGA, LGA, Structure (JPL)
- UHF Antenna (JPL)
- CDH & EPS (AstroDev)
- Attitude Control (BCT)

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**MarCO Overview:**
- **Volume:** 2x6U (12x24x36 cm)
- **Mass:** 14.0 kg
- **Power Generation:**
  - Earth: 35 W
- **Data Rates:** 62-8,000 bps
- **Delta-V:** >40 m/s

**Software:**
- FSW: *protos* (JPL)
- GSW: *AMPCS* (NASA/JPL)

**Operations:**
- **Primary:** DSN 34m
- **EDL:** Madrid 70m

**I&T:**
- In-house S/C I&T, testing, Tyvak
- NLAS/Launch Integration
NEA Scout (MSFC/JPL)
Near Earth asteroid reconnaissance via imaging

Target Detection and Approach with Wide-Field Imaging
Ephemeris determination and color typing

Target Reconnaissance with Medium Field Imaging
Volume, global shape, rotational properties, and local environment characterization

Close Proximity Imaging
Local morphology, regolith properties

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Lunar Flashlight*
A CubeSat with a solar sail to “shine light” on the distribution of water and other volatiles in the Moon’s permanently shadowed regions

*Mission Concept - Pre-Decisional – for Planning and Discussion Purposes Only
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INSPIRE: On-Board Autonomy to Locate Earth in Star Field

For further information see S. Chien, J. Doubleday, D. R. Thompson, or J. Castillo-Rogez

OCCAM (SIMPLEx concept): Rapid Science Re-Planning Following Plume

Apparent size of Earth in camera frame Shown for different mission phases
Small Satellites: A Revolution in Space Science

Final Report
Keck Institute for Space Studies
California Institute of Technology
Pasadena, CA
July 2014

Workshops: July 2012 and October 2012
Image: Earth-Sun L5 Space Weather Sentinels Constellation Concept
Future Mission Concepts (Others In Formulation)

RELIC*
Understanding energy transport from black holes
to the intergalactic medium
Keck Institute for Space Studies

*Proposed Mission - Pre-Decisional – for Planning and Discussion Purposes Only
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Future Mission Concepts (Others In Formulation)

**L5SWS***
Fractionated Earth-Sun L5 space weather base for prediction and understanding solar variability effects
*Keck Institute for Space Studies*

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