



Jet Propulsion Laboratory  
California Institute of Technology

# The Keck Institute Study Program on Small Satellites: A Revolution in Space Science

10<sup>th</sup> Annual CubeSat Developers' Workshop  
Cal Poly San Luis Obispo

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Pasadena, California, USA

The author acknowledges ideas, advice and co-authors from the participants in the "Small Satellites: A Revolution in Space Science" workshops organized by the W. M. Keck Institute for Space Studies

# Study Program Participants and Co-Author Acknowledgements

Vassilis Angelopoulos – UCLA

Manan Arya – Caltech

John Baker – JPL

Katharine Brumbaugh – UT Austin

Julie Castillo-Rogez – JPL

James Cutler – University of Michigan

Courtney Duncan - JPL

Dan Erwin – USC

Tony Freeman - JPL

Lou Friedman – The Planetary Society

Jason Hyon – JPL

Travis Imken – UT Austin

Rebecca Jensen-Clem – MIT

Michael Johnson – JA (co-organizer - external)

Laura Jones – Cornell University

Paulett Liewer – JPL

Glenn Lightsey – UT Austin

Michael Lisano – JPL

Martin Lo - JPL

Juergen Mueller - JPL

Neil Murphy – JPL

Stephen Murray – Johns Hopkins University

Charles Norton – JPL (co-organizer)

Sergio Pellegrino – Caltech (co-organizer)

Jordi Puig-Suari – Cal Poly SLO / Tyvak

Christopher Shaffer – UCLA

John Springmann – University of Michigan

Robert Staehle – JPL

John Steeves – Caltech

Stephen Unwin – JPL

Angelos Vourlidis – Naval Research Laboratory

Austin Williams - Tyvak Nano-Satellite Systems



# The Keck Institute for Space Studies (KISS)

## What is KISS?

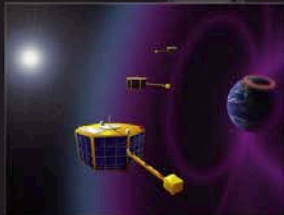
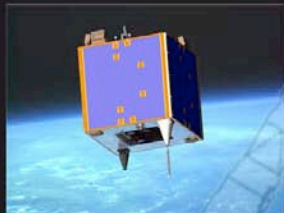
- Established at Caltech in 2008 with a \$24M grant over 8 years from the W. M. Keck Foundation
- “Think and Do Tank” primarily to bring together scientists and engineers for sustained interaction to develop new space mission concepts and technology
- Studies must concentrate on ideas with the promise of revolutionary advances in space mission capability
- Study programs require a JPL lead, a Caltech faculty lead, and an external lead synergistic with the program objectives

# Small Satellites: A Revolution in Space Science

## Study Program Objectives

- Conceive novel scientific observations, **uniquely enabled**, by small satellites (ESPA-Class to FemtoSats)
- Study astrophysics, heliophysics, and planetary science (including NEOs and small bodies)
- Identify the technology challenges necessary to realize forward-looking missions
- Establish a vision, strategy, and publishable set of scientific priorities that are relevant and inspirational for the scientific and engineering community

# Public Education Programs



for more information  
go to:  
[www.kiss.caltech.edu](http://www.kiss.caltech.edu)

The Keck Institute for Space Studies  
presents a short course for all interested  
researchers, faculty and students:

## Small Satellites: A Revolution in Space Science

Monday, July 16, 2012

8:15 am: refreshments

8:45 am: short course begins

Lees-Kubota Lecture Hall  
101 Guggenheim Building  
California Institute of Technology

**Shri Kulkarni (Caltech)**

*LIMSat*

**Andrew Kalman (Pumpkin Inc.)**

*Nine Years and Counting:*

*A Nanosatellite Designer's Perspective*

**James Cutler (Univ. of Michigan)**

*Recent Space Physics Science from RAX*

**Glenn Lightsey (UT Austin)**

*Capabilities of the SmallSat Platform*

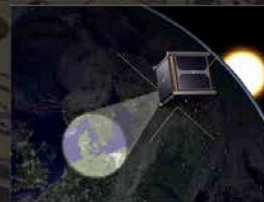
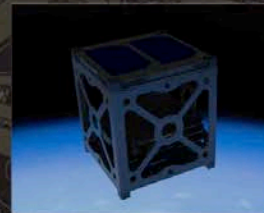
**Julie Castillo-Rogez (JPL)**

*SmallSat Concepts for Small Bodies, Mars and the Moon*

**Small Satellite New Exploration  
Concepts in Astrophysics Panel**

*Ranga Ram Chary (Caltech), Chris Martin (Caltech),  
Phil Nicholson (Cornell) & Vassilis Angelopoulos (UCLA)*

No registration is required for this free short course.  
Seating is limited and is available on a first come, first served basis.  
An informal light lunch will be provided by KISS for all attendees.



for more information  
go to:  
[www.kiss.caltech.edu](http://www.kiss.caltech.edu)

The Keck Institute for Space Studies  
presents an open lecture to all interested  
researchers, faculty and students

## CubeSat: An Unlikely Success Story

Professor Jordi Puig-Suari  
Cal Poly, San Luis Obispo

Tuesday, October 30, 2012

4:30 pm: refreshments

5:00 pm: lecture

Lees-Kubota Lecture Hall  
Guggenheim Building  
California Institute of Technology

CubeSat has become the de facto standard for small satellite development. These miniature spacecraft (smaller than a loaf of bread) are the choice for student satellites worldwide and are becoming a serious option for many missions being developed by traditional space organizations, from NASA and JPL to the Air Force and NSF.

However, 10 years ago, when the CubeSat standard was developed by a Stanford - Cal Poly team success was not guaranteed. In the talk, we will look back at the development of the CubeSat standard over the years.

We will explore some of the challenges facing the development team and try to identify some of the key factors leading to the standard's success. These lessons learned translate well to other innovative projects and may help support an environment that fosters innovation and out-of-the box thinking.

No registration is required for this free lecture.  
Seating is limited and is available on a first come, first served basis.



**Astrophysics**



**Heliophysics**



**Planetary**

## The Decadal Surveys

**“The goal of deploying a small and medium astrophysics mission every other year is not being met.”**

- From “2020 Vision: An Overview of New Worlds, New Horizons in Astronomy and Astrophysics”.

**“The (small satellite) projects have been deemed by peer review to have well-defined, important science objectives and to provide unique datasets. All ... carry the promise of precedent-setting measurements ”**

- From “Solar and Space Physics: A Science for a Technological Society ”.

**“A significant concern with the current planetary exploration technology program is the apparent lack of innovation at the front end of the development pipeline .”**

- From “Vision and Voyages for Planetary Science in the Decade 2013-2022 ”.

## Summary of Primary Concepts

Topic	Scientific Observation	Mission Concept
Astrophysics (UVIP-UV Reionization Probe)	Understanding the source and mechanism for reionization of the early universe	A-train style constellation of UV coarse spectral imagers
Astrophysics (SoftX)	Measurement of low-energy diffuse background from interstellar medium	X-ray spectroscopy in LEO with collimated CCD or CMOS detector
Astrophysics (Relic)	Understanding energy transport from black holes to the intergalactic medium	Low-frequency aperture synthesis with constellation of dipoles
Heliophysics (MagCon)	Global electro-dynamics of Earth's magnetosphere-ionosphere coupling	Constellation of energetic particle, low-energy instruments, Langmuir
Heliophysics (SPC)	First dedicated solar polar constellation mission for understanding variability, dynamo, and SS effects	Multiple constellations out of the ecliptic and in high incl. solar orbit
Heliophysics (SWS)	Space weather situational awareness for predictive modeling	Fractionated Space Weather Sentinel at L5
Planetary (Fly Trap)	Venus zonal wind flow measurement	Mother (ESPA) daughters (chipsat) with differential Doppler tracking
Planetary (Lunar Cube)	Lunar interior structure mapping and volatile composition	Mothership and multiple cubesats with seismometers
Planetary (Champagne)	Determine spatial, velocity distribution, and physical properties of planetary rings	Mother/daughters (chipsats) with accelerometers and mm-sensors

# RELIC Mission Concept

**Science Driver:** Understanding energy transport from black holes to the intergalactic medium

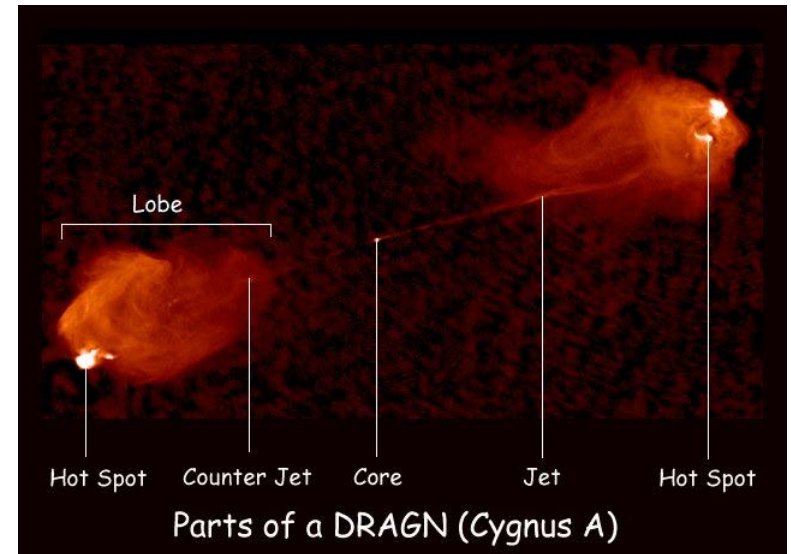
**Objective:** Image double-lobed active galaxies at frequencies below 30 MHz

**Methodology:** Aperture synthesis imaging using an array of greater than 10 simple dipole antennae (5m each in 6-axes) in a spherical array of order 1 km diameter using 3U CubeSats

**Technology Challenges:** Formation flying, on-board processing, antenna stowage and deployment, data downlink (mothership with high gain antenna needed)

**Uniqueness:** Low frequency array-based imaging must be done from space to cover the whole sky and resolve phase variation imaging below 10 Mhz (LOFAR)

**CONOPS:** Deployment beyond LEO at Earth-Sun L2 or a drift away orbit, or the moon in a low-gravity gradient environment



# Connecting the Sun to Earth

## CME as seen by STEREO A -- Event of June 2-8 2008

**Solar Terrestrial Relations Observatory (STEREO)**

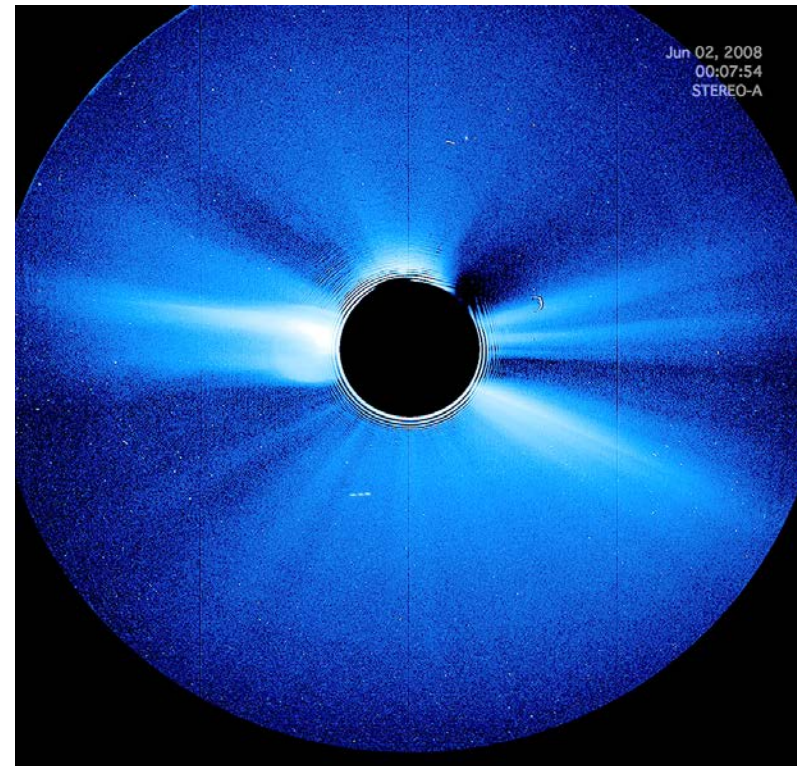
Using two observatories reveals 3D structure of coronal mass ejections

-PI: Russell Howard, NRL

### Heliospheric Imager



### Coronagraph



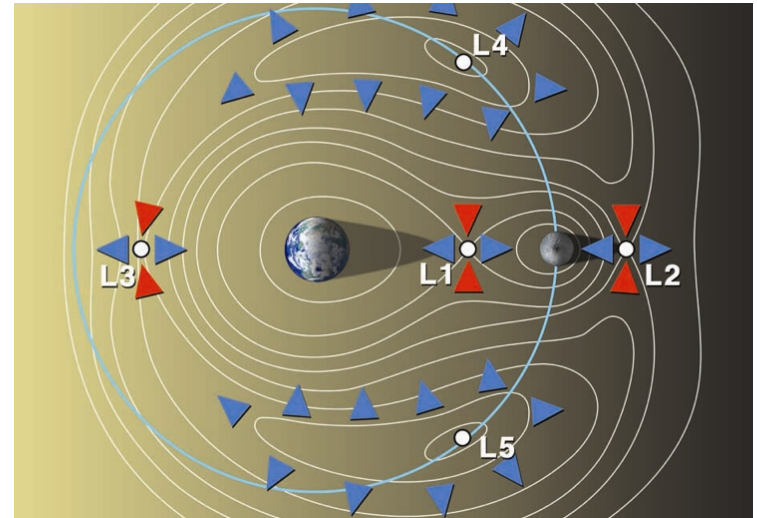
# Fractionated L5 Space Weather Sentinel Cluster Mission Concept

**Science Driver:** Space weather prediction and understanding the effects of solar variability on Earth and the space environment.

**Objective:** Would reveal the structure of the solar wind streams and the propagation of Coronal Mass Ejections (CMEs) from the Sun to Earth and improve predictive models for space weather situational awareness with permanence at L5.

**Methodology/CONOPS:** Would combine remote sensing and *in situ* instruments at the Earth-Sun L5 point. Use solar sails to reach L5. Divide mission into three or four 6U CubeSats: one SC for in situ fields and particles, one or two SC for the heliospheric imager, and one SC for communication to Earth all deployed incrementally

**Technology challenges:** Solar sail propulsion, L5 intracluster, incremental buildup and relay communication, radiation environment, instrument packaging and volume constraints



# Venus FLY TRAP Mission Concept

## Flying Loops Yielding-Tracks of Radio-tagged Aerodynamic Particles

**Science Driver:** Detailed 3D investigation of Venus' zonal wind flow activity as a function of altitude latitude. Provide 3D atmospheric motion information.

**Objective:** Data informs development of Venus Global Climate Model (GCM).

**Methodology:** Injection/tracking ChipSat probes (>100) in the middle atmosphere at a variety of latitudes from 2 motherships.

**Technology Challenges:** Differential Doppler tracking, instrumentation, aerodynamics, swarm communications with motherships.

**Uniqueness:** Dispersive and disposable smart particle tracking with orders of magnitude greater distribution of sampling than previous probes (Pioneer-Venus Orbiter). Potential for atmospheric structure measurements through radio occultation



# Mission Concept Instrument/Technology Capabilities

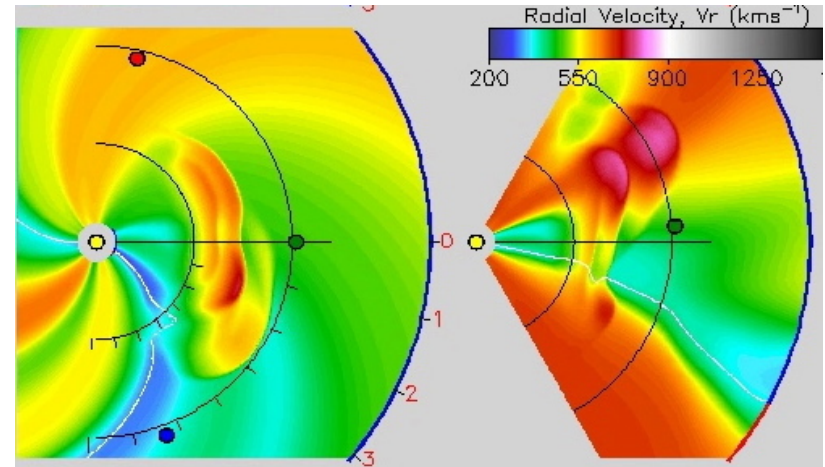
Concept	Payloads	Technology Challenges
Astrophysics (UVIP-UV Reionization Probe)	Arc-second resolution, 912-2400 AA band, ~25cm aperture optics with CCD UV detector	Pointing stability, UV coatings, high efficiency UV detectors
Astrophysics (SoftX)	X-ray spectrometer detector from 100-1000 eV with a single collimator	Mostly mature. Collimated CCD or CMOS detector and on-board processor for X-ray photon counting
Astrophysics (Relic)	5-meter dipole antennas in all 6-axes	Formation flying, constellation management, downlink, antenna deployment, in situ correlation
Heliophysics (MagCon)	DC & AC magnetometer, Langmuir probe, low- energy plasma instrument, energetic particle and electric field instrument	Instrument packaging and miniaturization, EMI/ EMC, propulsion, miniature deployment booms
Heliophysics (SPC)	Heliophysics imager, magnetograph, and others similar to MagCon	Instrument miniaturization, high data rate telecom
Heliophysics (SWS)	Heliophysics imager, magnetograph, and others similar to MagCon	Sail propulsion/station keeping at L5, relay communication, arc-minute pointing stability
Planetary (Fly Trap)	PicoSat/ChipSat and thin-film detectors with atmospheric sensors	Differential Doppler tracking, instrumentation, swarm communications
Planetary (Lunar Cube)	Micro seismometers	Lunar environment survivability, impact survivability
Planetary (Champagne)	ChipSat accelerometers and thin-film large apertures	Propulsion, tracking, telecom, extreme environment survivability



# L5 Sentinel SmallSat Concurrent Engineering Study

- Team “K” Study

- Concurrent engineering design for Fractionated L5 Sentinel Concept (FSWS)
- Heliophysics imager component, to identify technology gaps as a case study for novel space science SmallSat missions



- Primary Technology Challenges for FSWS

- Propulsion and station keeping at L5, transit relay communication, deployables, arc-minute pointing stability (control), instrument packaging and miniaturization

# L5 Sentinel Concurrent Engineering Study

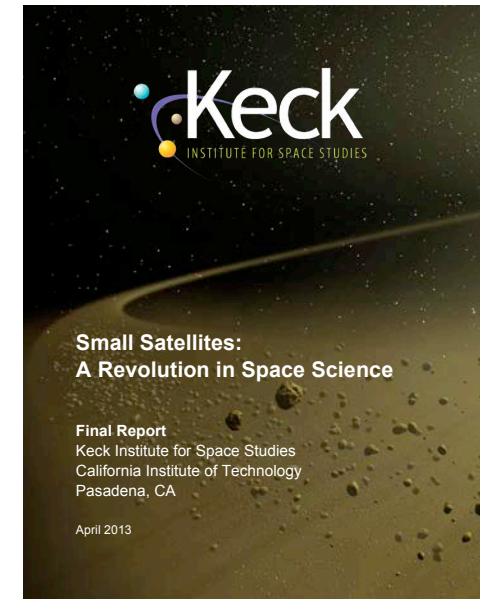
<b>SYSTEMS WORKSHEET:</b>							
<i>Cubesat</i>							
	<u>Mass</u> (kg)	<u>Subsys</u> <u>Cont.</u> %	<u>CBE+</u> <u>Cont.</u> (kg)	<u>Mode 1</u> <u>Power</u> (W) Cruise & Telecom	<u>Mode 2</u> <u>Power</u> (W) Science & Telecom	<u>Mode 3</u> <u>Power</u> (W) Anneal Detector	<u>Mode 4</u> <u>Power</u> (W) Safe
<b>Power Mode Duration (hours)</b>				24	24	24	24
<b>Payload on this Element</b>							
Instrument 1	3.000	30%	3.900	0.00	4.00	10.00	0.00
Instrument 2			0.000				
<b>Payload Total</b>	<b>3.000</b>	<b>30%</b>	<b>3.900</b>	<b>0.00</b>	<b>4.00</b>	<b>10.00</b>	<b>0.00</b>
<b>Spacecraft Bus</b> <small>do not edit formulas below this line, use the calculations and override tables instead</small>							
ACS	1.000	10%	1.100	6.00	7.00	6.00	6.00
Command & Data	0.100	2%	0.102	0.20	0.20	0.20	0.20
Power	1.400	2%	1.428	0.20	0.20	0.20	0.20
Propulsion	1.910	30%	2.483				
Structures & Mechanisms	1.900	10%	2.090				0.00
Cabling	0.581	30%	0.756				
Telecom	0.500	10%	0.550	1.50	5.00	1.50	1.50
Thermal	0.914	10%	1.005				
<b>Bus Total</b>	<b>8.305</b>	<b>15%</b>	<b>9.514</b>	<b>7.90</b>	<b>12.40</b>	<b>7.90</b>	<b>7.90</b>
Thermally Controlled Mass			9.514				
<b>Spacecraft Total (Dry)</b>	<b>11.305</b>	<b>19%</b>	<b>13.414</b>	<b>7.90</b>	<b>16.40</b>	<b>17.90</b>	<b>7.90</b>
Subsystem Heritage Contingency	2.109	19%	19%				
System Contingency	1.283	11%	11%	3.40	7.05	7.70	3.40
<b>Spacecraft with Contingency</b>	<b>14.696</b>	<b>of total</b>	<b>w/o addl pld</b>	<b>11.30</b>	<b>23.45</b>	<b>25.60</b>	<b>11.30</b>
Propellant & Pressurant1	0.090						
<b>Spacecraft Total (Wet)</b>	<b>14.786</b>						
<b>Cubesat Allocation</b>	<b>14.000</b>						
<b>Launch Vehicle Margin</b>	<b>-0.786</b>	<b>-6%</b>					
<b>JPL Design Principles Margin</b>	<b>19%</b>	<b>30% required</b>					

## Mass/Power/Margin Analysis During Transit-Mode Operations

Pre-Decisional – for Planning and Discussion Purposes Only  
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# Recommendations and Next Steps

- Final Report In Progress
  - [kiss.caltech.edu](http://kiss.caltech.edu)
- Recommendations
  - Will address science opportunities, technology maturation (i.e. compact ASRG, cryogenics, Direct-To-Earth telecom, etc.), and other topics supporting beyond LEO exploration





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