Science-Driven CubeSat Missions to the Moon

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Purpose: We are in the process of evaluating application of the CubeSat Paradigm for deep space exploration, a frameword we refer to as LunarCube [1]. We are conducting systems definition and design activities, with focus on implementing enhanced thermal and radiation protection; attitude control, communication, navigation and tracking beyond earth orbit; power for science-driven applications; as well as propulsion requirements for cis-lunar space operation, as particular drivers for longer duration operation in lunar orbit or on the lunar surface. The end result will be cost-effective, generic design(s) for a cross-section of future high priority space or surface payloads for planetary, heliophysics, and astrophysics disciplines, the requirements for which are described in Table 1.

The CubeSat Paradigm: Over the last decade, CubeSat has evolved to support cutting edge multi-platform, multi-disciplinary science as well as key SmallSat hardware and software technology R&D, in Earth orbit, e.g., the scientifically useful monitoring of Earth's atmosphere and climate by several experiments (e.g., CINEMA, CubeSat for Ions, Neutrals, Electron, and Magnetic Fields) [2]. Recently CubeSat has been proposed as a model for a lunar swirl study mission [3]. Incorporating advances in the consumer electronics industry, the decade of development has seen the continuous reduction in size, mass, and power, and increase in processing capability of onboard avionics and power systems. CubeSat use of resources, including cost and development time, are kept low by using a standard "bus," standardized interfaces, and shared access by guest "instruments" to all subsystems using existing SmallSat protocols. This paradigm is similar to that commonly used by NASA in its first, and well into its second, decade, when launch rates were far higher and costs far lower [1]. Part of its appeal is that CubeSat model has afforded universities access for hands on student education subsidized by NSF, NASA, DOD, and other agencies.

Progress in Extending the CubeSat Paradigm: NASA Ames has already shown leadership in the use of SmallSats, such as LCross, for lunar mission design over the last decade, and is in the process of producing a report on current cubesat activities at NASA centers. Several organizations (e.g., Planetary Systems, Planetary Services) are developing 6U and 12U versions of the ubiquitous 3U 'PPOD' packaging and deployer. NASA WFF is developing a 54U cubesat 'carrier' that can be attached to an ESPA ring. Both ULA and SpaceX have proposed Earth escape launchers and cubesat carriers to provide transportation to targets beyond Earth orbit [4]. JPL and collaborators will be flying INSPIRE, the first cubesat mission to leave Earth orbit, in 2015. We are reporting here the results of an ongoing in-depth study at GSFC to design and develop a cubesat platform for a planetary target capable of meeting science requirement challenges of conventional missions as well as demonstrating technology [5,6]. The Astrophysics, Heliophysics, and Earth Applicaitons Divisons of the Science Mission Directorate have already implemented cubesat development options in their sensor and supporting technology development programs.

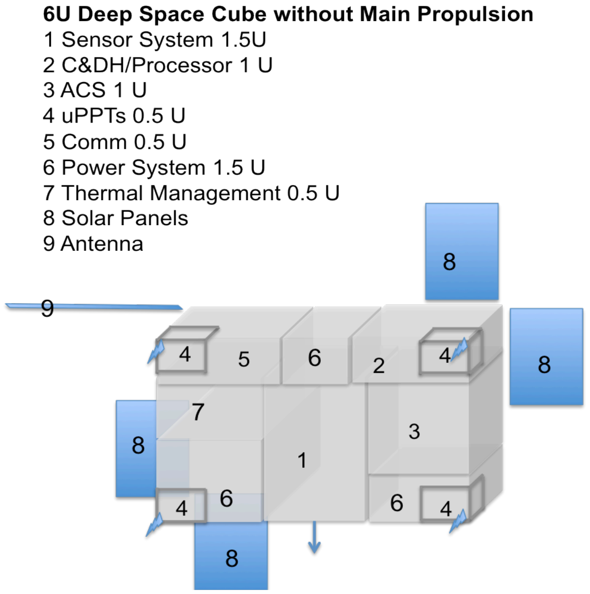

Figure 1: 6U Configuration L-WaDi Deep Space Cube from Fy13 IRAD work.

Development of LunarCube Concept: We are looking at a cross-section of progressively more challenging missions, incuding an orbiter, an impactor, and a pathfinder observatory, and considering designs using technology available now, in five years, and in ten year. The Moon is an ideal 'test' target because, as an atmosphereless, heavily bombarded body which experienced some degree of interior differentationa, it can act as an analogue for a broad cross-section of solar system enviornments and processes, as well as a testbed for technologies needed to operate in those environments. Our current mission focus is an orbiter with a single instrument (Lunar Water Distribution (LWaDi), a high spectral resolution near infrared spectrometer, using state of the art hardware and software. The mission goal is to characterize water and water

Representative Candidates for LunarCube Missions

Candidates	Lunar Water Distribution	Lunar Polar Impact Outflow	ROLLS Pathfinder
Concept	Nature of water components and their distribution	Measure ion, plasma, dust, volatile outflow after impact	Radio astronomy and imaging of solar radio bursts below terrestrial cutoff (10MHz) pathfinder
Type of Measurements, Instrument(s), Heritage	Near IR, 1 to 4 microns, .01 micron spectral resolution (240 8-bit channels), SNR 10dB, detection of features (wavelength, band center and width) associated with water type and component, imaging not required. Super compact NIR spectrometer with cryocooler.	1) Low E ion analyzer being developed for CubeSat (Mariner 2 ion spectrometer, AMPTE IRM, CATS MEMS 0-30 KeV electrostatic optics; 2) ULF electric field and plasma density DC to 20kHz (electric field .2 mV/M) plus optional Langmuir probes (Dynamic Ionosphere CubeSat Experiment); 3) UV spectrometer (LADEE UV spectrometer), 150-400nm, .5 nm spectral resolution	Radio receiver/riometer, 1 to 10 MHz (Lazio et al, Advances in Space Research 48, 1942-1957, 2011). supported by radio astronomy antenna(s) – wire of ~50 m total length or less, antenna deployer, preamp, CPU, data storage, downlink antenna and controller, thermal system, power system, solar arrays, housing. Subsequent versions of ROLSS are anticipated
Resources	2 kg, 2W, <2U, <10 mbits/ day	1) <1 kg, <1W, <1U; 2) <1W, 1U stowed (2 10-m wire booms for plasma, 2 8-cm booms for Langmuir), 1kg; 3) 2kg, 3W, 4U.	4 kg, 5W, additional peak power for one-time antenna deployment, periodic data downlink. 1U, data volume could be reduced to <100 bits per sec. Desirable: higher datarate.
Operation Location, Modes, Duration	lunar orbit; minimum 9 (3 latitudes x 3 times of day) measurements/day for three lunar cycles, 6 month baseline.	Operating on limited (10% duty cycle in cis-lunar space, 100% duty cycle on 'last leg' capture by Moon's gravitation field until impact polar crater baseline. Desirable: fly small 'swarm' to generate greater detectable signal to be seen remotely. <hours for 'last leg'.	Lunar surface, nearside, near lunar equator. Survive at least one diurnal cycle (baseline), multiple cycles through several duty cycles desirable. Data collection and downlink modes.
Tall Poles, Special Needs	Optics, temperature monitored, nominal operation 150K via passive thermal. In-space propulsion. Protect windows from contamination. Comm drives pointing requirements.	Greater Volume required than 6U. Electromagnetic shielding. Nominal operation -50 to 50 degrees C with knowledge of temperature. Comm not science drives pointing requirements.	Thermal: surviving lunar night. Deployment of antenna. baseline single low mass wire. Desirable: tens of meters of polyimide antenna perhaps using 1D solar sail deployment mechanisms.

components for small areas representative of major lunar terrains and features as a function of latitude (upper, mid, equatorial), and time of day (dawn, mid-morning, noon, mid-afternoon, dusk). New flight dynamics software technology has turned out to be 'game-changing': We are developing the capability to create readily available families of low energy transfer routes to cislunar space which require far less fuel than conventional routes.

Current Activities: We have been focused on exploring the trade space (mass, power, volume, availability, mission duration) for the key subsystems, as well as for the sensor system. The result is a design for a deep space cubesat bus, with or without an onboard propulsion system (Figure 1).

Sensor: We have designed a 1.5U high resolution (10 nm) IR spectrometer operating from 1.3 to 3.7 microns. A compact cryocooler maintains the HCT detector at 150K, requiring an additional 5W+ of power.

Power: Deployable gimbaled cubesat solar panel arrays from several manufactor, including MMA Design and TUI, could provide required power.

Propulsion and Attitude Control: We can combine existing components either available or under development, including Reaction Wheel Assemblies, Star Trackers, and Busek micro-pulsed propulsion thrusters, in order to provide stationkeeping and momentum dumping capabilities without the use of magnetic torque bars used in Earth orbit (taking advantage of the Earth's magnetic field). Microthrust propuslions systems, particularly the Busek Xe ion thruster, could provide adequate delta V for lunar orbital insertion from GEO, making the vehicle substantially larger than 6U, but still within the cubesat formfactor. The propulsion system would require 70W during cruise, and thus a larger gimbaled solar panel array. Thus, we also consider the option of delivery to the Moon without an onboard propulsion system.

Thermal Design: The gimbaled solar panel assembly, fully deployed, is large enough to act as a sun shield for the small form factor spacecraft, mitigating thermal design challenges faced by larger orbiters.

Communication, Navigation and Tracking: The compact S-band/X-band transceiver under development combined with low stowed volume directional antenna would be adequate to support the required bandwidth for data downlink and radio navigation.

C&DH and Processing: The 'mini' version of the GSFC SpaceCube processor would provide the required control and processing functions. Low

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