LunarCube: Advancement of Solar System Exploration with the CubeSat Paradigm P.E. Clark[1], R. MacDowall[2], W. Farrell[2], N. Petro[2], R. Cox[3], A. Vasant[3], S. Schaire[4] [1]Catholic University of America@NASA/GSFC, Greenbelt, MD 20771, [2]NASA/GSFC, [3]Flexure Engineering Inc., [4]NASA /WFF (Correspondence email: Pamela.E.Clark@NASA.gov).

Purpose: We are in the process of evaluating application of the CubeSat Paradigm for deep space exploration, often referred to as LunarCube [1]. Over the course of this year, we are conducting systems definition and design activities, with focus on enhanced guidance, navigation, and control as well as propulsion requirements for cis-lunar space operation, and thermal requirements as the dominant drivers for long duration operation 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 [4]. 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 even second, decades, 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 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. Several NASA centers, including Wallops and JPL, have already developed a 6U CubeSat design, meant to be more robust in terms of longer duration and survival in the deep space environment, as well as capable of more advanced attitude control, navigation, and communication beyond Earth orbit, with the goal of supporting high priority deep space science activities [5,6]. JPL just completed and GSFC is in the midst of year long studies to investigate the use of the CubeSat paradigm for deep space, as described above. The first Interplanetary CubeSat and LunarCube workshops were held last year, and are planned for the coming year [7,8]. The NASA Office of the Chief Technologist has initiated programs to develop core technologies critical for deep space operations, including in space propulsion, proximity operations, and advanced communication capabilities to date.

Development of LunarCube Concept: LunarCube development plan is progressive and includes testing of later stage core technologies in earlier stages. Stage 1 (LunarCube 1) supports enhanced 1) profile: somewhat longer duration that CubeSat (many months instead of many weeks); 2) form factor: from 3U to a minimum of 6U, but potentially larger volumes, as needed; 3) radiation and thermal environment design for deep space (with greater radiation hardness provided, for example, by MilSpec components, and accommodation for passive thermal design) and short-term operation on the lunar surface (potentially by using limited duty cycle); and 4) testing for in-space propulsion, communication, and active attitude control and navigation systems. Stage 2 (LunarCube 2) enhances capability by incorporating state of the art or even currently 'under development' technologies in several key areas: 1) electronics and software; 2) precision navigation, control, propulsion; 3) full deep cryo operation for 'cold cubes'; and 4) advanced payload integration. Full operation on the lunar surface would be possible. At this stage, the LunarCube could be a virtual 'smart phone' with a variety of experiments, as open access software applications.

Current Activities: We have developed science and preliminary design requirements, initiated trade studies, and conceptual designs for three mission concepts, representing various levels of technological challenge (see Table next page). Each of these concepts is possible as a result of work done, particularly over the last decade, toward development of miniaturized, or even MEMS versions, of standard space payload instruments.

References: [1] Clark et al, 2013, JoSS (in publication); [2] https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/cinema; [3] Garrick–Bethel et al, 2011, http://www.lpi.usra.edu/meetings/leag2011/pdf/2038.pdf; [4] https://www.gumstix.com/cbg.html; [5]Staehle et al, http://arc.aiaa.org/doi/abs/10.2514/6.2012-5218AIAA Space 2012; [6] LunarCube Workshop Online, 2012, http://www.youtube.com/watch?v=WQMQPhW2zxM, [7] http://www.iCubeSat.org, 2012; [8] http://www.lunar-cubes.com, 2012.

Table 1: 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, .02 micron spectral resolution (150 8-bit channels), SNR 10dB, detection of features (wavelength, band center and width) associated with water type and component, imaging not required. Compact version of AVIRIS Chandrayaan (e.g., UCIS)	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, 1500 bytes per 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	Halo orbit at L1, cycling orbits, or stable lunar orbit; 9 (3 latitudes x 3 times of day) measurements/day for three lunar cycles (84 days) 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.