LUNARCUBE: CREATING A NEW PARADIGM FOR LOWER COST, HIGHER ACCESS, AND GREATER CAPABILITY SYSTEMS AND INSTRUMENTATION FOR PLANETARY EXPLORATION. Pamela E. Clark, Catholic University of America; Robert MacDowall, NASA/GSFC; Russell Cox and Abraham Vasant, Flexure Engineering, Inc.; Michael Rilee, Rilee Systems Technologies; Scott Schaire, NASA/WFF; Benjamin Malphrus, Morehead State University

Purpose: The Moon is not only the closest and most accessible extraterrestrial frontier. The lunar surface, with its rugged terrain, long diurnal cycle, and wide range of extreme thermal and illumination conditions varying as a function of latitude and local relief, represents a great portion of the entire range of conditions found throughout the solar system. The lunar surface is thus an ideal ‘test bed’ for exploring planetary surface processes and origins as well as for developing core technologies required for planetary exploration. The lunar environment has, and can continue to provide options for low cost missions of high scientific and technological value. Thus, any sound approach to planetary exploration should prioritize access to the Moon. The question is how to provide such access at a time when the conventional approaches to space exploration are unable to provide adequate support to achieve planetary exploration goals.

CubeSat Approach: We are proposing LunarCube, an extension of the affordable and successful CubeSat approach, to facilitate access to the Moon. CubeSat has already encouraged and increased access to Earth orbital space over the last decade. CubeSat provides standards for bus design and operation for low–cost, focused–objective, Earth orbital missions via open access documentation and even online purchasable kits [1, 2], facilitating the implementation process, and reducing development costs, risks, and time. The bus provides standardized interfaces and shared access by guest ‘instruments’ to all subsystems using CubeSat protocols. Four key aspects of specified design are: 1) profile: short duration, low earth orbit; 2) form factor: multiple 10 cm cubes (U), typically varying from 0.5 to 3 U; 3) technology impact: low, incorporating off the shelf electronics and software; 4) risk: Class D, based on the rationale that CubeSat standards have been improved and demonstrated with use, and failures have far less impact, in terms of expenditures and size of groups involved, than conventional government sponsored ‘missions’. Part of its appeal is that CubeSat afforded universities access for hands on student education. After a decade of development, this approach is beginning to yield scientifically useful monitoring of Earth’s atmosphere and climate through combined experiments (e.g., CINEMA, CubeSat for Ions, Neutrals, Electron, and Magnetic Fields) [3]. Most recently CubeSat has been proposed as a model for a lunar swirl study mission [4].

LunarCube Concept and Core Technologies: LunarCube uses a similar approach for the lunar surface by maintaining the same standard on risk, thereby keeping costs low, but extending the current CubeSat concept in two stages to include additional capability required for deep space operation in five key areas: 1) profile: increase duration from months to years; 2) form factor: grow to at least 6U as needed; 3) control: active attitude control and propulsion, made sustainable with onboard intelligence for routine multi-platform operation; 4) information transfer: more robust communication and C&DH to support onboard processing, made sustainable with onboard intelligence for routine multi-platform operation, and 5) thermal/mechanical design: greater hardness to deep space radiation and ruggedness for extreme thermal variation, potentially using MilSpec components initially, but ultimately requiring state of the art cold temperature electronics and power developments for deep cryo operation.
Accomplishment of the first two, and an adequate level of accomplishment of the third and fourth (LunarCube 1.0) would give access to lunar orbital space to provide, for example, communication satellite capability for cis-lunar or deep space. Work at NASA Wallops has led to the development of a somewhat more robust and larger 6U CubeSat concept [5]. Partial accomplishment of the fifth (LunarCube 1.5), would allow multiple platform access to and operation, as well as survival and operation for at least a limited duty cycle on, the lunar surface. The somewhat larger volume would potentially allow several users to fly experiments, as in the ISS ‘nano’ rack concept [6]. Stage 2 (LunarCube 2.0) would require raising the technology impact, enabling incorporation of state of the art or even currently ‘under development’ technologies in several key areas resulting in fully implementing onboard intelligence (3 and 4) and deep cryo design (5) in electronics, power systems, mechanisms (moving parts), precision navigation and control, and 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 ‘nano–rack’ representing a variety of experiments, as open access software applications.

Efficient Operation in Extreme Environments: Designing power systems to operate at cold temperatures is especially challenging, particularly when access to radio-isotope driven power supplies is so limited. Current solutions typically involve some form of ‘hibernation’ for limited duty cycle operation on the lunar surface. Indications are the Li-based battery technologies will probably be able to operate down to -100 degrees C within the next few years [7], but for operating at the extremely cold temperatures in the permanently shadowed areas, down to 25K, we will probably need high temperature superconductor systems now under development [8,9,10]. HTS based systems for cooling, power generation, transmission wire, energy storage (superconducting magnetic energy storage or flywheel), and regulation, are currently being tested for the large-scale efficient power generation, but further work is required at the small scales that are normally used in the laboratory. HTS-based technologies, although currently relatively low TRL, would provide the most optimal solutions for operating at cold temperatures. HTS is also promising for magnetic shielding [11]. Cold temperature analogue (SiGe) and digital (ULT ULP) electronics that will currently operate at these ‘cryo’ temperatures even more efficiently and with lower noise are available now [12,13] and awaiting an opportunity to be employed in the design of an entire package, redesigned to operate at a lower voltage. Thermal and mechanical design must provide a shield from extreme environmental conditions as well as deep space radiation on the lunar surface. Various radiator/cryocooler designs have been proposed for dealing with lunar daytime conditions as a function of latitude [12,14], and for dealing with cooling during lunar night [12,15]. High temperature superconductors could also provide the basis for efficient mechanisms for applications where ‘moving parts’ are required to operate under cryogenic conditions where minimal power is available. Also under development by Flexure Engineering is a cryovac test chamber that could operate at three lunar surface temperature regimes that exist near the lunar poles. Such a system could be used to simulate and observe surface processes and to test equipment for use at the lunar poles.

OnBoard Intelligence: Additional autonomy at every stage is highly recommended to support the adaptability needed for multiple systems that meet the demands of the distributed network of scientists and other stakeholders efficiently with minimal resources. Onboard intelligence also supports sustainability, minimizing the need for ‘ground control’ that would otherwise greatly increase cost as the number and complexity of system, and the need for remote communication and control, grows. Robust onboard intelligence is essential for robotics that allow maneuverability in any environment and the resiliency in behavior and capability for
Adaptable, reconfigurable communication and C&DH capability are critical to move from the one of a kind ‘mission’ to the sustainable ‘work station in space’ model.

Frontier is a tool currently under development [16,17] that could provide the basis for such onboard intelligence capable of absorbing and utilizing lessons learned and thus evolving from a tool to a tool user: an adaptable framework consisting of a decision engine with evolving intelligence based on a genetic algorithm–driven evolving neural interface with an evolving synthetic neural system consisting of neural basis functions for the human and tool interfaces and a specially designed stability algorithm to balance rule– and choice–driven inputs originating from either side facilitate the design evaluation and selection process. The adaptable framework is increasingly capable of dynamic reconfiguration of parameters and rules associated with tools and resources, as well as selection of tools most optimally matched to stakeholder needs through pattern recognition in response to ‘lessons learned’.

**Communication:** Frontier is built on an open source, web services oriented environment which is designed to support distributed, multi–user, concurrent access to resources and tools, modeling and development services, databases, simulation and scenario development, analysis, and evaluation. This would adapt readily to ‘multiple broadcast stations’ in space, creating a communication infrastructure with OSI layer 2 and layer 3 adaptations [18], and analogous to setting up a network of mobile cell phone towers. We will need multi–channel communication along the lines of existing practices [18] for a Dedicated Channel plus open Channel, to process universal and mission specific signals. Although RF may be used for shorter distance communication between spacecraft, for longer distances, optical systems, instead of RF, will be preferable, as they can transmit at higher data rates for less mass and power [19].

**Potential Applications:** Applications already identified include not only communication satellite clusters but lunar and space environmental monitoring packages in orbit and on the surface. A Cubesat-like bus could be used to support the concepts already proposed for sounding of the lunar limb [20], a solar occultation experiment package in lunar orbit [21], or magnetometer-equipped penetrators for study of lunar swirls [4]. Perhaps the ultimate longer term application would be extreme mobility rovers and sampling devices with ‘moving parts’ that could take advantage of high temperature superconductor-based magnetically driven mechanisms. Extreme mobility rovers [22] with robust intelligence capable of operating 3D reconfigurable node-and-strut-networks and stowing into extremely small volume would be ideal for reconnaissance in the rugged terrain associated with the polar regions, providing the low temperature operation problems had been solved. Two concepts for sampling systems currently being considered include TEGA used in the Mars lander, and RESOLVE, a combined drilling, sample arm, and multi-sample analysis system proposed as a lunar volatiles prospecting mission [23]. Even astrophysical observatories may be possible if considered in a modular ‘nanorack’ context. We are currently engaged in a study to reconsider ROLSS [24], Radio Observatory on the Lunar Surface for Solar Studies, an interferometer with distributed antennas, as a lunarcube mission. As for getting packages to the surface in the near term, the Astrobotic lunar lander mission concept being developed for the Google X-Prize has room on board and space for sale for a ‘rack’ of lunar cubes.

**Instrumentation:** Over the last decade, investment from technology development programs has supported efforts to ‘microsize’ (tenths of U’s, tenths of kg’s) not only subsystems but instruments in order to reduce resources required for payloads [25]. As a result, SmallSat and even CubeSat appropriate versions for many key instrument types exist, and, where these don’t exist as yet, concepts do. Key instrument types would include those that can provide direct
elemental abundance information (Ray region: Gamma-ray, X-ray, and Neutron spectrometers), major geochemical sub-component or mineralogical abundance (Visible/Near Visible Region: UV, visible, Near IR, Mid IR spectrometers), physical component and surface distribution (Longwave Region: thermal IR, passive and active microwave and radio instruments), energetic particle or molecular component distribution (mass spectrometers, particle analyzers), and field distribution or interior characterization (magnetometers, gravimeters or radio science experiments, seismometers). The greatest progress has already been made in the extensively used visible/near visible region where versions of high resolution ‘microsized’ cameras and digital spectrometers already exist [e.g., 26,27] as do low power lasers to support spectroscopy [27]. In the ray region, X-ray spectrometers have already been significantly downsized, as solid state X-ray detectors have become smaller and more efficient [25], and concepts for gamma-ray and neutron spectrometers of smaller mass and size, which could potentially operate in a ‘nanorack’ context, exist and await further funding for full development [28]. More compact, lower mass and power versions of longwave instruments, ranging from the mini-Thermal Emission Spectrometer [29] to Ground Penetrating Radar [30], have already been developed. Microsize versions of magnetometers [31], electric field instruments, electrometers, and magnetic susceptibility meters already exist [32], as do concepts for miniaturized seismometers [33], the elements of which could be flown in a ‘nanorack’. Particle Analyzers and Mass spectrometers, although limited in volume reduction because of the need for high voltage power supplies, can potentially be redesigned with multiple smaller dimension collectors with smaller overall volume, and be deployed as ‘nanoracks’ [34]. Progress does need to be made in creating versions of these instruments capable of very efficient, long duration operation in extremely cold, high radiation environments. Ray region instruments are particularly sensitive to radiation damage [25].

Technology Demonstration Supporting LunarCube: SmartSats is a planned flight demonstration of technologies in three key technology areas critical for low cost, high value operation in Earth orbit and beyond: 1) autonomous close proximity operations (relative orientation and positioning, docking, rendezvous, station keeping, deorbiting, interacting with chaotically tumbling targets) for a small swarm (3 active 3U CubeSats and one passive target) utilizing GSFC patented Synthetic Neural System Nervous Net Attitude Control and Neural Net Target Discrimination, Tracking, and Prediction leveraged from previously supported developments in support of NASA ST-8 choice driven system for an autonomous navigation demonstration, and DARPA System F6 intelligent decision engine, and 2) In-Space primary propulsion utilizing Busek resistojet thrusters with the relatively high Delta-V and high thrust required for proximity operations) leveraged from developments in support of the Air Force NanoSat Program; 3) Novel RF inter-spacecraft communication system requiring COTS omni-antenna and Honeywell Dependable Multiprocessor (DM) for processing leveraged from NASA ST-8 and the DOD SMDC TechSat. CubeSat bus design, building, integration, and testing will be provided by Morehead State University. The baseline new technologies will be exercised to characterize each spacecraft’s ability to take part in proximity operations. During an initial checkout phase, the focus is on demonstrating individual spacecraft capabilities that address BAA requirements. These include high precision control, microthruster propulsion, a full checkout of the sensor package, approach/avoidance maneuvering, and inter-spacecraft communications. Once key technologies are characterized, the SmartSat formation will provide a multi-spacecraft system that can be operated as one spacecraft. Starting with individual spacecraft, progressively more sophisticated on-orbit behaviors will be performed as experience
The orbits envisioned are at ~500km and mission lifetime between 6 months and a year. Most operations will have the spacecraft working in close proximity (<< 1km) and most work occurring at less than 10 m. We are examining formations requiring minimal ΔV and anticipate moving between “string-of-pearls,” “breathing,” and non-keplerian formations during different experimental phases involving multiple approach/avoidance and multi-spacecraft strategies. Onboard COTS GPS sensors will provide information for both onboard GNC and the ground-based planning & ephemeris support. HTSI and MSU ground segment resources provide the excellent telemetry and command coverage needed for proximity operations testing.

**Current Status of LunarCube**: We are developing a prospectus and requirements document and strawman kit to support phase 1 and phase 2. The first International LunarCube workshop to evolve those requirements and a preliminary design for the LunarCube platform will be held in early November of 2012 [35].