

LunarCube: Using the CubeSat Approach to Support Access to Deep Space for Science-Driven Exploration via the Lunar Surface

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Take Home Message:

Problem: How to meet ambitious exploration goals and provide cutting edge science while expending far fewer resources

Proposed Solution: LunarCube, an extension of the affordable and successful CubeSat approach, to facilitate access to the Moon.

Whereas:

Funding is declining, costs increasing for conventional planetary exploration.

very low-cost CubeSat model now significant method for access to LEO, evolving from standardized package kits to science-driven, multi-institutional, multi-platform and second generation design. Extensive NSF and NASA subsidized use in academia created 'hands on' experience for this generation of students

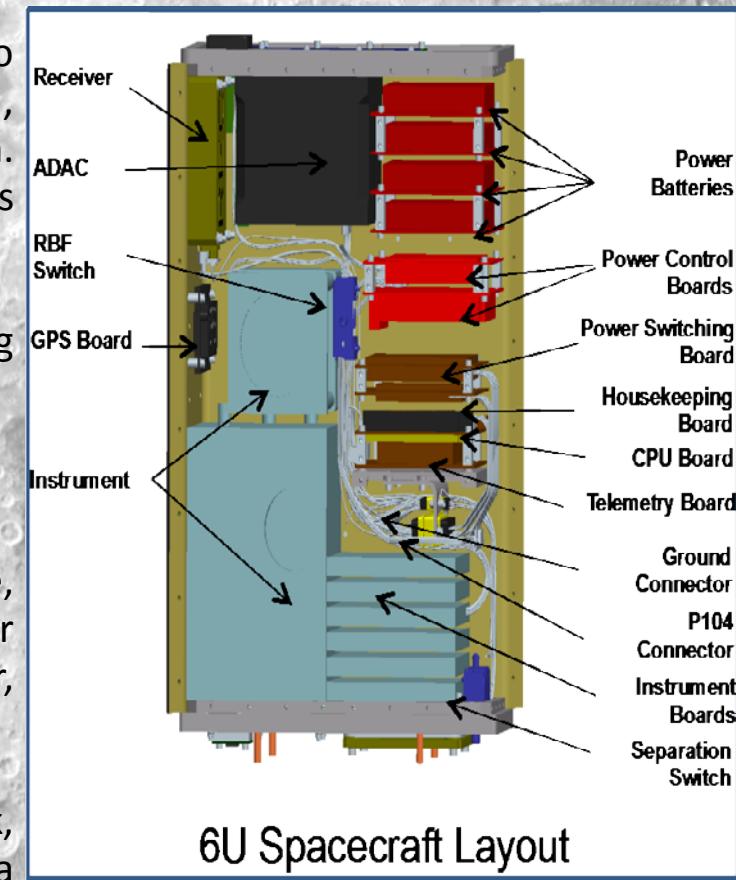
interest in this approach for deep space applications growing dramatically (MIT Interplanetary CubeSat Meeting)

GSFC, WFF, and collaborators (See 6U Layout) are:

examining use of analogous framework for access to deep space, supporting representative cross-section of lunar, Mars, and other applications at varying degrees of difficulty (flyby, probe, orbiter, lander)

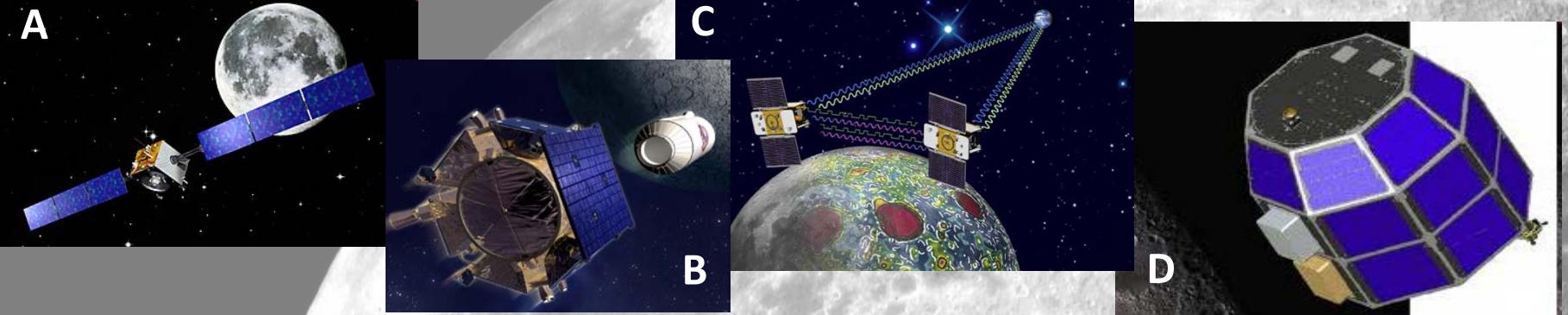
Incorporating science concepts and requirements framework, identifying modifications and new technology needed to support a science-driven deep space model, in order to

design a deep space prototype bus, and a prototype for a candidate mission



Why the Moon?

- The Moon is the closest and most accessible extraterrestrial frontier.
- The lunar surface, represents a great portion of the entire range of conditions found throughout the solar system due to its
 - Rugged terrain
 - Long diurnal cycle
 - Varying extreme thermal/illumination conditions particularly in polar regions
 - Space radiation environment
 - Analog conditions for most of the real estate in the solar system
- The lunar surface is thus an ideal ‘test bed’ for
 - exploring planetary surface processes and origins
 - developing core technologies required for planetary exploration.
- Any sound approach to planetary exploration should prioritize access to the Moon



Lunar “Small” Heritage

- A SmallSat SMART-1
- B SmallSat Impactor LCROSS
- C Distributed SmallSats Grail
- D SmallSat LADEE

Some LunarCube Proposed Concepts

- Distributed CubeSats Lunar Swirl Impactors
- ColdCube orbital tech demo, science lander
- Solar Occultation Orbiter (LunarSox)
- Global Water Distribution from L1 and Orbit
- Solar-induced Dusty Plasma Processes Orbiter
- In-Situ Sample/Surface Characterization Network
- Geophysical Surface Package Network (ILN)
- Environmental Surface Package Network
- Heliophysical or Astrophysical Observatory Lander

Table 1 Stakeholders

Science User Communities	Geoscience Studies (Interior, Surface, Exosphere, Magnetosphere) Heliophysics Astrophysics/Astronomy
Providers	Standard Bus Subsystem Hardware Subsystem Software Launch System
Planners/Developers	Architecture Level (Program Managers, Designers) Project Level (Project Engineers, Designers) Instrument or Tool Developers Technology Developers
Institutions	NASA DOD, DOE, DOT Academia Big Aerospace 'New' Focused Capability Aerospace International Interests

CubeSat: Successful Basis of LunarCube Approach

CubeSat ‘kit’ approach to increase participation and access to Earth orbital space through standardization, facilitated implementation, reduced development costs, risks, time. Four key aspects include:

profile: short duration, low earth orbit;

form factor: 10 cm cubes (1U standard), typically containing structures with several options for standard overall lengths (from 0.5 to 3 U);

technology impact: low, incorporating off the shelf electronics and software;

risk: Class D, standardization resulting in multiple use ‘heritage’ and decreased impact and probability of failure AND lower cost

Result: Proliferation of participants, evidenced by migration from single educational to multi-institutional efforts leading to capability for multi-functional spatially and temporally distributed measurements, greater scientific impact. Evidence of basis for investment in sustainable infrastructure in Earth orbit.



CXBN
2U 2.5 kg 15W

Phasing in Enhanced Capabilities for LunarCube

Maintain same standard on risk to keep costs low, create basis for sustainable infrastructure beyond Earth orbit, provide interesting science and develop core technologies. Extend CubeSat concept in stages to include additional features directly relevant to survival

- 1) profile: increase duration from months to years;
- 2) form factor: grow to at least 6U as needed;
- 3) active spacecraft attitude control, inter-spacecraft distance and direction knowledge and control (formation flying), in-space propulsion, made low resource and sustainable with onboard intelligence, particularly for multi-platform operation
- 4) information transfer: low power, higher bandwidth long-range communication, inter-spacecraft communication, C&DH to support onboard processing, made low resource and sustainable with onboard intelligence, particularly for multi-platform operation,
- 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, power storage developments for deep cryo operation, more efficient power production at greater solar distances.

Phasing in Extended Capabilities for LunarCube

Stage 1.0 Earth to Earth Orbit or cis-lunar space (Example Communication Station) supporting demonstration of core technologies, including propulsion, communication, and onboard intelligence, cis-lunar science missions and asset placement.

Stage 1.5 Earth to Lunar Surface (Example Environmental Monitor): Partial accomplishment of extreme environment survival and operation, supporting multiple platform or ‘nanorack’ access, for at least a limited duty cycle on, the lunar surface.

Requires implementing technologies already available or under development

Stage 2 Earth to Lunar Surface with full operation anywhere on lunar surface

requires raising the technology impact, enabling incorporation of state of the art or even currently low TRL technologies in several key areas

Requires fully implementing onboard intelligence and deep cryo design in electronics, power systems, mechanisms (moving parts), precision navigation and control, and advanced payload integration.

Ultimately, LunarCube virtual ‘smart phone’ in, possibly in a ‘NanoRack’ with shared services (power, communication, data handling) representing a variety of reconfigurable experiments, as open access software applications as part of master workstation Network fortified with different functions with modularized ‘Cube Cloud Compute’.

Potential Instrument Payload Status						
Region	Type	Performance	Resources	Operational Constraints	Status	Candidate?
Ray Region	X-ray	Target Elemental Abundance, Radiation Background; in situ X-ray source, rapid composition assessment	3kg, <3U, <5W	solar illumination (orbital), nadir-pointing, collimation (target characterization), need solar monitor, high voltage power supply	Solid state compact XRS, concepts for in situ sample characterization	Close to cubesat ready, combined XRF/XRD w/in decade
	γ-ray and neutron	Target Elemental Abundance, H abundance, neutron and proton background; in situ neutron source, composition-dependent albedo	<5kg, 5U,<10W,	Nadir-pointing, collimation (target characterization), high voltage power supply, computationally intense, isolation	Concepts for compact GRS and NS components	3-5 1U cube modules w/in decade for combined γ-ray/neutron spectrometer
Visible/Near Visible	Vis/Near IR	Photo Interpretation, mineralogy (Fe-bearing for NIR), water components	2kg, 2U, 5W	Active pointing, variety of formats (wide and narrow angle) desirable, solar illumination selection and knowledge	Reasonable resolution digital camera, imaging spectrometer microsizing underway	Close to CubeSat ready. JPL M3 heritage
	UV	Atmosphere/exosphere species, surface Al-bearing minerals	3kg, 4U, 3W	Telescope optics geometry constraints, more sensitivity less resolution than mass spec	UVVS spectrometer used for Messenger mission	MASCS
LongWave (mid to far IR, uwave, radio)		Physical component and surface characterization	2.5kg, 5W, 4U (IR), 16kg,25W (SAR)	Nadir pointing, selection and knowledge of illumination (IR), (Accurate and precise pointing (radar)	Compact TIR, radio, need work on microsizing components for radar	Mini-TES, mini-SAR
Fields		Magnetic and gravity fields, interior characterization	<1kg, <1U, <2W	isolation	Microsized versions already	Close to CubeSat ready, ROMAP design line
Particle/Molecular		Electrons, ions, neutrals, gas molecules, dust distribution	3-5kg, 5-6U, 5-6W	spinning may be desirable (increase coverage), high voltage power supply, design depends greatly on application	Microsized and no moving parts sample characterization particle analyzer, mass spectrometer concepts	Multi-Cube modules within decade for electrons and ion; STROFIO rotating mass spec

Some Potential Science Applications

Target	Type	Description	Payload Need
Earth	Multi-platform (temporal and spatial distribution) system studies, interferometry	Flexible Climate, weather, space weather, disasters, human activity monitoring	1-2kg, 1-2U each
Earth Orbit	Large aperture Virtual reconfigurable observatories, technology testing	Solar, galactic, extra-galactic studies	1-2kg, 1-2U each
Moon	NIR Water distribution from L1/L2 (on way to Moon) and lunar orbit	Critical phase varying disk integrated and mapped variation in bound/adsorbed water	2kg, 2U (in 6U)
Moon	dusty plasma package in lunar orbit	Magnetic storm induced solar plasma/dust/exosphere interactions	2kg, 2U (in 6U)
Moon, Mars	In Situ Sample/Surface Characterization Network or rovers	Origin, distribution, sources of volatiles and major rock types	5kg, 5U each (in ??U)_
Moon, Mars	Geophysical Surface Network (seismic, mag field, heat flow	Interior structure and composition, dynamics	5kg, 5U each (in ??U)
Moon, Mars	Environmental Surface Network radiation/particle/dust/volatiles	'space weather' or weather/climate	5kg, 5U each (in ??U)
Moon	Penetrators with magnetometers	Origin of lunar swirl anomalies	2kg, 2U (in 6U)
Moon	Large aperture Surface Network low frequency radio receiver/antenna observatories	extrasolar planet magnetosphere detection; solar radio bursts; pathfind early universe studies	??
Moon	Solar occultation orbiter	Solar and relativistic studies	5kg, 5U (in 12U)
Small Bodies	'target of opportunity' multi-platform surveys	Asteroid populations, small moon populations of larger planets	2kg, 2U each (in 6U)

Table 2 Comparison Chart

Onboard Intelligence for Proximity Operations

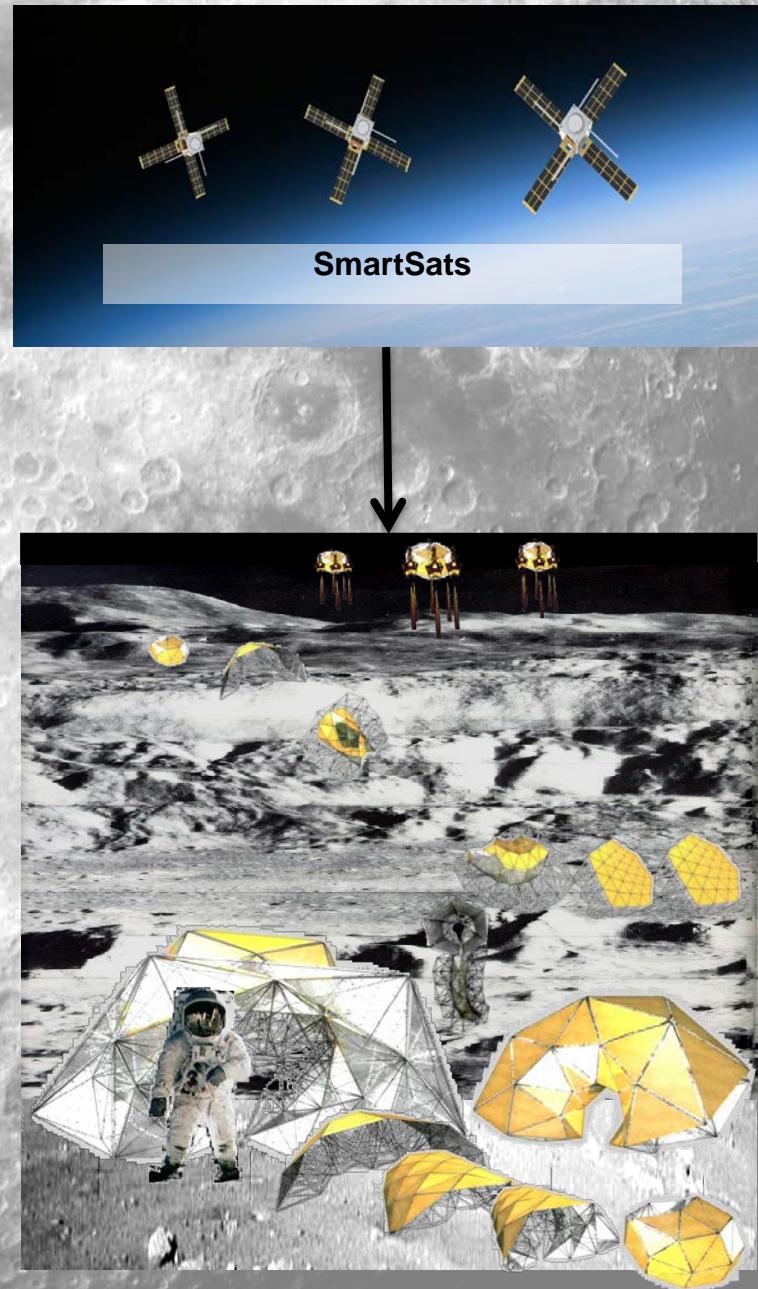
SmartSats Concept:

3 3U Morehead State University bus leveraging developments for NASA CXBE with 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 and DARPA F6.

Morehead State University 60GHz RF System with omni-antennas for distance and direction determination, inter-spacecraft communication, and atmospheric sounding

Honeywell Dependable Multiprocessor (DM), with GPS determination capability, leveraged from NASA ST-8 and the DOD SMDC TechSat.

In-Space primary propulsion utilizing Busek resistojet thrusters leveraged from developments in support of the Air Force NanoSat Program and demonstrating sufficient Delta-V and ISP to support our proximity operations



The Future

Successful incorporation of LunarCube approach will decrease costs for future planetary exploration by one or two orders of magnitude, provided continuous modest (compared to costs of flagship missions) investment in several core technologies.

One area of ‘core technologies’ are improving capability of miniaturized instruments, or testing and developing concepts for reduced volume of geometry-driven instruments.

Candidates for LunarCube approach could meet or exceed decadal survey objectives, including sample return (see Staehle, 2012, AIAA Space 2012) or considerably improved in situ measurements.

Several CubeSat-based missions could be flown for a small fraction of the cost of conventional missions (tens of millions as opposed to hundreds of million per year, based on, e.g., comparison of MIT ExoPlanetSat at \$5 M vs. the Kepler mission at \$600 M)

Many supporting technologies and some instrument systems could be demonstrated in orbit (5 to 10 LunarCube class for cost of one SMEX, even assuming costs are one order of magnitude greater than standard cubesat mission).

A minimal infrastructure, still under development by NASA in collaboration with the private sector, could get LunarCubes to GEO for low-cost providing access to cis-lunar/lunar space or the lunar surface to jump-start the process.

Conventional high priority Discovery, Frontier or Flagship class planetary mission concepts could be systematically replaced by distributed SmallSat network alternatives.

NASA OCT is providing opportunities (e.g., Edison, Franklin, GCT) to test core technologies on a variety of SmallSat platforms, providing the key technologies necessary for deep space operation, within the next 5 years. Cooperation with SMD and HEOMD would greatly facilitate that process.



Questions?
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CubeSat Systems and their implications for LunarCube

Sensor System defined by user

Telemetry, Tracking, Control (Communication) and Attitude Determination and Control (ADC)
(Stabilization, Navigation, Propulsion)

CubeSat typically uses GPS and passive stabilization (magnetic (line up with Earth's magnetic field) or gravitation (offset center of mass). LunarCube, to operate in deep space, must use active stabilization (sun sensors, star trackers, accelerometers, micro-thrusters or momentum wheels..adding mass and volume).

Power Generation and Distribution (PGD) (Power, Wire Harness)

LunarCube in later phases replace conventional with radiation hard, ultra low power, ultra low temperature electronics, power systems

Mobility

CubeSat relies on transportation infrastructure to Earth Orbit, as will LunarCube to points beyond Earth Orbit, and even on lunar surface

Layout Design, Circuit Board Design

Major Subsystems fit within Standard Housing, 'wired' to each other as appropriate, and properly Interfaced with Carrier/Launcher (up to 3U, 3 kg) in Earth Orbit.

Two Ways to hitch a ride to the Moon

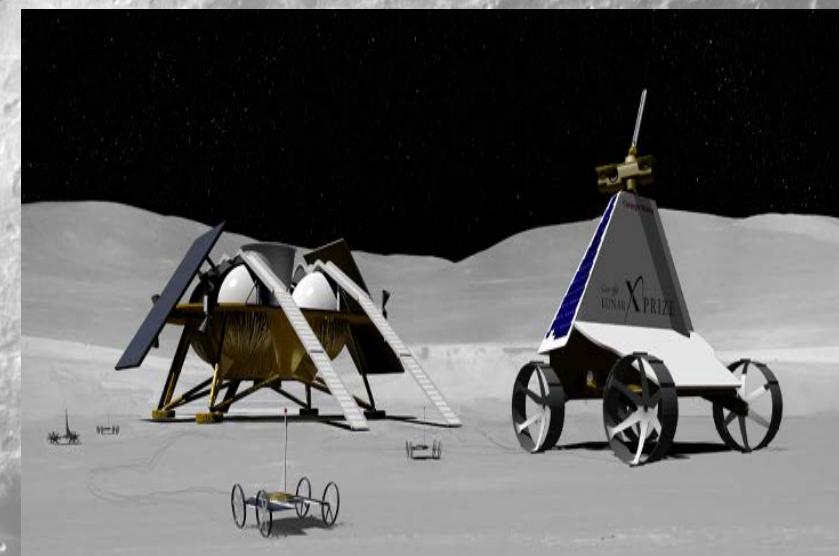
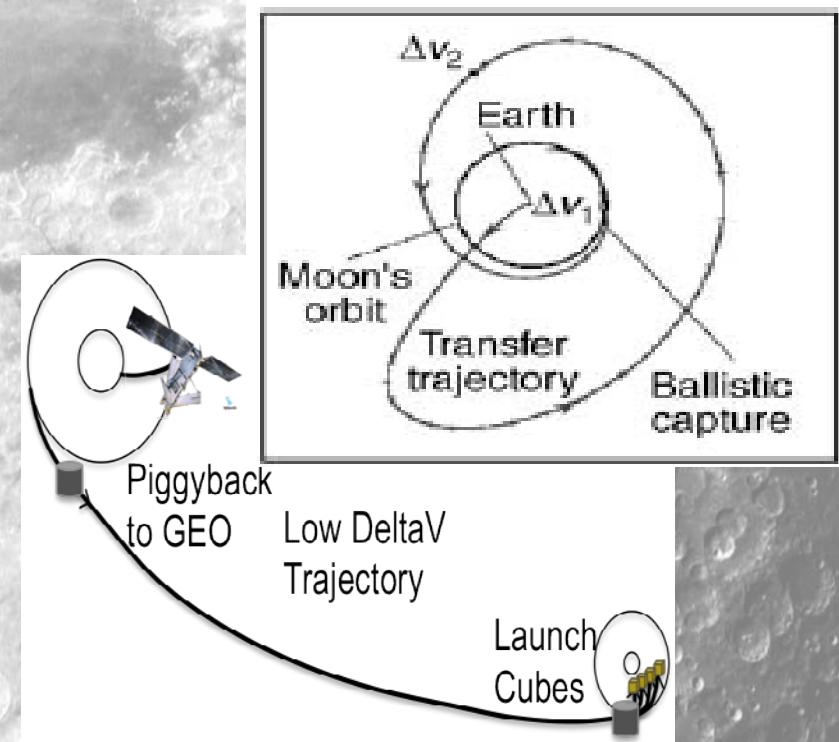
1) Lunar Swirls mission mode

- Hitch a ride on someone else's GEO insertion
- Use ultra-low Delta-V trajectory to Moon
- Ship launches LunarCubes in cis-lunar space
- 10-20/year GEO launches next decade
- Potential 10+ orbital opportunities next decade

2) Ride along on a lander

- The Astrobotic lander has several 100 U worth of space under the lander deck
- Hitch a ride on one of their demonstration missions or fly standby on future paid missions
- Assume 3 Google XPrize teams fly 1-2 missions
- Assume 3 national programs fly 1-2 landers
- Potential 10+ lander missions in 2015 - 2025

Thus, potential 20+ opportunities for near-zero launch cost missions in 2015 - 2025.



Two models CubeSat/Implications for Development, Implementation, and Operation

Conventional Single Cube

LunarCube requires innovative design of housing for greater thermal and space radiation protection, active stabilization, with associated mass and volume penalty

LunarCube requires longer duration operation in more extreme environments requiring greater interconnectivity and complexity in design, flight plan and operation

Advantageous for current applications needing distributed self-similar assets

Payload Cube Rack with Shared Subsystems

Dedicated Instrument Cubes with standardized interfaces to connect to external dedicated and shared subsystem cubes.

Greater need for Early Phase Planning and greater integration and testing efforts upon cube delivery before launch

Simpler individual cube design, savings of mass and power in return for greater need for planning and operational complexity

Appropriate for applications needing current in situ complexity, or future distributed reconfigurable assets

Table 1 CubeSat Technology Development

Time Frame	2000-2005	2005-2010	2010-2015	2015-2020	2020-2025
Target	Earth Orbit		to Lunar Orbit		to Lunar Surface and beyond Earth-Moon system
Costs	<<1 million		millions		tens of millions (or less) depending on number and type of participants
Science	incremental	platforms providing monitoring in orbit, in situ measurements, measurements, somewhat more useful Earth Ap	testing multi-platform with identical instrument packages of known position, allowing temporal and spatial resolution of 3D systems, interferometry	fully implement formation flying in orbit and into deep space as basis for sophisticated survey or 'discovery' science	nanorock, distributed, fractionated applications
Core Capabilities					
CubeSat Bus	basic bus and deployment system	standardization	6U with robust deployment system, standardization	Earth-Moon, testing for lunar orbit	3D control for landing on Moon
In-Space Propulsion	testing for Earth orbit	Earth orbit, testing for Earth-Moon	testing active for controlled operation, formation	Earth-Moon, testing for deep space	landing
Advanced GNC	innovative passive				
Communication	UHF	UHF, S band, standardization	UHF, other options, testing intra-spacecraft comm (selected frequencies or laser) in Earth orbit	intra-spacecraft comm Earth-Moon, testing for deep space	relay from lunar surface
Power		Incorporate more robust, more efficient batteries, increase effective surface area solar panels for deep space	test more compact batteries for longer duration, lower temperature limited duty cycle	surface operation	24/7 operation without RTGs anywhere on lunar surface
Onboard Intelligence/processing	simulation	testing for proximity operations, processing	testing for entire system control		autonomic 'synthetic nervous system' w/ or w/out humans in loop
Thermal/Mechanical Design		apply and test design for deep space (cold T, high radiation)	perform on limited duty cycle on lunar surface, apply and test design for cryo conditions	anywhere on lunar surface	

The Extreme Lunar Environment

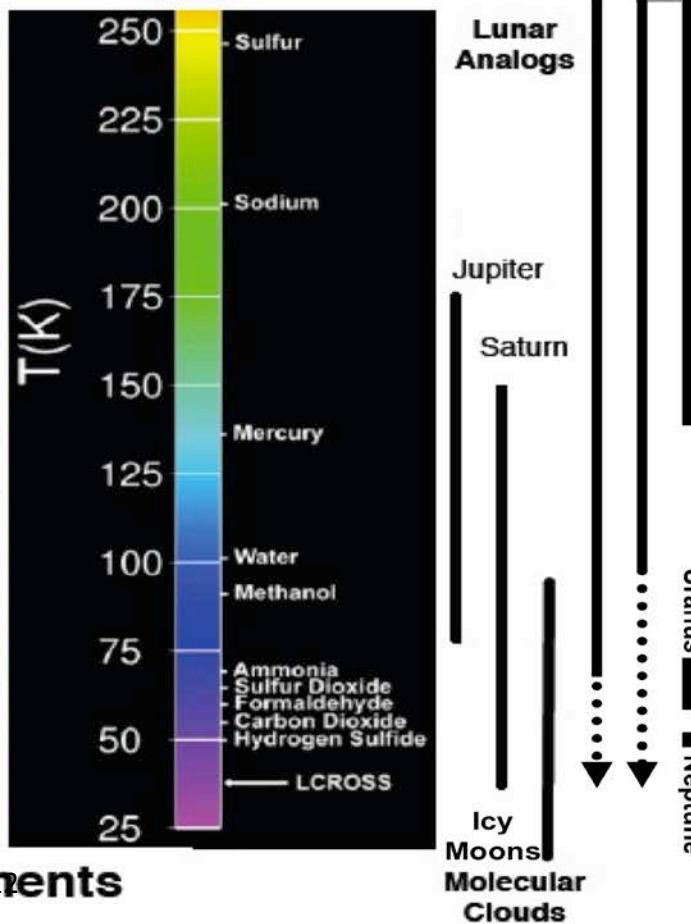
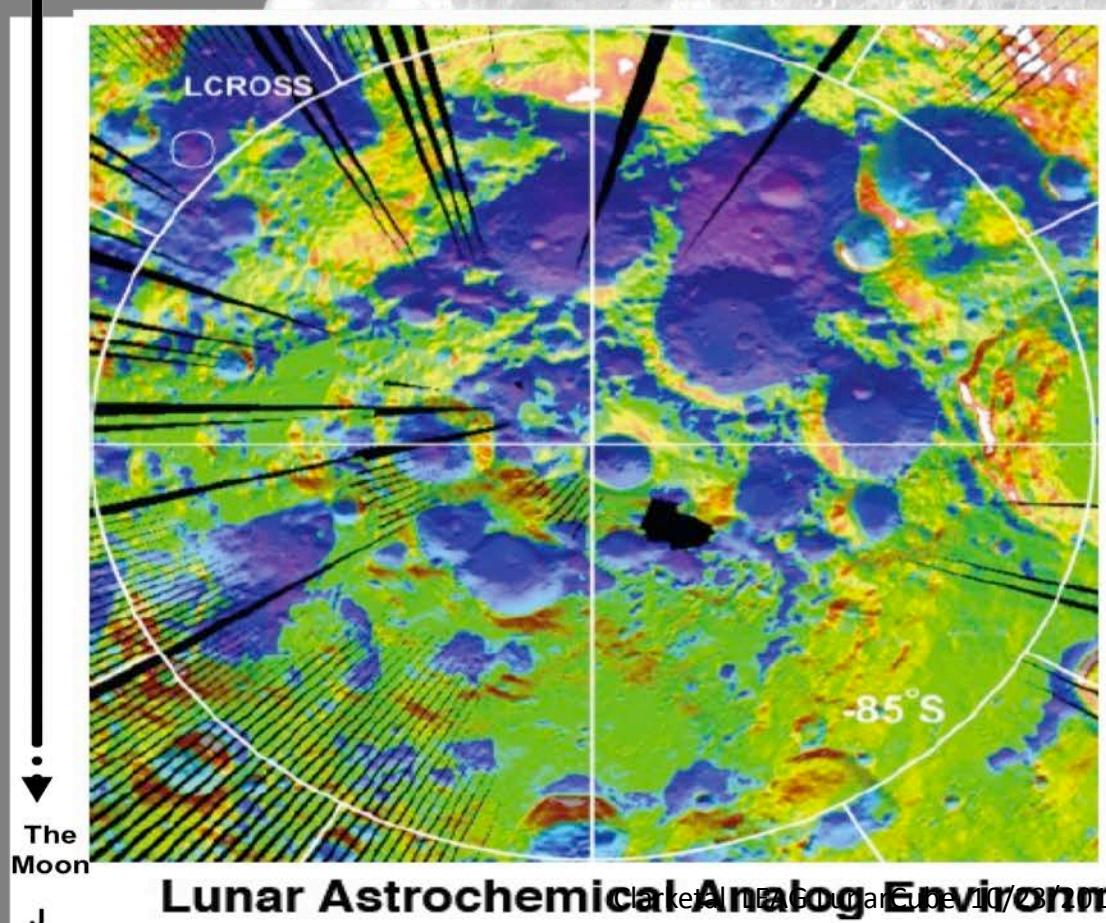
Thermal Extremes

Unmitigated Space Radiation

Abrasive Dust

Location	Day Temperature and Length	Night Temperature and Length
Low Latitude	400K, 14 days	120K, 14 days
Near Polar	220K, permanent	<25K, permanent

Mercury
NEOs
Mars



Newly Discovered Processes involving Volatiles on the Moon and by Implication Elsewhere

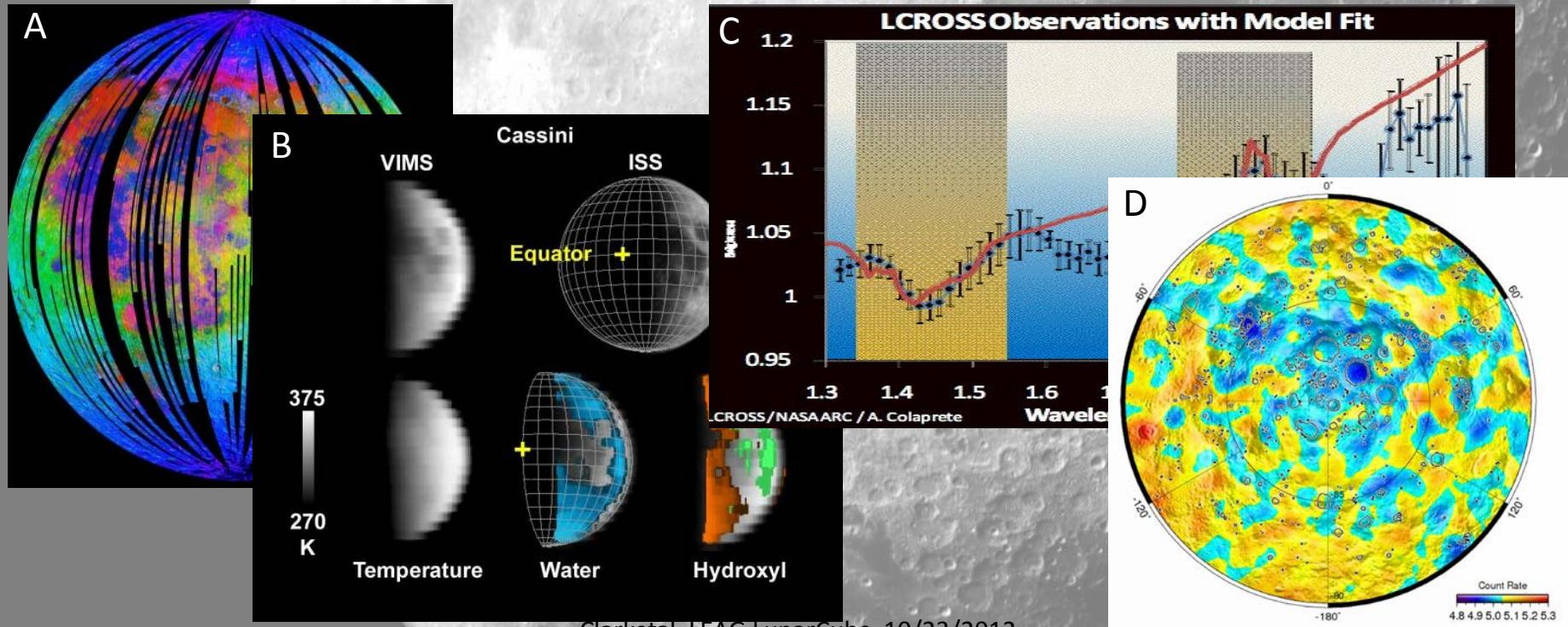
The presence of volatiles and complexity in their distribution has been confirmed from several recent sources:

Near IR temperature-dependent diurnally varying surface water and mineral bound water bands from Chandrayaan M3 and Cassini VMS (A, B)

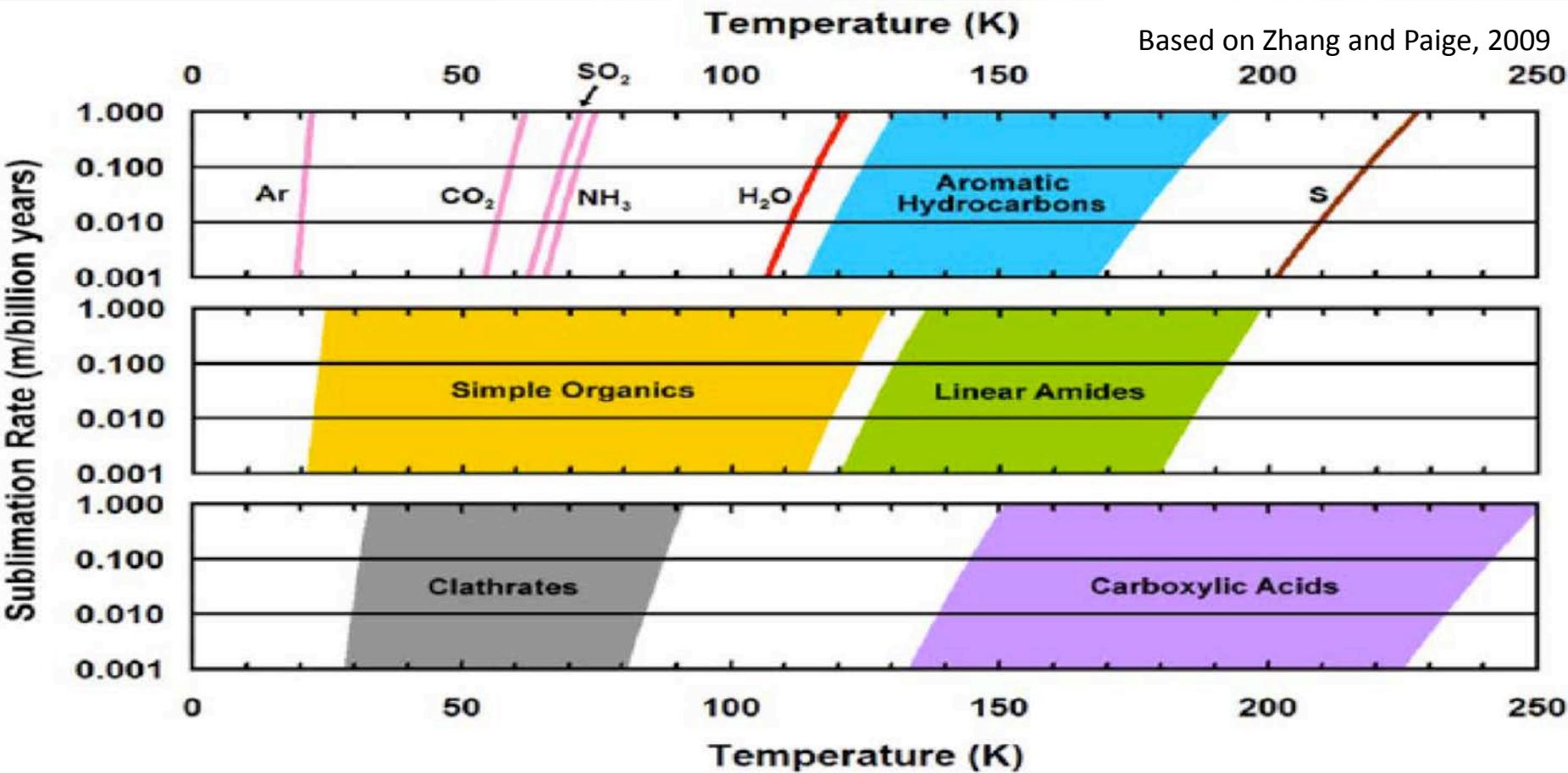
possible surface water, unidentified volatile bands induced by impact (LCROSS) (C);

LRO LEND hydrogen-dependent (to 1 meter depth) depressed epithermal neutron flux (D).

Ground based radar confirmed polar ice deposits and MESSENGER XRS confirmed presence of sulfur on Mercury.



Volatile Activity as a Function of Temperature on Atmosphereless Bodies



- Vacuum evaporation rates calculated as function of temperature for representative organic and inorganic compounds. In terms of volatility (F):
 - inorganic volatiles (except S), simple organics, clathrates > Water
 - Water > aromatic hydrocarbons, linear amides, carboxylic acids

Frontier, Intelligent Decision Engine for Stable Adaptable Complex Systems

P.E. Clark,¹Catholic University of America, Team Lead

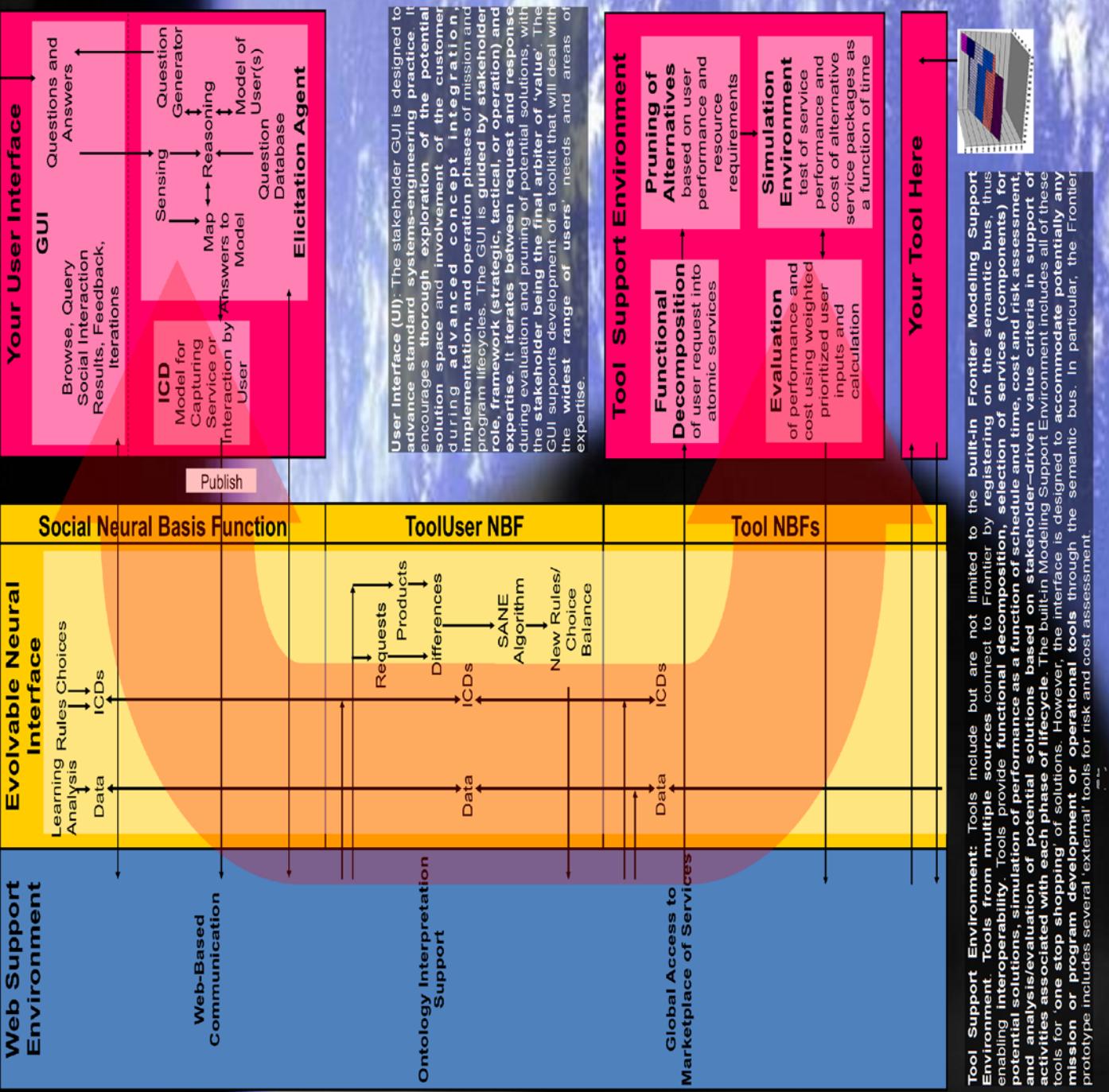
M.L. Rilee², S.A. Curtis³, S.C. Bailin⁴

²Rilee Systems Technologies LLC, ³Terubotics, ⁴Knowledge Evolution Inc.

Overview: Frontier is an adaptable, stably reconfigurable, web-accessible intelligent decision engine. Frontier, when completed, will be capable of optimizing the designing, simulating the operation of, and operating complex systems - particularly multi-asset systems distributed spatially and temporally, in response to evolving needs and environment.

Intelligent Decision Engine (IDE): The most innovative aspect of Frontier, the IDE absorbs and utilizes lessons learned, thus morphing from a tool to a tool user. The IDE is an adaptable framework based on a genetic algorithm and semantic neural system, with a stability algorithm that balances rules (the "emotional" component) and choices (the "reflective" component). The IDE will be increasingly capable of dynamically reconfiguring parameters and rules for the selection of tools best matched to stakeholder needs. Through the IDE, Frontier serves as an adaptable design tool, enabling development and utilization of highest-value support cluster assets for the widest range of stakeholders, and matchmaking to encourage investment in technologies required to support cluster flight.

Web Support Environment (WSE): Frontier, using a semantic bus implemented via the W3C semantic web standard (OWL), will support distributed, multi-user, concurrent access to resources and tools, including the human and tool interfaces, modeling and development services, databases, simulation, scenario development, analysis, and evaluation. Through the semantic bus, the WSE supports open interface standards for adaptably sharing virtually any tools and models as resources.



Impact: How Frontier Advances State of the Art

The Evolving Neural Interface of the Synthetic Nervous System (Intelligent Decision Engine) supports advanced heuristics by balancing rules and choices in design process.

Unlike previous design tools, we **don't use rules alone, simply adding more rules as complexity increases**, actually becoming more brittle.

Our 'rules' are deterministic if/then statements. 'Choices' our non-deterministic aspects of design.

In primitive natural systems, simple, efficient rules are hard coded by evolutionary processes (core rules), or learned from experience in survival (situational rules). We have core and situational rules.

We go beyond limitations of such 'rules of thumb' heuristics to include and profile choices from a variety of individuals, thus eliminating cognitive biases occurring in such systems.

Involve, iterate between demand and supply perspectives in development and execution for 'training'

	Situational <i>associated with structure & behavior of solutions</i>	Core <i>associated with structure & behavior of Frontier</i>
Rules <i>predicate-consequent i.e. requirements</i>	Operational Scenario Elements -Demand Spec Models -Supply Spec Models	NBF Behaviors -Translations & Learning -Data Flow & Capture -Algorithm Implementation -Tool & Component Integration
Choices <i>pattern recognition & heuristic/fuzzy logic i.e. nondeterministic</i>	Engineering Alternatives -Providers -Systems -Subsystems -Models	Tools -Frontier MSE -Previous F6 VCDM Tools -TA1-4 Tools -NBFs & the Web

