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

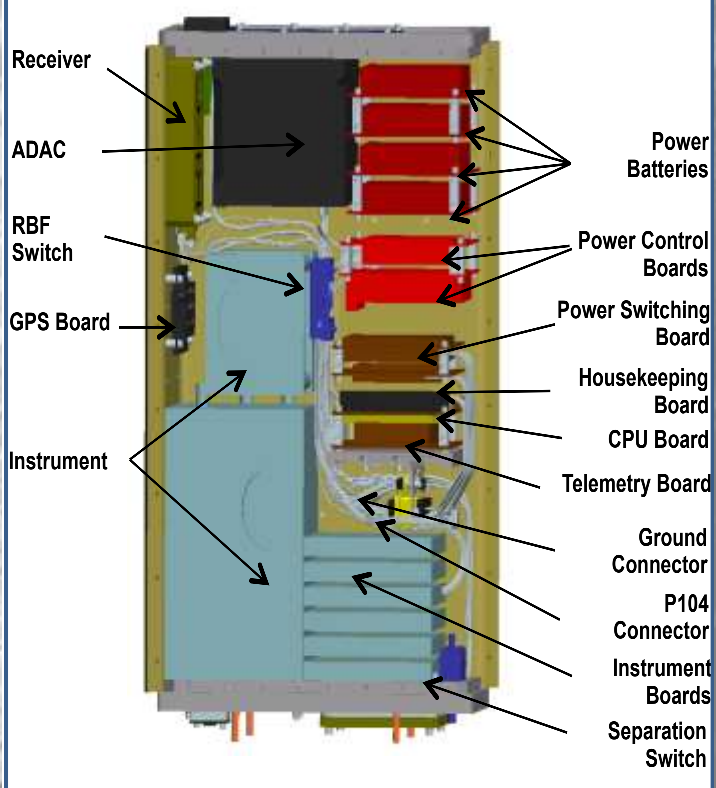
interest in this approach for deep space applications growing dramatically (MIT Interplanetary CubeSat Meeting)

GSFC, WFF, and collaborators 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



6U Spacecraft Layout

Why the Moon?

•The Moon is the closest and most accessible extraterrestrial frontier.

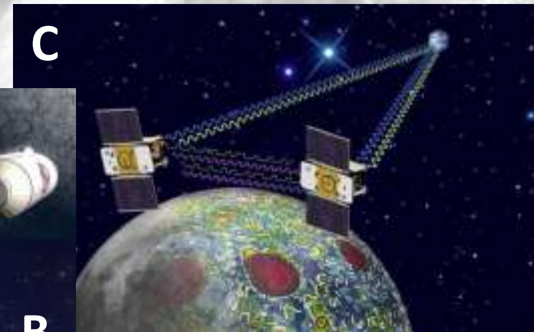
•The lunar surface, represents a great portion of the entire range of conditions found throughout the solar system due to its

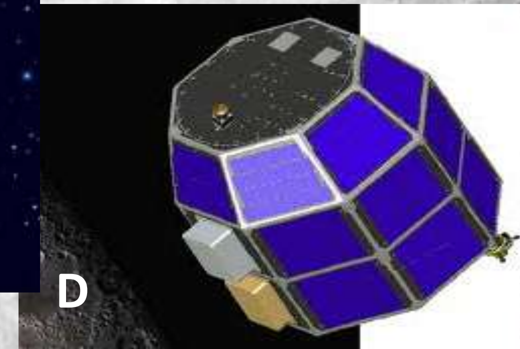
- Rugged terrain
- Long diurnal cycle
- Varying extreme thermal/illumination conditions particularly in polar regions
- Space radiation environment
- Analog conditions for most of the real estate in the solar system

•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
SmallSat SMART-1
SmallSat Impactor LCROSS
Distributed SmallSats Grail
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): Accomplishment of 1, 2, partial accomplishment of 3 (control) and 4 (information transfer).

Stage 1.5 Earth to Lunar Surface (Example Environmental Monitor): Partial accomplishment of 5 (environmental design) supporting multiple platform or 'nanorack' access, survival and operation for at least a limited duty cycle on, the lunar surface.

Requires implementing technologies already 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 'under development' 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.

Full operation on the lunar surface would be possible Ultimately, LunarCube virtual 'smart phone' 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 combined XRF/XRD	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

Spacecraft	#	Level	Total Mass	Total Cost $	Cost $ Launch	Notes
Track Record						
1U CubeSat	1	Standard Educational	1 kg	55K	15K	Based on Heyman, 2009
1U CubeSat	3	Standard Educational	3 kg	140K	45K	Same launch cost (3U volume in PPOD), first model highest cost
3U CubeSat	1	Standard	3-4 kg	110K	45K	Cost more than 1U, but, unlike 3 1U, can share systems
3U CubeSat	3	Standard	9-12 kg	290K	135K	Need 3 slots, 1 per PPOD
3U CubeSat	1	Standard bus, Active, Tech Demo	4 kg	4.5M	1M	Standard bus, but active propulsion, greater risk mitigation, more expensive launch, new technologies development costs
3U CubeSat	3	Standard bus, Active, Tech Demo	12 kg	11M	3M	Compare 1 and 3 3U costs
Conventional Missions						
Secondary: LCROSS	1	One of a kind/much COTS, Class D	1768 kg	79M	250K	LCROSS 'launch' cost is the ESPA ring for the Atlas V launching LRO the primary payload
SmallSat: GRAIL	2	One of a kind w/ some reuse GRACE	466 kg	496M	51M	
Discovery:MESSENGER	1	One of a kind, Class A	510 kg	450M	45M	
New Frontiers: New Horizons	1	One of a kind, Class A	478 kg	700M	138M	
Flagship: MSL	1	One of a kind, Class A	3893 kg	2.5B	175M	
Great Observatory: Spitzer SpaceTelescope	1	One of a kind, Class A	950 kg	2.2B	50M	
Projected Costs when 'new capability' needed by LunarCube, and support for active propulsion, become 'standard'						
6U CubeSat/LunarCube	1	Bus standard with new capability	12 kg	5M	500K	Based on NASA Wallops preliminary study for Earth orbit plus propulsion system and other capabilities for LunarCube estimate
6U CubeSat/LunarCube	3	Bus standard with new capability	36 kg	12M	1.5M	Compare 1 and 3 3U costs
Projected NASA Planetary Decadal Survey Cumulative Costs for Next Decade						
Discovery Class	5	One of a kind, Class A	?	2.5B	?	Candidate Field Open (500M/mission)
New Frontiers Class	2	One of a Kind, Class A	?	2.1B	?	Select among Comet Sample Return, Lunar Sample Return, Saturn Probe, Trojan Tour, Venus Explorer, Lunar Geophysical Network, Io Observer (1.05B/mission)
Flagship Class	1	One of Kind, Class A	?	2.5B	?	All candidates above cost cap: Mars Sample Return (3.5B), Jupiter Europa Orbiter (4.7B), Uranus Orbiter Probe (2.7B)

Toward Onboard Intelligence

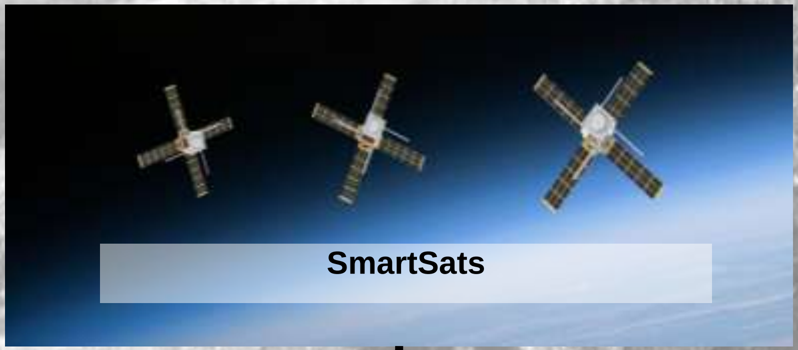
SmartSats Concept: 3 3U Morehead State University bus leveraging developments for NASA CXBE with

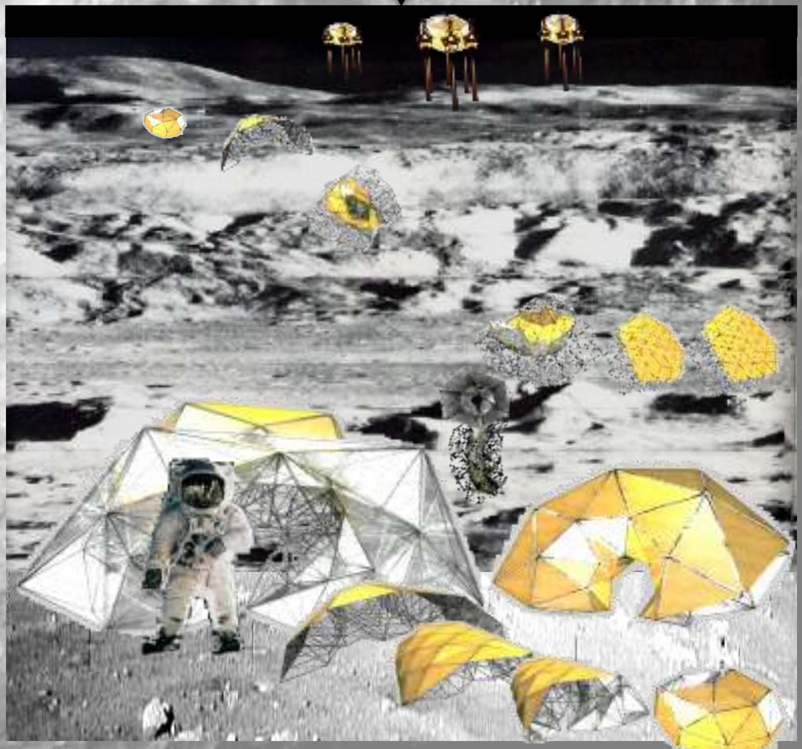
GSFC patented Synthetic Neural System Nervous Net Attitude Control and Neural Net Target Discrimination, Tracking, and Prediction leveraged from previously supported developments in support of NASA ST-8 and DARPA F6.

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?

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

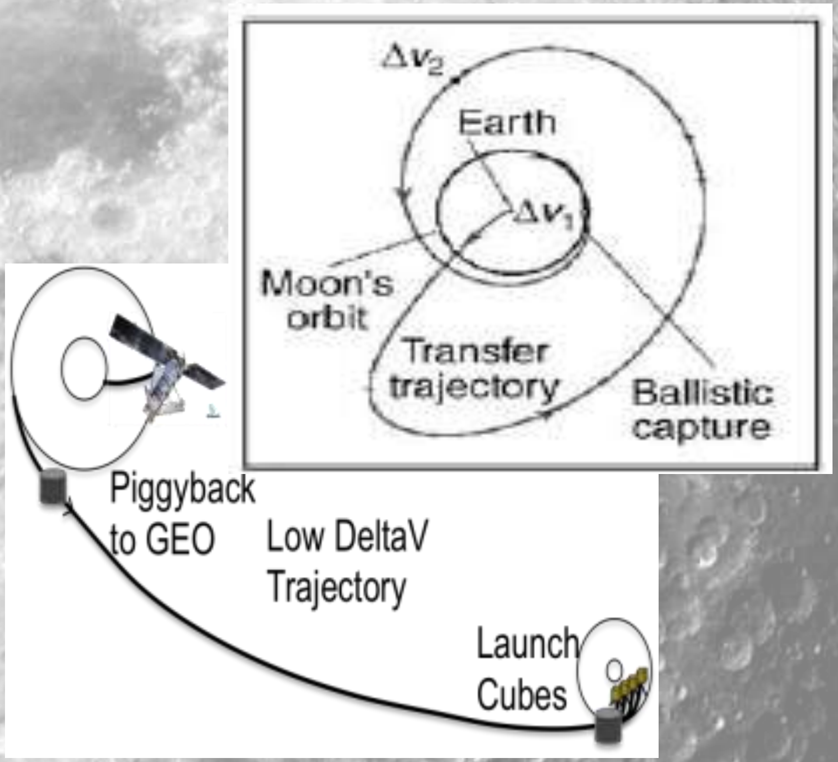
2) Ride along on a lander

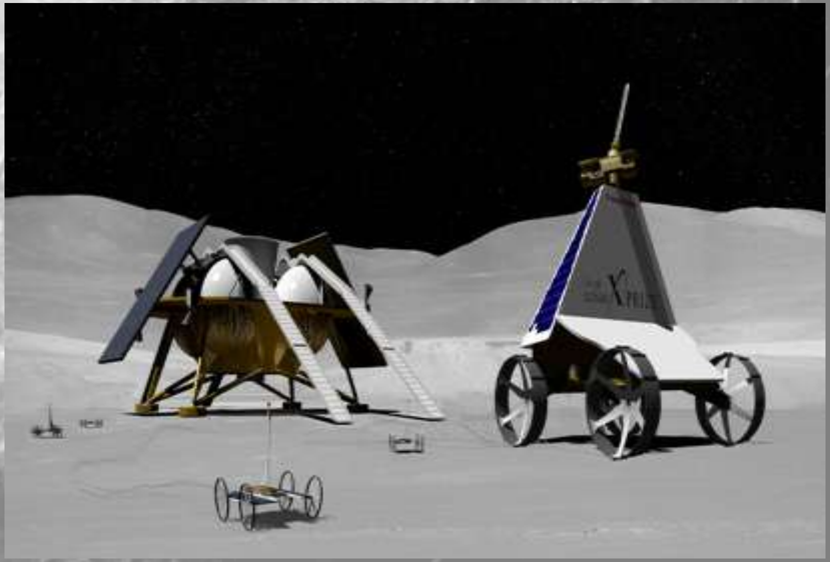
- The Astrobotic lander has several 100 U worth of space under the lander deck

- 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

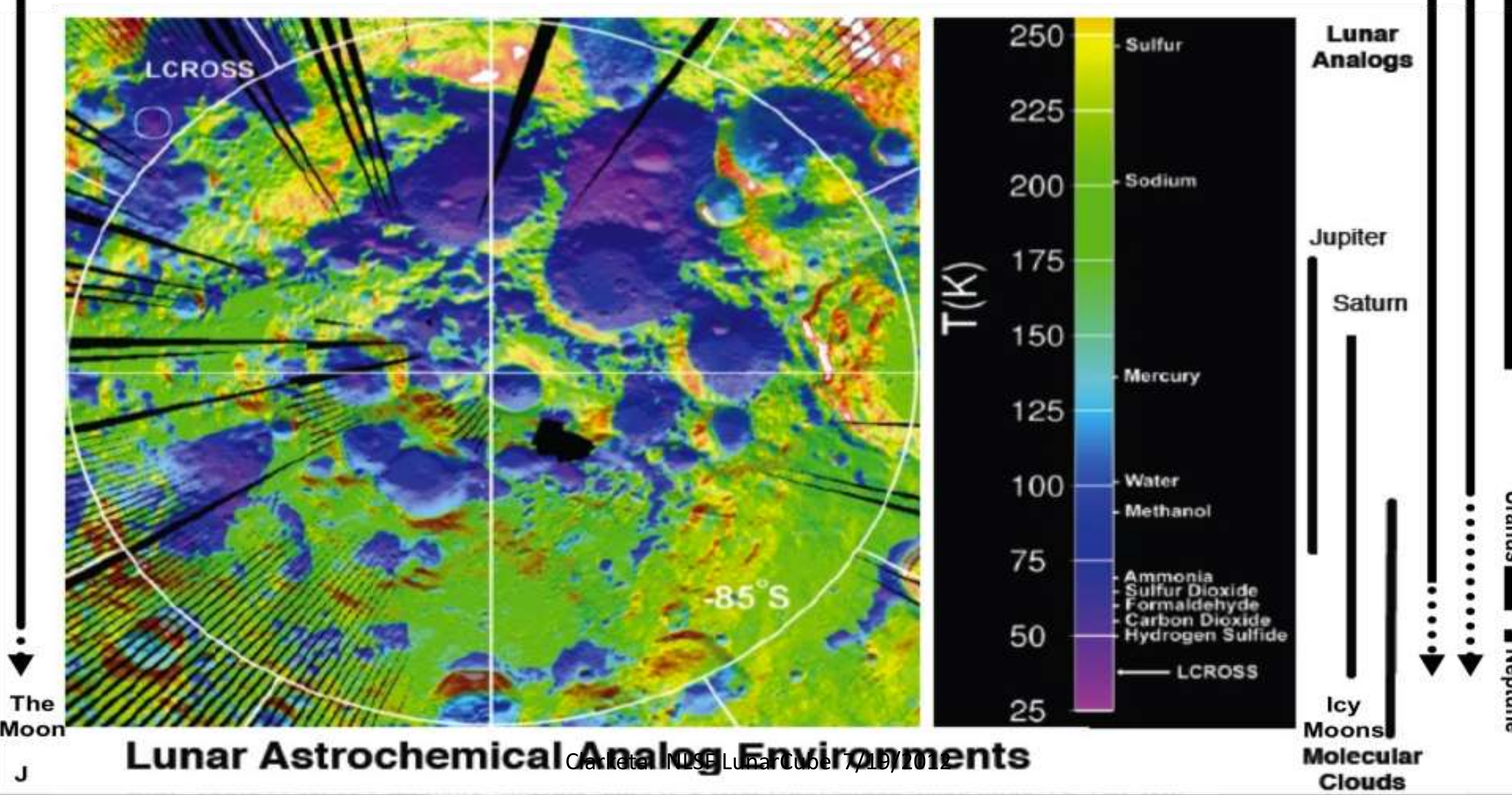
Table 1 CubeSat Technology Development

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	monitoring in orbit, in situ measurements, incremental	platforms providing complementary 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 science	survey or 'discovery' science
Core Capabilities					
CubeSat Bus	basic bus and deployment system	standardization	6U with robust deployment system,	standardization	nanorock, distributed, fractionated applications
In-Space Propulsion		testing for Earth orbit	Earth orbit, testing for Earth-Moon	Earth-Moon, testing for lunar orbit	3D control for landing on Moon
Advanced GNC		innovative passive	testing active for controlled operation, formation	Earth-Moon, testing for deep space	landing
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	24/7 operation 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



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

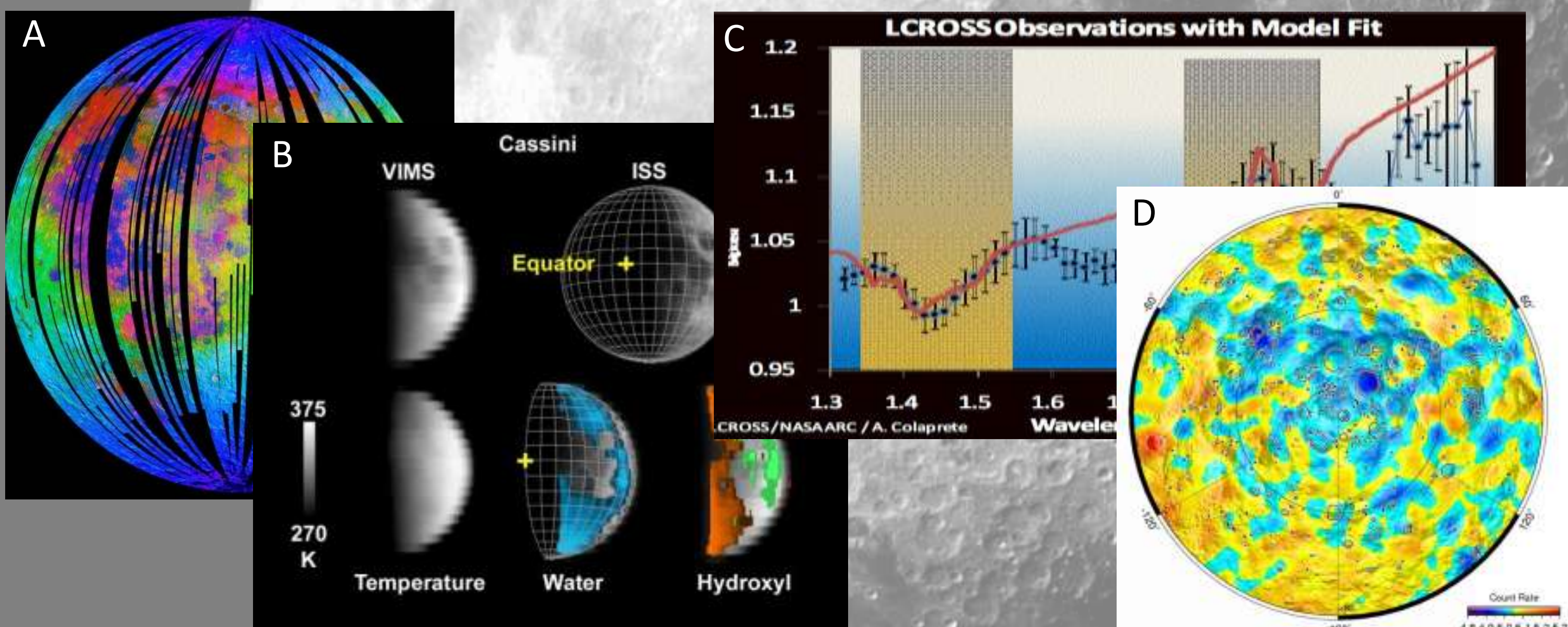
The presence of volatiles and complexity in their distribution has been confirmed from several recent sources:

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

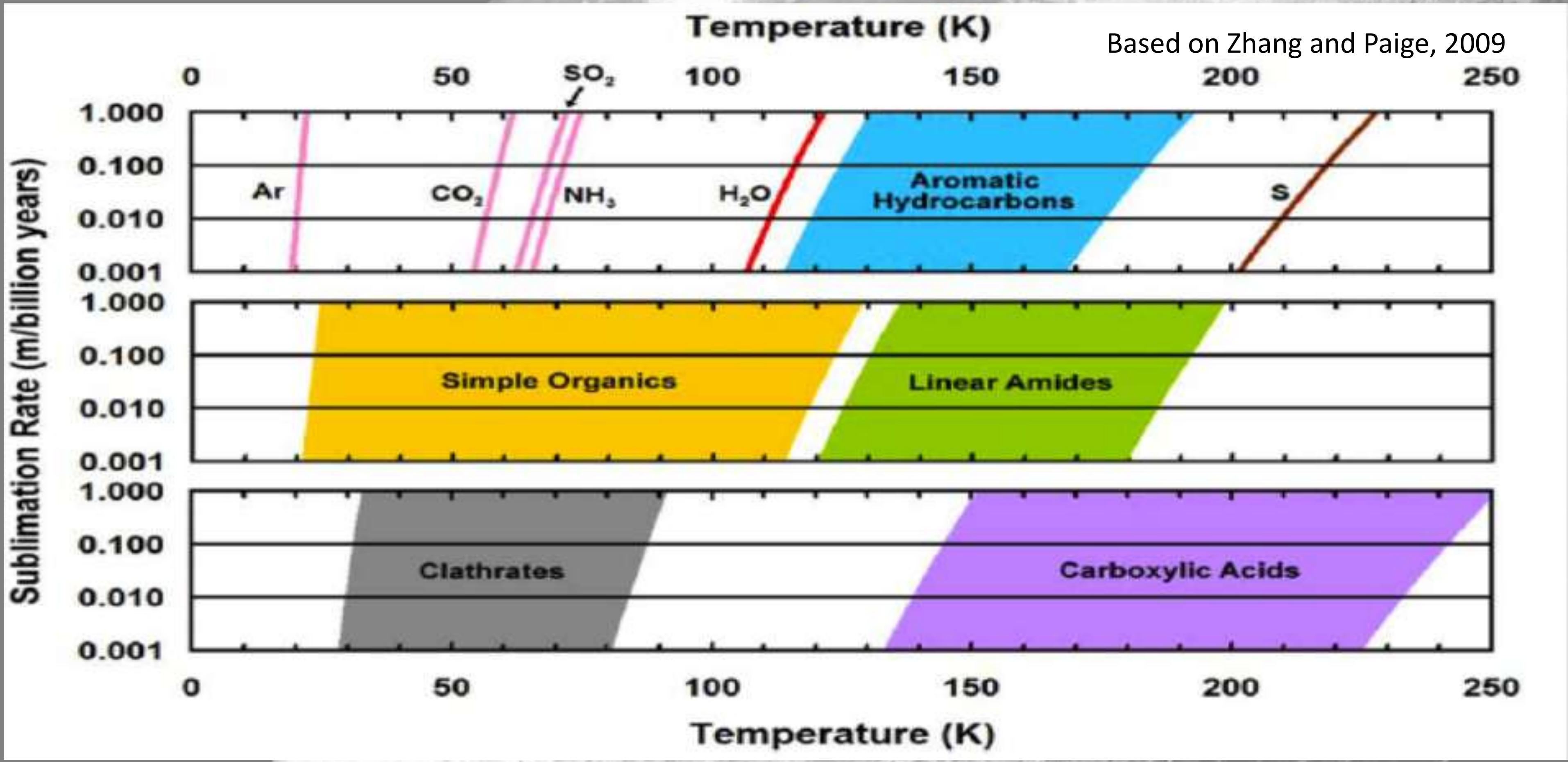
possible surface water, unidentified volatile bands induced by impact (LCROSS) (C);

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

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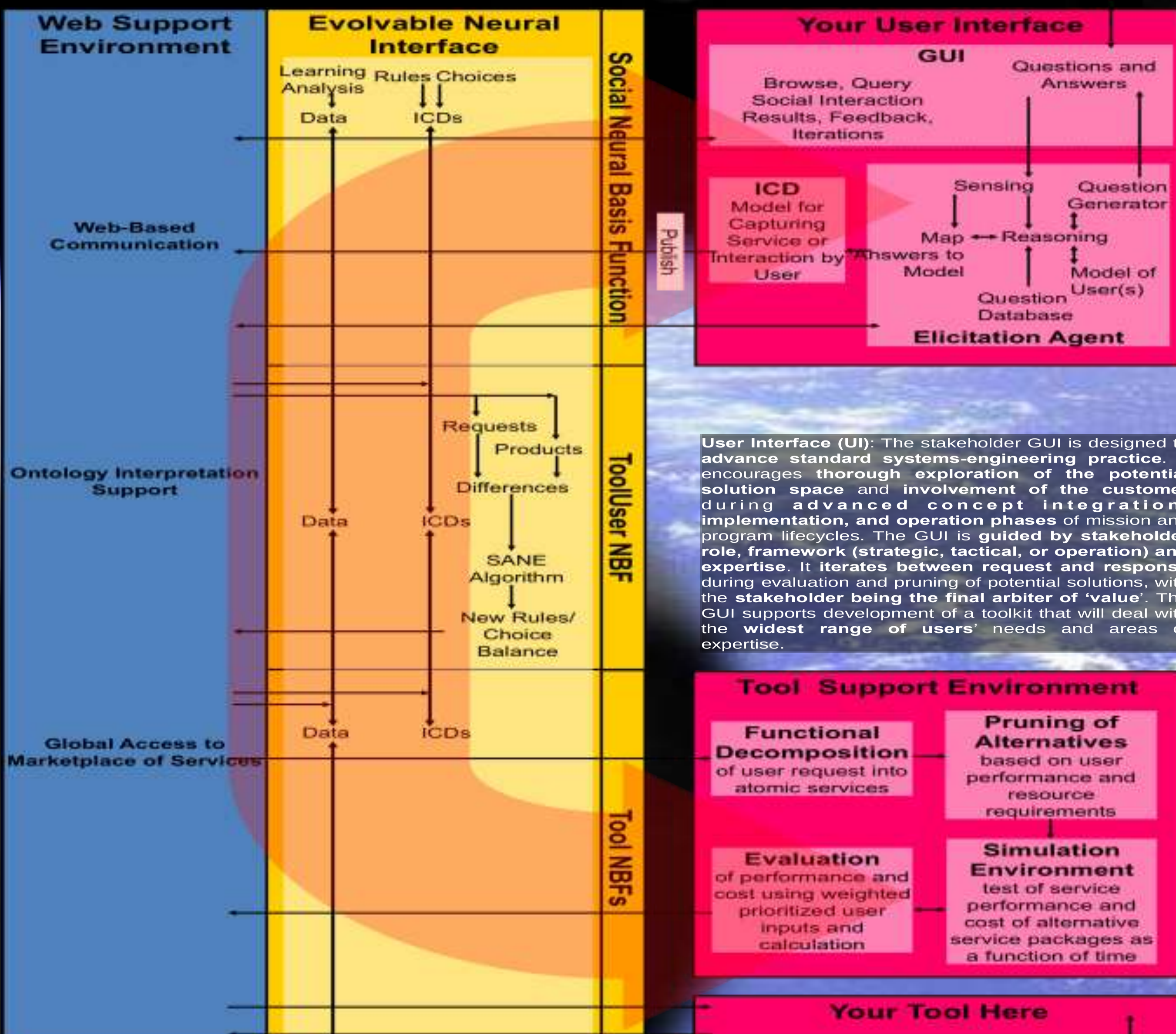
Overview: Frontier is an **adaptable, stably reconfigurable, web–accessible intelligent decision engine**. Frontier, when completed, will be capable of **optimizing the designing, simulating the operation of, and operating complex systems** - particularly multi–asset systems **distributed spatially and 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 synthetic 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 fractionated 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.



User Interface (UI): The stakeholder GUI is designed to **advance standard systems-engineering practice**. It encourages **thorough exploration of the potential solution space** and **involvement of the customer during advanced concept integration, implementation, and operation phases** of mission and program lifecycles. The GUI is **guided by stakeholder role, framework (strategic, tactical, or operation) and expertise**. It **iterates between request and response** during evaluation and pruning of potential solutions, with the **stakeholder being the final arbiter of 'value'**. The GUI supports development of a toolkit that will deal with the **widest range of users'** needs and areas of expertise.

Tool Support Environment: Tools include but are not limited to the **built-in Frontier Modeling Support Environment**. **Tools from multiple sources** connect to Frontier by **registering on the semantic bus,** thus enabling **interoperability**. Tools provide **functional decomposition, selection of services (components) for potential solutions, simulation of performance as a function of schedule and time, cost and risk assessment, and analysis/evaluation of potential solutions based on stakeholder–driven value criteria in support of activities associated with each phase of lifecycle**. The built-in Modeling Support Environment includes all of these tools for '**one stop shopping**' of solutions. However, the interface is designed to **accommodate potentially any mission or program development or operational tools** through the semantic bus. In particular, the Frontier prototype includes several 'external' tools for risk and cost assessment.

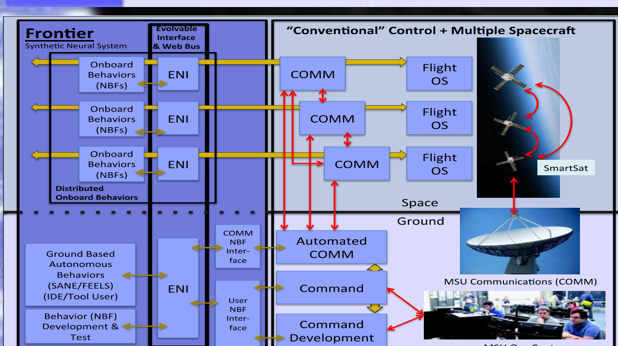
Resource(Requirements

Requirement	Available	Margin	Bus(minus(Comm	Comm	60GHz	DM	Prop
Mass(kg	4	0.2	<2	0.5	0.1	0.4	1.1
Volume((U	3U	0.2	1.2	0.2	0.1	0.5	1
Power/ave(W	56W	?	?	3	1.5	5	5
Power/peak(W	?	?	?	?	?	9	10

Schedule(Phase(1:(8(months,(Phase(2:(28(months,(Phase(3:(9(months
Margin(Phase(1:(1(month,(Phase(2:(2(months,(Phase(3:(6(months

Schedule and Sequence of Operational Modes
Month 1
Week 1: Checkout Operational Modes
Launch & Deployment
Power up and Recharge Battery, Subsystem Checkout
Perform Individual POC
Test Ground Comm Modes
Match Orbital Parameters (String of Pearls)
Restore Nominal Distance
Inter-Object D&D Determination
Test Science Observation Mode
Test use of Onboard Intelligence System to support these operations
Week 2 Test Nominal Formation Flying (stirng of Pearls)
Test Inter-Spacecraft Communication Modes
Maintain orientation and distance between active and passive object
Maintain orientation and distance between 2 active objects
Perform Science Observation Mode during selected orbits >1 times a day
Test use of Onboard Intelligence System to support these operations
Week 3 Test Formation Flying Modes with Non-Keplerian Elements
Change orbital parameters of active object relative to passive object while maintaining nominal distance
Change orbital parameters of active object relative to another active object while maintaining nominal distance
Change orbital parameters of active object relative to 2 passive objects in 'string of pearls' while maintaining equilateral nominal distances
Change orbital parameters of active object relative to 2 active objects in 'string of pearls' while maintaining equilateral nominall distances
Test use of Onboard Intelligence System to support these operations
Perform Science Observation Mode during selected orbits >1 times a day
Week 4 Test proximity operation Modes
Successive Close Approach between active and passive object
Successive Close approach between 2 active objects
Successive increase in separation between active and passive object
Successive increase in separation between 2 active objects
Successive Close approach between 3 active objects
Successive increase in separation between 3 active objects
Test use of Onboard Intelligence System to support these operations
Perform Science Observation Mode during selected orbits >1 times a day
Months 2 and later
Week 1: Repeat Week 1 for training and successively greater dependence on Onboard Intelligence System
Week 2: Repeat Week 2 for training and successively greater dependence on Onboard Intelligency System
Week 3: Repeat Week 3 for training and successively greater dependence on Onboard Intelligence System
Week 4: Repeat Week 4 for training and successively greater dependence on Onboard Intelligence System

	Situational associated with structure & behavior of solutions	Core associated with structure & behavior of Frontier
Rules	**Operational Scenario Elements** -Demand Spec Models -Supply Spec Models	**NBF Behaviors** -Translations & Learning -Data Flow & Capture -Algorithm Implementation -Tool & Component Integration
Choices	**Engineering Alternatives** -Providers -Systems -Subsystems -Models	**Tools** -Frontier MSE -Previous F6 VCDM Tools -TA1-4 Tools -NBFs & the Web



Impact: How Frontier Advances State of the Art

The Evolving Neural Interface (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'

Frontier Applied to Operation of SmartSat 3 3U CubeSat Concept

SmartSat Concept: Demonstration of autonomous close proximity operations critical for deep space operation, including knowledge and control of orientation and position to support formation flying, close approach, stationkeeping, changing orbital parameters, and active/passive object interactions, with progressively greater onboard intelligence drive by Frontier intelligent decision engine (IDE).

Elements on Morehead State University 3U Standard CubeSat Bus:

1) IDE based on 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;

2) Morehead State University 60GHz RF System with omni-antennas for distance and direction determination, inter-spacecraft communication, and atmospheric sounding (science mode);

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

4) 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.

SmartSat Autonomy: Three levels, from lowest level health & safety and control software baseline flight software (BFS) mainly on the standard C&DH platform, to two higher levels associated with SNS running as DM application and consisting of low- and high-level controllers implemented as composable software elements called Neural Basis Functions (NBFs).

Low level NBFs emit command sequences to the BFS to drive spacecraft behaviors. High-level NBFs interact mostly with other NBFs to deal with more complex or symbolic tasks, for example, selecting between safing alternatives or collision avoidance trajectories.

Key autonomy technologies to be demonstrated:

1) Nervous net-based controller, a low-level AC-NBF (based on Frigo and Tilden at LANL) Coupled nonlinear, chaotic oscillators generate control signals, which are translated into commands for the ACS. Large deviations from target trajectories handled automatically in real-time. The nonlinear, chaotic oscillators ergodically search their phase space, providing nonlinear corrections to drive the system towards the target trajectory. The discretized oscillators are solved efficiently numerically: simulations have shown good control and excellent performance in dramatically off-nominal situations.

2) Real-time target pose estimator, PE-NBF (based on a relatively conventional feed-forward artificial neural net (ANN), but featuring accelerated learning based on the use of an extended Kalman-filter (EKF).

a) real-time pose estimation of cooperative and noncooperative targets based on a priori simulation-based training. Simulations of this approach to pose estimation have shown excellent time-performance, start-up latency, and good accuracy.

b) Real-time pose estimation based on a PE-NBF reconfigured using parameters derived during ground-based training based on data obtained from the spacecraft.

c) Migration of the PE-NBF reconfiguration/learning to the spacecraft DM itself, providing an on-orbit learning ability.

At this preliminary stage, most high-level functions, e.g. mission planning, etc., performed on the ground with people in the loop. For the SNS, most high-level NBF functions will be programs to execute DM-based SNS technology demonstrations, such as driving the low-level NBF tests or supporting computations offloaded to the DM. One high-level test to consider is to couple data from the PE-NBF and the AC-NBF to maintain or attain a particular orientation trajectory with regard to an uncooperative, dynamic target.

Operation:

Test the flight computer/DM system architecture in which sensor information is processed by the DM and then used by the flight computer during command execution, underlying the NASA Synthetic Neural System (SNS) approach to spacecraft autonomy.

Implements spacecraft (smart/autonomy control) behaviors/protocols/operations as Neural Basis Functions (NBF, essentially software elements built according to certain rules described in NASA/SNS-related patents).

Test protocols in progressively more risky maneuvers, starting with Pointing/Orienting/Controlling (including AC-NBF and PE-NBF) and communication, then sensing mode (described below) for the baseline mission, and then in achieving specified distances between 2 active assets, then 3, then with a 'passive' target, then in maintaining formations, all at progressively smaller distances.

Preflight software Simulation: protocols developed for smart software to support multi-spacecraft operations described below, providing autonomy for communication, attitude control, and navigation to support multiple spacecraft operations.

Impact: How Frontier Advances State of the Art

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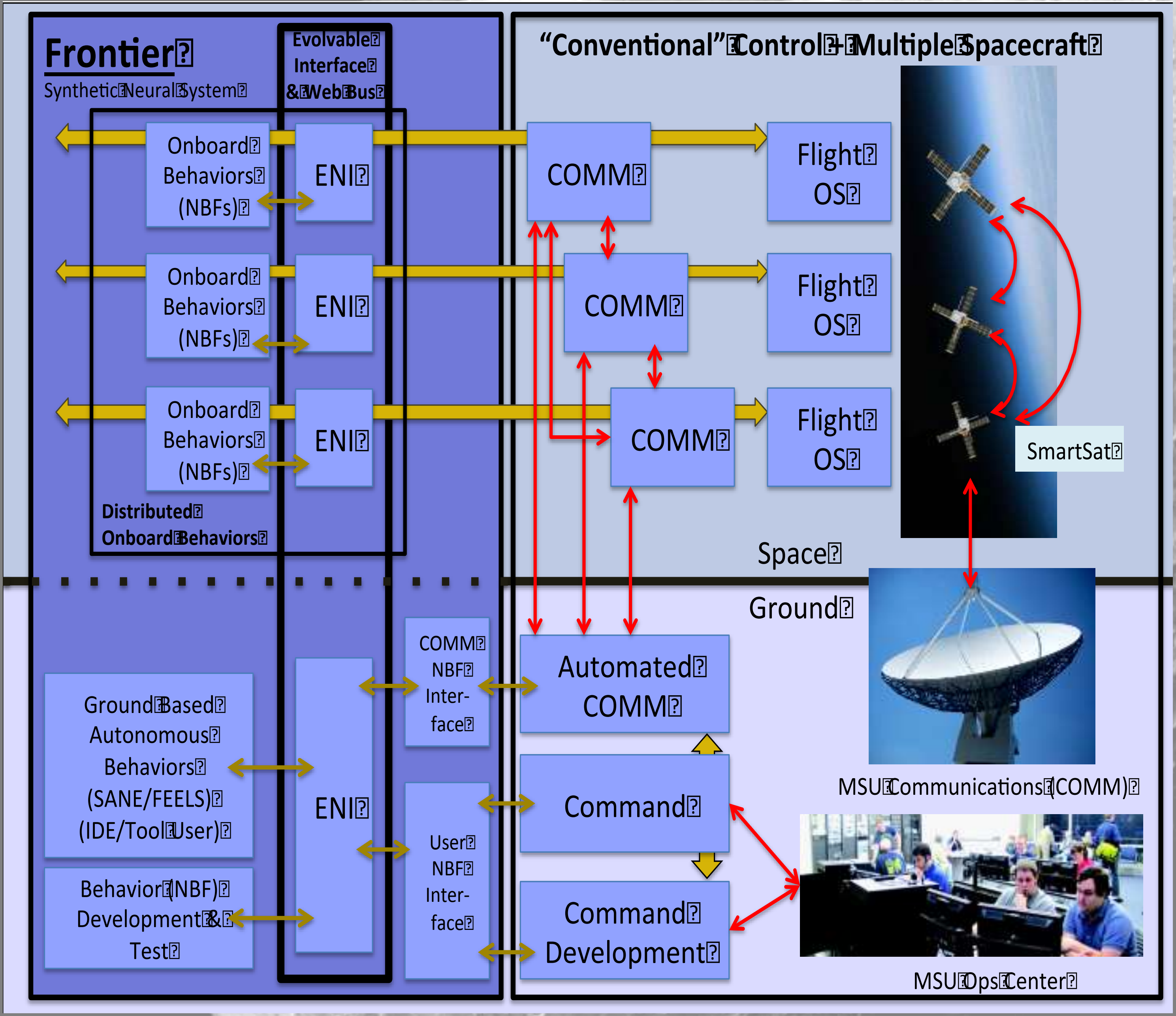
We go **beyond limitations of such 'rules of thumb' heuristics to include and profile choices from a variety of individuals, thus eliminating cognitive biases occurring in such systems**.

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

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



Frontier
Synthetic Neural System
Evolvable Interface & Web Bus
"Conventional" Control + Multiple Spacecraft
Onboard Behaviors (NBFs)
ENI
COMM
Flight OS
Onboard Behaviors (NBFs)
ENI
COMM
Flight OS
Onboard Behaviors (NBFs)
ENI
COMM
Flight OS
SmartSat
Distributed Onboard Behaviors
Space
Ground
COMM NBF Inter-face
Automated COMM
Ground Based Autonomous Behaviors (SANE/FEELS) (IDE/Tool User)
ENI
Command
MSU Communications (COMM)
User NBF Inter-face
Behavior (NBF) Development & Test
Command Development
MSU Ops Center