LunarCube: Using the CubeSat Standard to Support Access to 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.

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

•The lunar surface is thus an ideal 'test bed' for

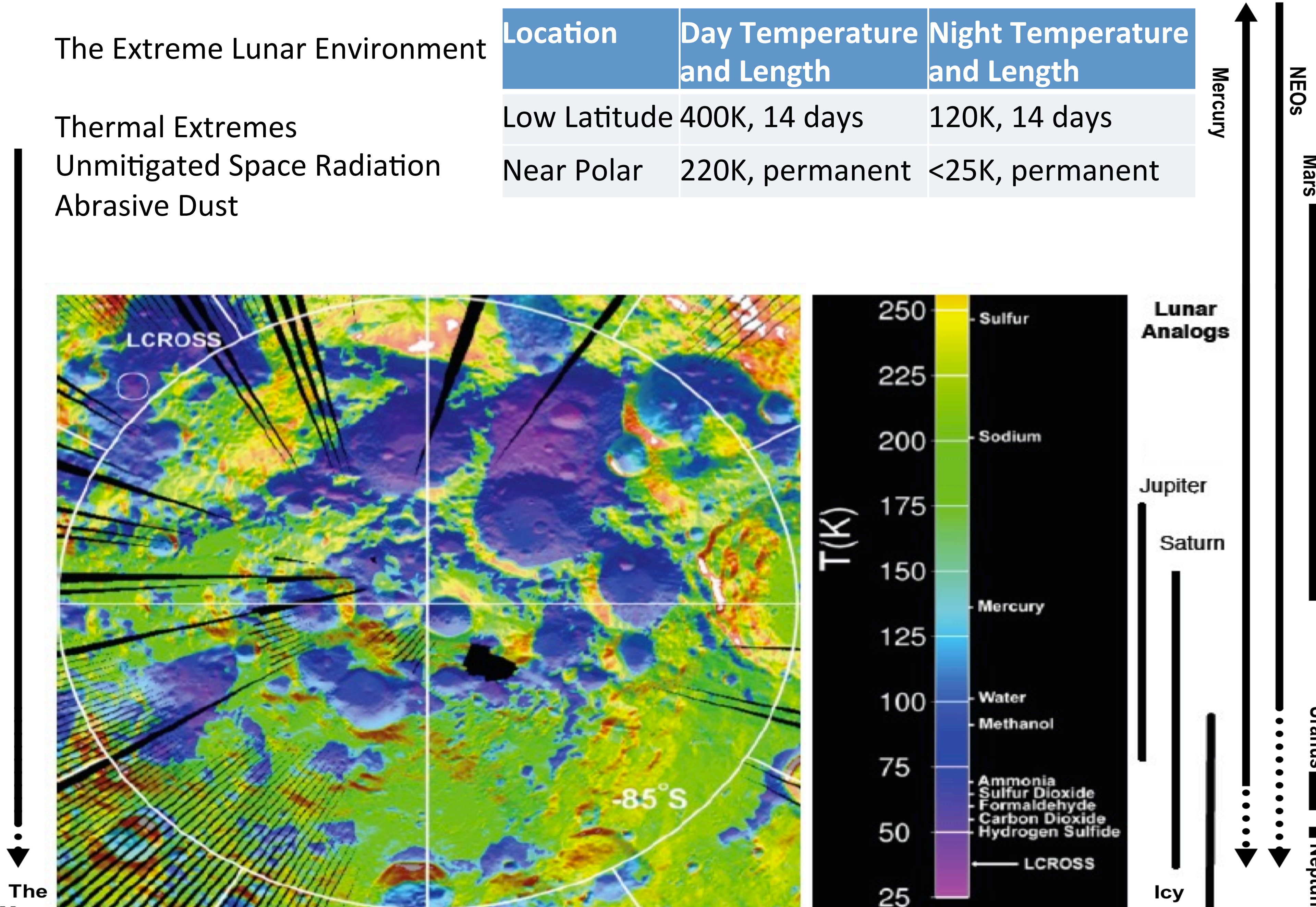
- exploring planetary surface processes and origins
- developing core technologies required for planetary exploration.

• Any sound approach to planetary exploration should prioritize access to the Moon

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

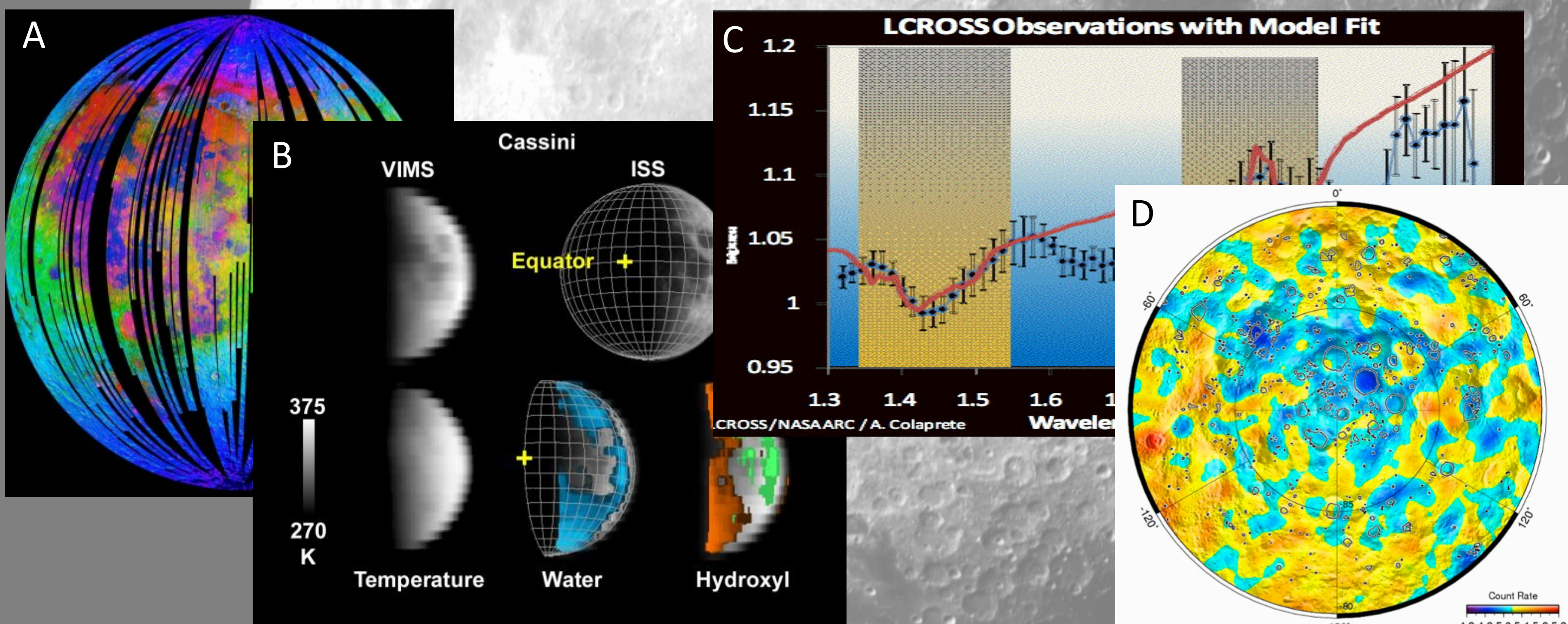


Lunar Astrochemical Analog Environments

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:

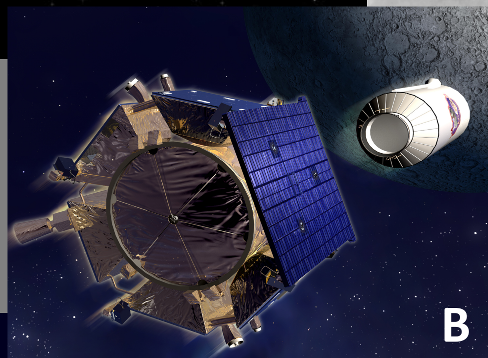
- Near IR temperature-dependent diurnally varying surface water and mineral bound water bands from Chandrayaan M3 and Cassini VMS (A, B)
- possible surface water, unidentified volatile bands induced by impact (LCROSS) (C);
- LRO LEND hydrogen-dependent (to 1 meter depth) depressed epithermal neutron flux (D).
- Ground based radar confirmed polar ice deposits and MESSENGER XRS confirmed presence of sulfur on Mercury.

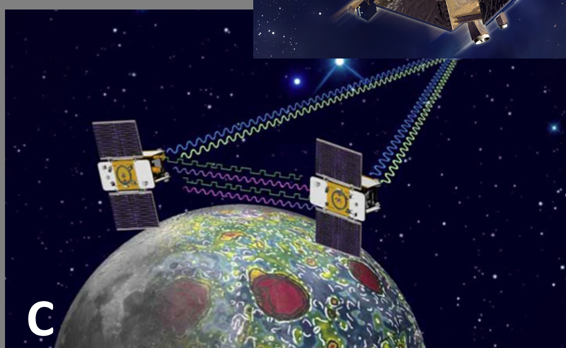


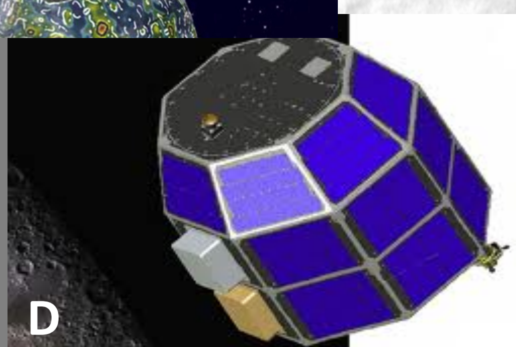
Lunar "Small" Heritage

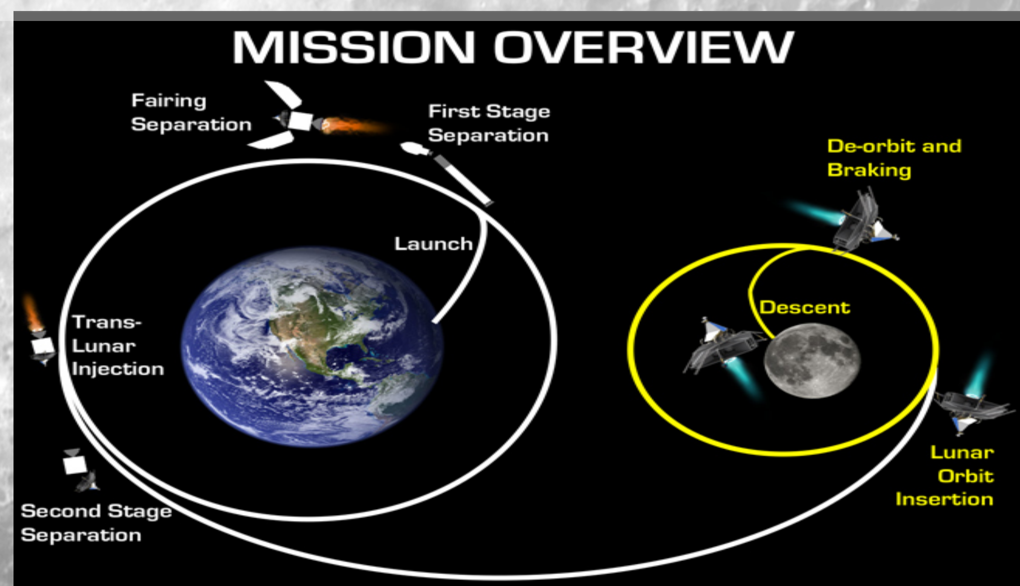
SmallSat Smart-1 (A)
LCROSS (B)
Distributed SmallSats Grail (C)
SmallSat Ladee (D)

Proposed Distributed CubeSats Lunar Swirl Impactors
Proposed ColdCube (passive 60K in Earth orbit)
Proposed Coldcube demo HTS radiation shielding
Proposed Solar Occultation Orbiter (LunarSox)
Proposed Astrobotic NanoRack Lunar Lander









CubeSat: Successful Basis of LunarCube Approach

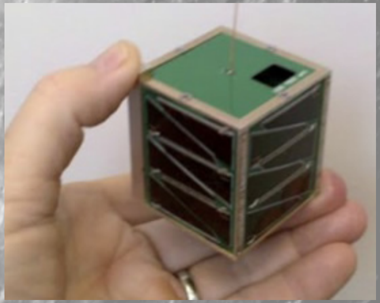
CubeSat 'kit' approach to increase participation and access to Earth orbital space through standardization, facilitated implementation, reduced development costs, risks, time. Four key aspects include:

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.

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) 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,

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.

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.

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 (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 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'.

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

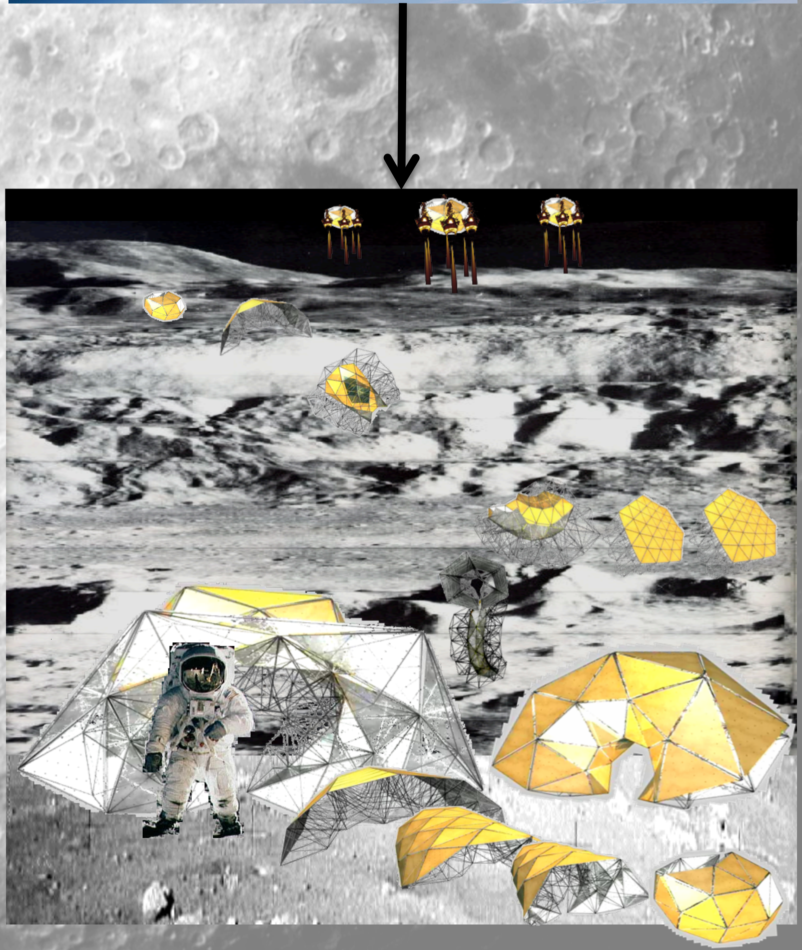


Table 1 CubeSat Technology Development

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 les depending on number and type of participan
Science	monitoring in orbit, in situ measurements, incremental	small number of platforms providing complementary measurements, somewhat more useful Earth Ap science	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, nanorack	standardization	nanorock
In-Space Propulsion		testing for Earth orbit	Earth orbit, testing for Earth-Moon	Earth-Moon, testing for deep space	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 form lunar surfa
Advanced Design and Integration			multiple platforms with calibrated instruments		nanorack
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
Extreme Environment 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

Table 3 Potential Instrument Payload Status

Type	Contribution	Status	Candidate?
Ray Region (Xray,Gray, Neutrons, protons	Elemental Abundance, Protons, Neutrons, Radiation Background	Solid state compact XRS, GRS and NS components potentially modularizable	Large Cubesat to 'nanorack'
Visible/ Near Visible (IR, UV)	Photo Interpretation, mineralogy	Reasonable resolution Digital camera microsizing well advanced	Largely CubeSat ready
LongWave (TIR,uwave, radio)	Physical component and surface characterization	Compact TIR, need work on microsizing components for rest.	Large CubeSat to 'nanorack'
Fields	Magnetic and gravity fields, interior characterization	Microsized versions already exist	Largely CubeSat ready
Energetic Particle/ Molecular Component	Electrons, ions, neutrals, gaseous molecular components distirbutions	Concepts for microsizing particle analyzers and mass spectrometers exist, need work	'nanorack'

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
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'						
3U CubeSat/LunarCube	1	bus standard with new capability	4 kg	1.1M	450K	Estimated
3U CubeSat/LunarCube	3	Bus standard with new capability	12 kg	2.8M	1.3M	Estimated
6U CubeSat/LunarCube	1	Bus standard with new capability	12 kg			Based on NASA Wallops preliminary study
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)

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

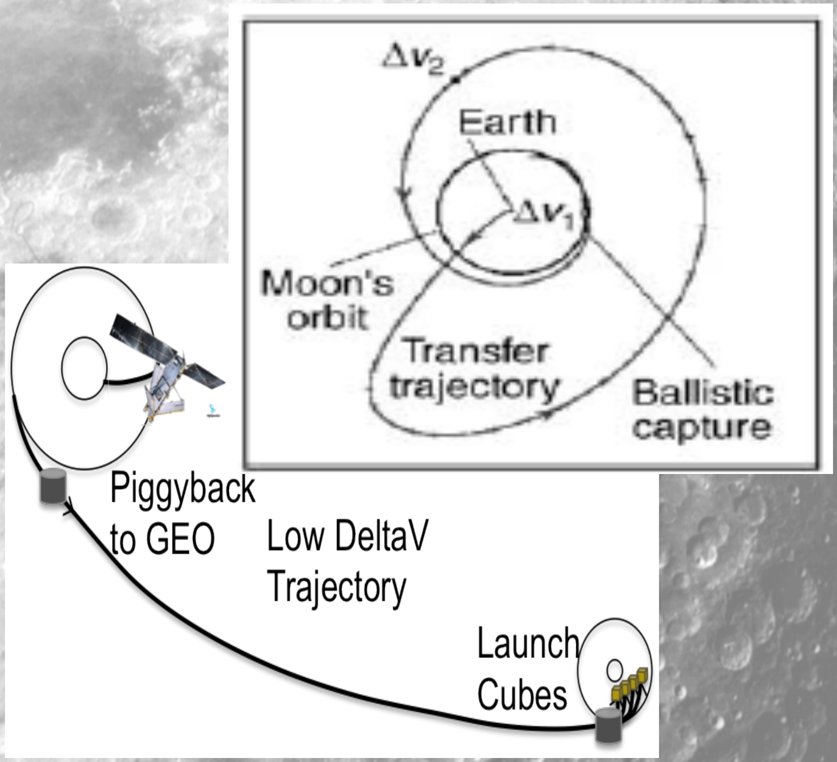
CubeSat relies on transportation infrastructure to Earth Orbit, as will LunarCube to points beyond Earth Orbit, and even on lunar surface

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

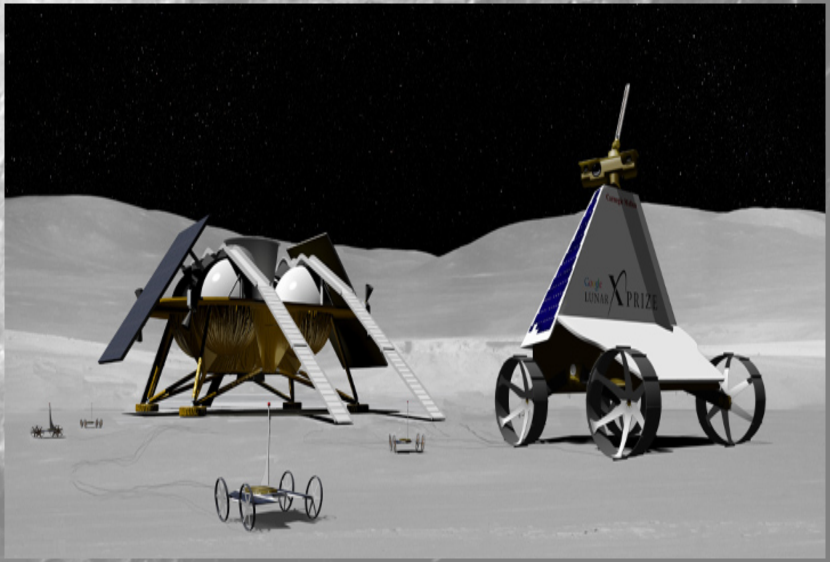


2) Ride along on a lander

- 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

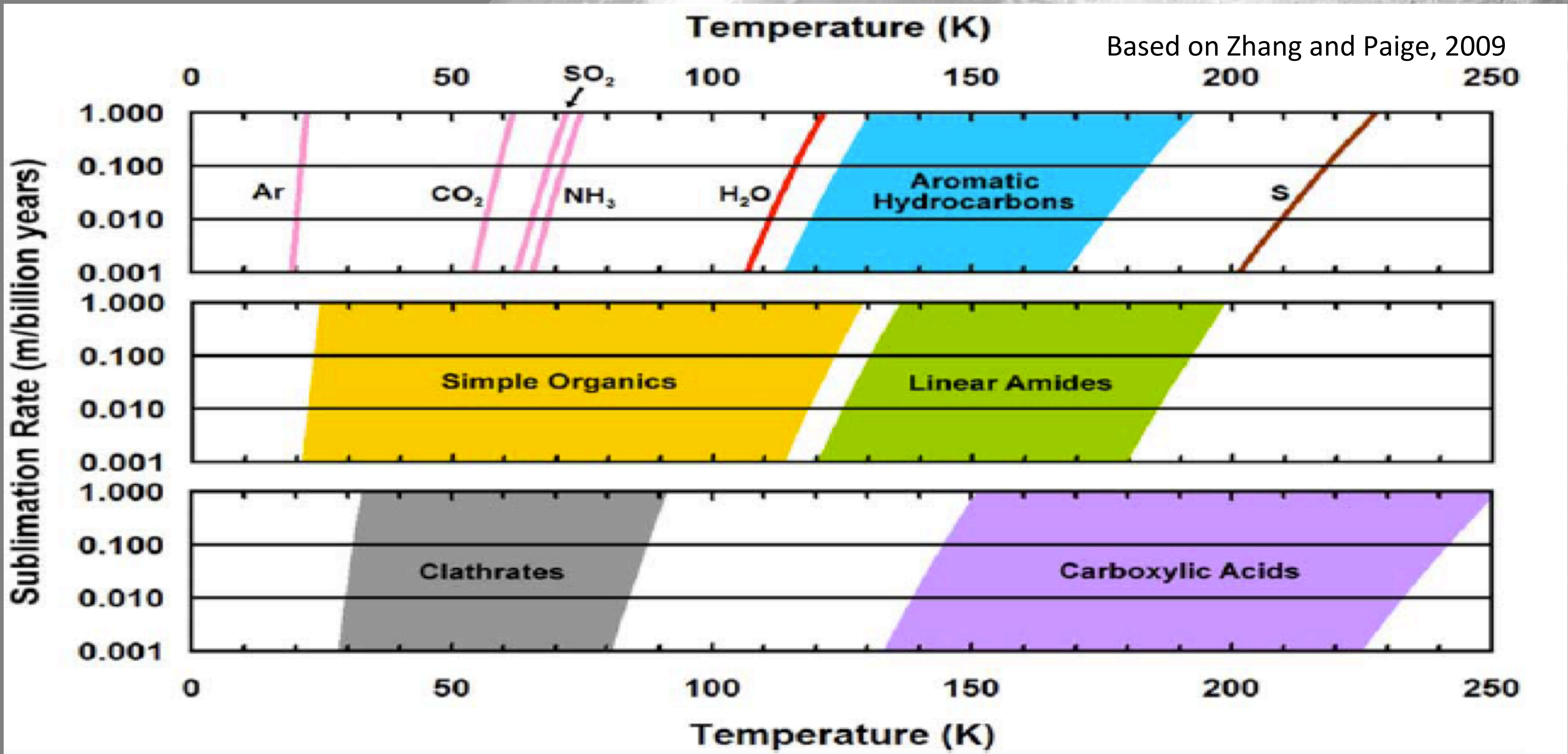
Conventional Single Cube

- 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

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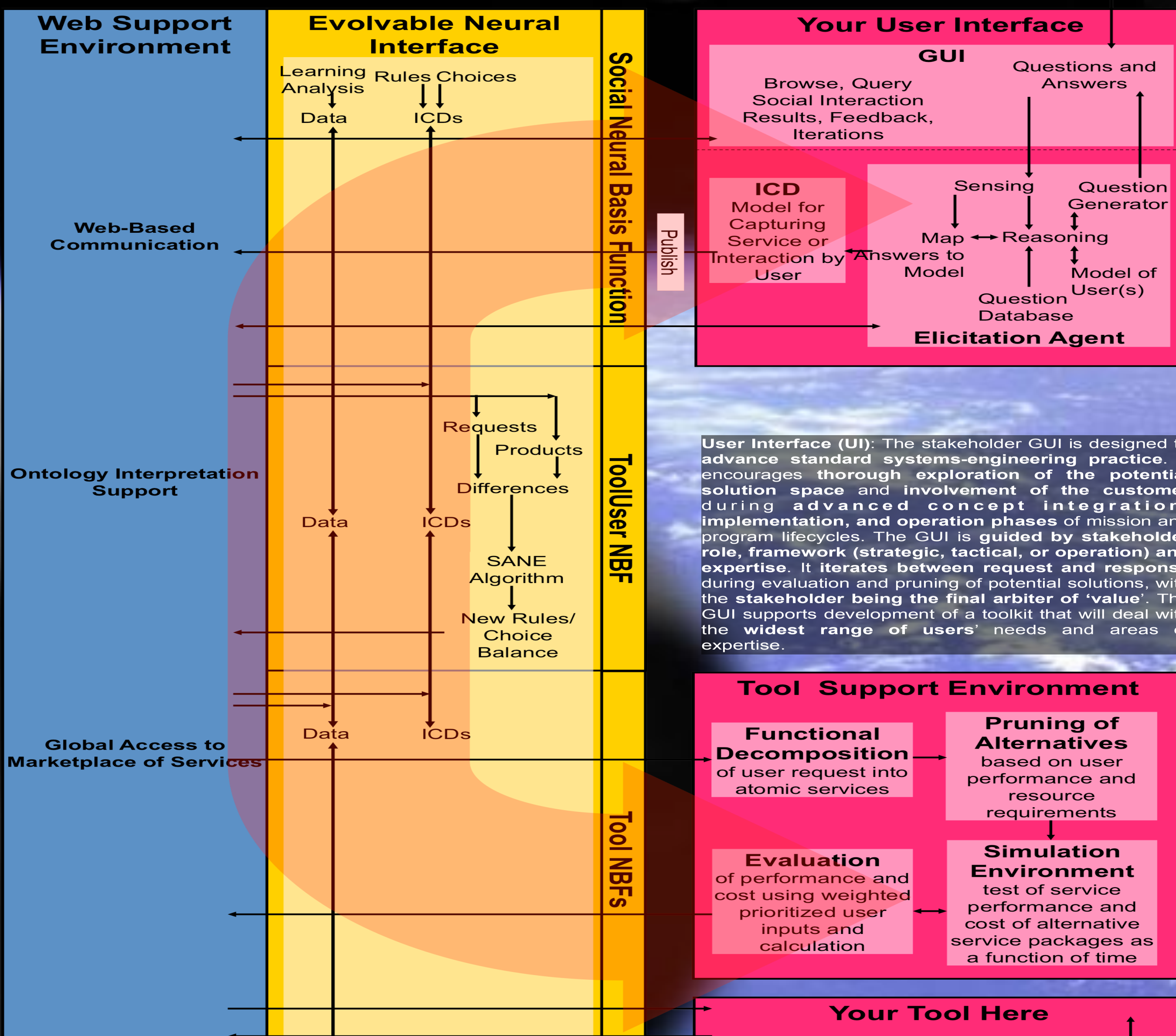
Overview: Frontier is an **adaptable, stably reconfigurable, web–accessible intelligent decision engine**. Frontier, when completed, will be capable of **optimizing the designing, simulating the operation of, and operating complex systems** - particularly multi–asset systems **distributed spatially and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

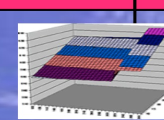
Intelligent Decision Engine (IDE): The **most innovative aspect** of Frontier, the IDE **absorbs and utilizes lessons learned**, thus morphing from a **tool to a tool *user***: The IDE is an **adaptable framework based on a genetic algorithm and synthetic neural system**, with a **stability algorithm 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.

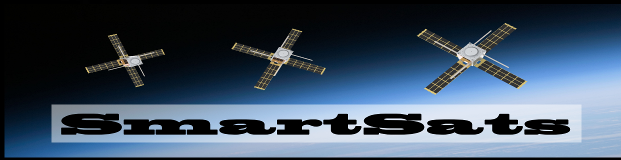
Web Support Environment (WSE): Frontier, using a **semantic bus** implemented via the W3C semantic web standard (**OWL**), will support **distributed, multi–user, concurrent access to resources and tools,** including the **human and tool interfaces, modeling and development services, databases, simulation, 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.





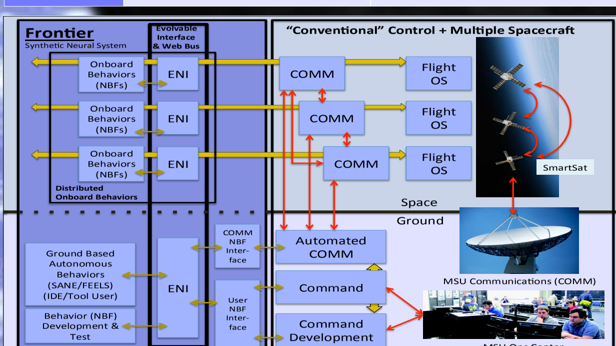
Resource Requirements

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 Intelligence 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 *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



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.