CubeQuest CHALLENGE

A Government Prize for Advanced CubeSat Technologies for Affordable Deep Space Science and Exploration Missions

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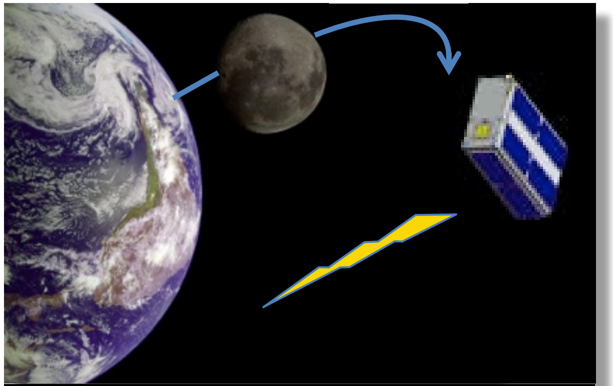
Cube Quest Challenge Administrator

AIAA Space 2016 – September 13, 2016

Outline

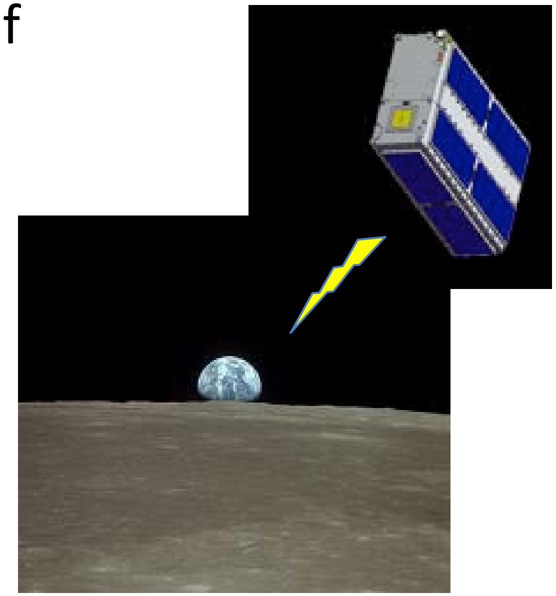
- CubeSats and Future of Space
  - Role of CubeSats
  - Current CubeSat Limitations
- Cube Quest Challenge Objectives
  - History of Government Challenges
  - Centennial Challenges Program
  - EM-1 Launch Opportunity
  - Filling the Gap: Future Needs
  - Cube Quest Challenge Architecture
  - Rules and Prizes
  - Challenge Firsts
  - Current Status
- Advancing Technologies by Cube Quest Teams
  - Communications
  - Propulsion
  - Other Technologies
- Cube Quest as Prize Competition Trailblazer



Get your CubeSat to the moon,
work the best
survive the longest
win big prizes!

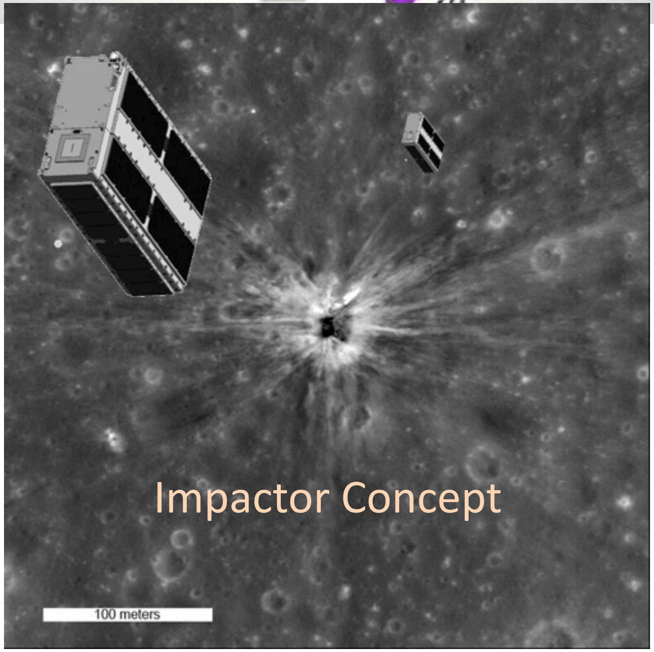
CubeSats in Deep Space

- Advantages over traditional satellites:
  - Low cost
  - Low mass
  - Standard LV interface
- Developed, deployed in fraction of time, cost, of traditional “high-stakes” satellite
- Interchangeable secondary payloads
  - increased launch opportunities
- Array of small CubeSats > single conventional probe:
  - asteroid seismographs
  - array of Mars weather stations
  - distributed , temporally correlated measurements
  - redundancy at the system level; robust system of systems
  - nodes for antenna arrays or telescope arrays

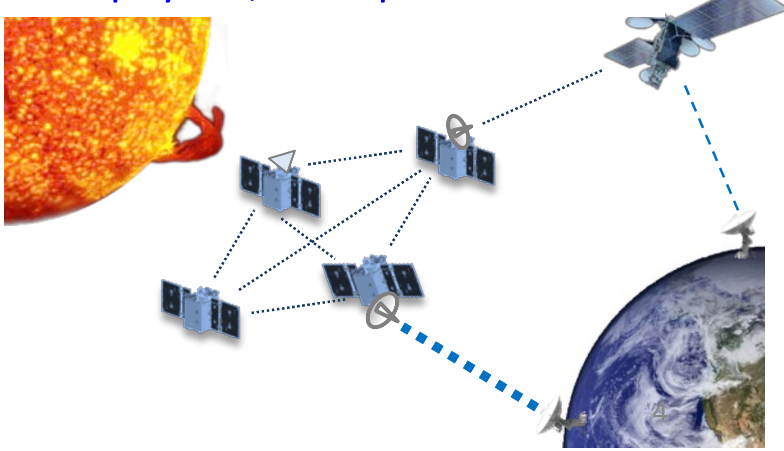


CubeSats in Deep Space

- Astrophysics:
    - Distributed RF and Optical Arrays on affordable satellite constellation
    - Affordable, time-correlated (simultaneous) multi-point observations of NEOs (mass density, albedo, etc)
- Planetary Explorations:
    - Distributed measurements (Ex: surface seismographic; Mars “weather systems”, multi-site impactors to detect lunar subsurface volatiles, etc.)
    - Co-ordinated assets (Ex: landers paired with orbiting relays)
- Heliophysics:
    - Global coverage
    - Multiple observations of transient events (Ex: radio occultation)
    - Geographically distributed time-correlated “space weather” measurements
- Earth Science
    - Global coverage (multiple)
    - Time correlated weather, oceanic observations



Heliophysics, Multipoint Science



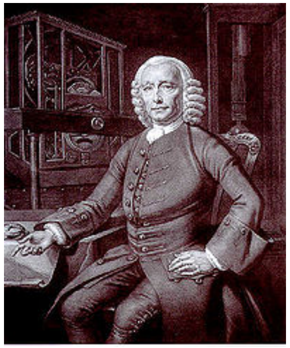
Current CubeSat Limitations

To-date, CubeSats haven’t ventured beyond LEO:

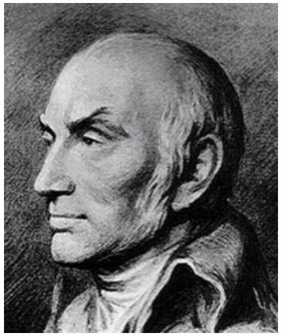
Limitation	SoA	Deep Space Missions Need
Limited comm range	Low-gain dipoles or patches mainly used	high gain directional antennas needed
Limited comm data rate	Low power, amateur band transmitters mainly used	High-power, high frequency, wide bandwidth transmitters needed
Lacking radiation tolerance	COTS, low-cost parts used; more benign environment of LEO	Radiation shielding, fault detection, fault tolerance
Lacking in-space propulsion	Not demonstrated (except solar sails); chemical fuel/pressurized containers prohibited	High thrust, high ISP needed; chemical, electrical, solar
Depend on Earth-based nav references	Passive magnetorquers used; GPS or magnetometers sense Earth’s magnetic field	Start trackers, moon/sun sensors, radar altimeters and other sensors needed for deep space

Cube Quest Challenge rewards citizen inventors who demonstrate CubeSat solutions in space

History of Government Challenges



In 1761, John Harrison (clock maker) solved the British maritime navigation challenge

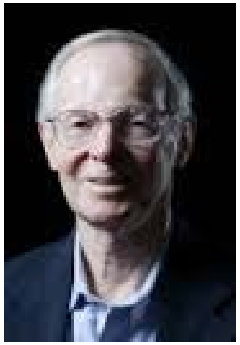


In 1809, Nicolas Appert (baker) solved the Napoleon challenge for food preservation

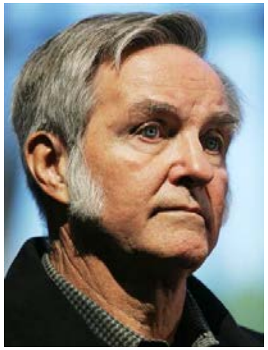
In 1901, Alberto Santos-Dumont (coffee plantation heir) won the French airship challenge

In 1910, Georges Chavez (pilot) won the Milan Committee challenge being the first to fly over the Alps

In 1927, Charles Lindbergh (mail pilot) won the Orteig Prize being the first to fly across the Atlantic Ocean



In 1977 & 1979, Paul MacCready (aeronautic engineer) won the Kremer Prizes for human-powered flight challenges



In 2004, Burt Rutan (aerospace engineer) won the X-Prize Ansari challenge being the first private entity to enter space twice within two weeks

In 2007, Peter Homer (unemployed engineer) won the NASA Astronaut Glove challenge by making a better glove

Centennial Challenges Program

- NASA STMD's Centennial Challenges Program, initiated in 2005, named after Wright Brothers' Kitty Hawk flight
- Engages public in advanced technology development
- Prizes for solving problems of interest to NASA and the nation
- Competitors based in US; not supported by government funding.
- Since 2005, there have been eight challenge categories, resulting in more than 20 challenge events to date.
- More than $6 million in prize money has been awarded to more than 17 different teams
- Summer 2013, work began on Cube Quest Challenge

Current
Centennial Challenges:

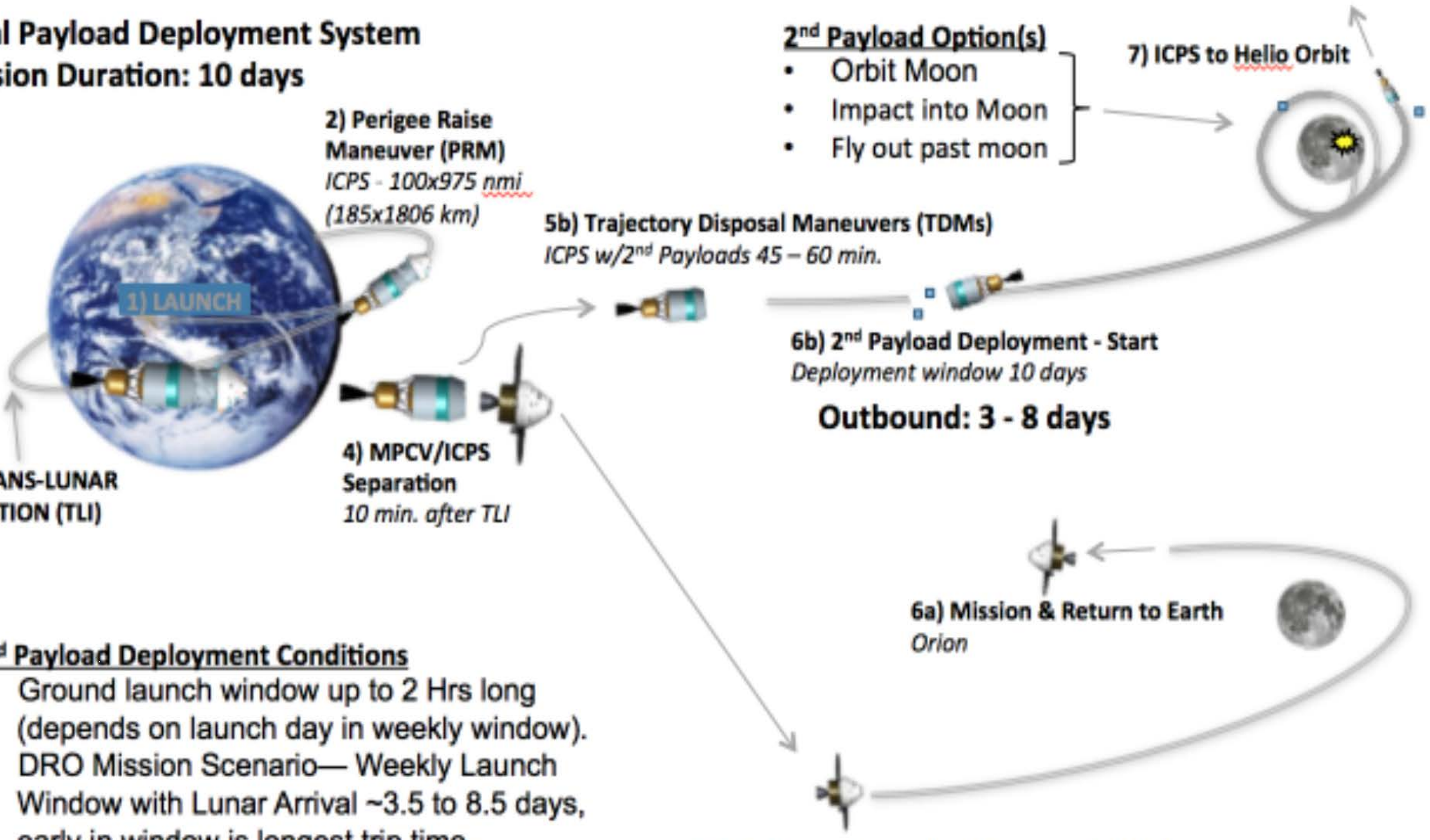
- Sample Return Robot
- 3-D Printed Habitat
- Mars Ascent Vehicle
- Cube Quest

EM-1 Launch Opportunity

- NASA's first non-crewed lunar flyby mission of Orion from SLS
  - Launch in late 2018
- Capacity for thirteen 6U-sized CubeSats
- Secondary Payloads deploy after Orion departure into lunar flyby trajectory

EM-1 Launch Opportunity - 2

Total Payload Deployment System
Mission Duration: 10 days



1) LAUNCH

2) Perigee Raise Maneuver (PRM)
ICPS - 100x975 nmi (185x1806 km)

3) TRANS-LUNAR INJECTION (TLI)
ICPS

4) MPCV/ICPS Separation
10 min. after TLI

5a) Trajectory Correction Maneuvers (TCMs)
Orion

Outbound: 3 - 8 days

5b) Trajectory Disposal Maneuvers (TDMs)
ICPS w/2nd Payloads 45 – 60 min.

6a) Mission & Return to Earth
Orion

6b) 2nd Payload Deployment - Start
Deployment window 10 days

Outbound: 3 - 8 days

2nd Payload Option(s)
- Orbit Moon
- Impact into Moon
- Fly out past moon

7) ICPS to Helio Orbit

2nd Payload Deployment Conditions
- Ground launch window up to 2 Hrs long (depends on launch day in weekly window).
- DRO Mission Scenario— Weekly Launch Window with Lunar Arrival ~3.5 to 8.5 days, early in window is longest trip time.
- End of the disposal maneuver, the ICPS is at 26,750 km Earth Radius, inertial velocity of 5.279 km/s.

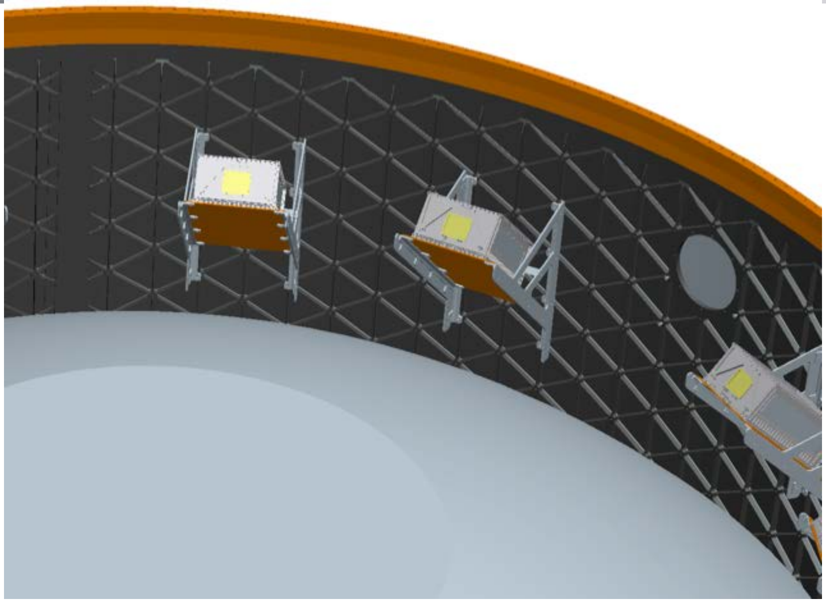
EM-1 Launch Opportunity - 3

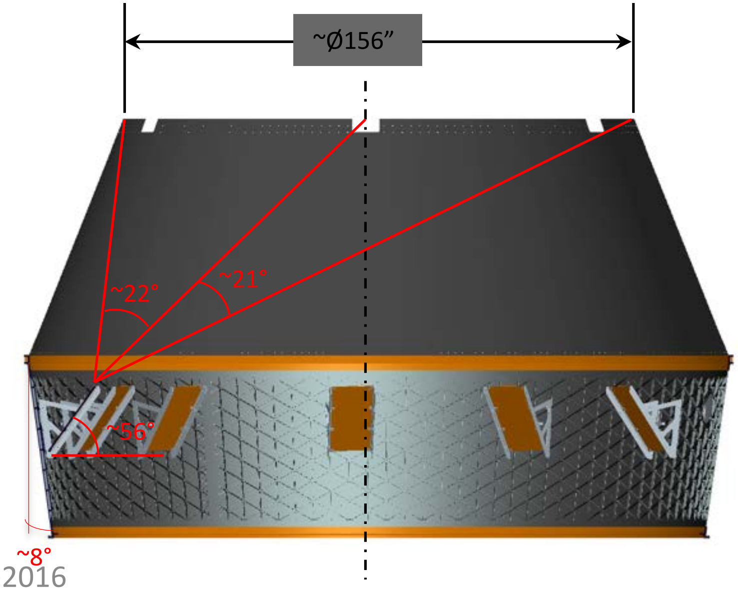
Eleven 6U/12U payload locations
6U volume/mass is the current standard (14 kg payload mass)

Payloads will be “powered off” from turnover through Orion separation and payload deployment

Payload Deployment System Sequencer; payload deployment will begin with pre-loaded sequence following MPCV separation and ICPS disposal burn

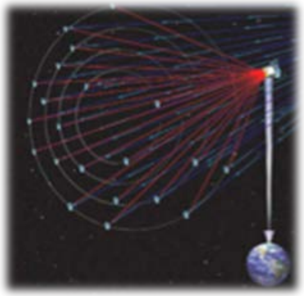
Payload requirements captured in Interface Definition and Requirements Document





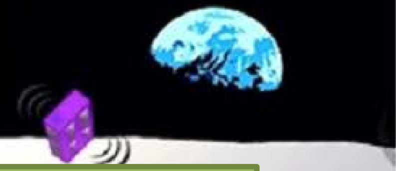
Designing Cube Quest

- Considered 5 competitive scenarios
  - Lunar flyby long-distance comm
  - Lunar Impactor
  - Lunar Orbiter
  - 2 Sat Comm Relay
  - Proximity ops in cisLunar environment
  - (Lunar Lander not evaluated, as impractical dV req’t)
- Each scenario depends, relatively more or less, on CubeSat capabilities:
  - Propulsion
  - Deep space survival
  - Comm
  - Power
  - Pointing
- Each scenario applies, relatively more or less, to future needs/goals
  - Precursor missions
  - Earth Science
  - Heliophysics/Space Weather
  - Space Warrior



Select the Scenario that develops the most capabilities, with greatest applicability to needs/goals

Challenge Goal Pugh Matrix



Combined Long-distance comm, Orbiter mission, optimal Cube Quest "missions"

Good Comm and G&NC Capability; Good Applicability

Requires 2 sats

Good Comm and G&NC Capability; Good Applicability

Requires 2 sats

Too Much Prop

Challenge Goal

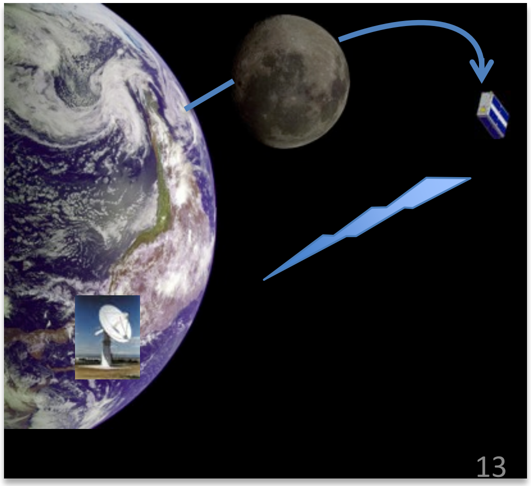
		Long-Dist Comm		Impactor		Orbiter		2-Sat Comm Relay		Prox Ops		Lander
Capability	Propulsion	-	No Prop Needed	0		+	Most Prop Needed	-	No Prop Needed	-	No Prop Needed	NOT FEASIBLE
	Pointing	0		0		0		0		+	Most pointing	
	Comm	+	Longest range	+	Hi BW Comm burst (before impact)	0		+	2-way relay	0		
	G&NC	+	Determine Earth Direction	0		0		+	Determine Child's Trajectory	0		
	Power	0		0		0		0		0		
	Survival	0		-	Shortest Mission	0		0		0		
		+1		0		1		+1		0		N/A
Applicability	Space Warrior							√	situation awareness			
	Heliophysics							√	multipoint obs	√	multipoint obs	
	Lunar Exploration	√	comm relay?	√	volatile det	√	revisit ground tracks	√	landed assets comm relay			
	Planetary Sci	√	comm	√	volatile det	√	autonomous orbit	√	landed assets comm relay			
	Earth Sci							√	multipoint obs			
	Atmospheric Sci							√	multipoint obs			
	Exploration goals	√	comm	√	in situ recon	√	autonomous orbit	√	NEO recon	√	NEO recon	
		3		3		3		7		2		N/A

Deep Space Communications

- Challenge:
  - *[Farthest distance, largest volume, fastest rate - transmitted data](#)*

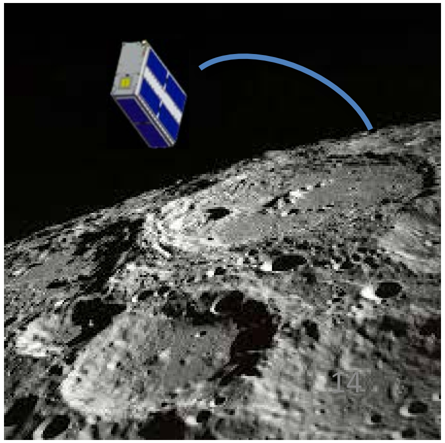
- Demonstrates:
  - Comm: award for farthest comm on certain date
  - Ground Stations: challengers can provide their own deep space ground stations, off-loading heavily subscribed DSN assets
  - Survival: award for farthest comm
  - Power: survival in cold environment
  - Pointing: aim directional antenna, camera
  - Propulsion, G&NC to point antennas

- Applications:
  - Planetary missions
  - NEO/NEA surveyor/precursor



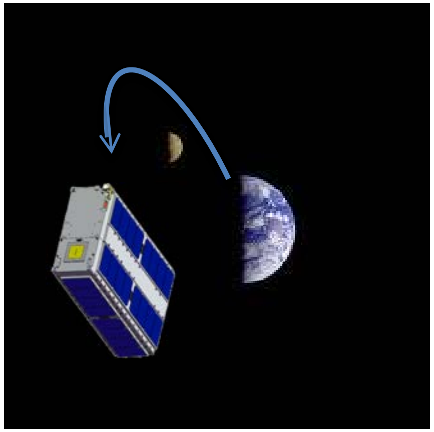
Lunar Orbit

- Challenge:
  - *Achieve verifiable lunar orbit*
- Demonstrates:
  - Propulsion: 700-900 m/s dV for Lunar Orbit Injection
  - Pointing: hi-gain antenna, articulated solar arrays
  - G&NC: navigate without benefit of GPS or Earth’s magnetic references
  - Power: perform while coping with lunar and Earth eclipse periods
  - Survival: achieve orbits and survive longest
- Applications:
  - NEO missions
  - Earth Science
  - Pathfinders, In-situ resource surveyors
  - Heliophysics
  - Planetary science
  - Lunar Science



Longevity

- Challenge:
  - *Survive the longest in lunar orbit or 4M km range*
- Demonstrates:
  - Rad tolerance in deep space (where CubeSats have not ventured before)
  - Power generation and management away from Earth
  - Thermal management in deep space
  - G&NC: point antennas without benefit of GPS or Earth’s magnetic references
  - G&NC and propulsion: station keeping while in lunar orbit
  - Long distance communcaitons, command and control
  - Autonomy
- Applications:
  - NEO missions
  - Earth Science
  - Pathfinders, In-situ resource surveyors
  - Heliophysics
  - Planetary science
  - Lunar Science



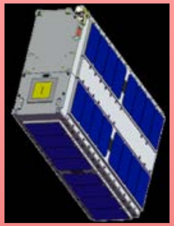
Stimulating Advanced Tech for Deep Space CubeSat Operations

- Objective: Achieve Lunar Orbit
- Requires:
  - Propulsion, high dV
  - Navigation without GPS or Earth's magnetic field
- Objective: Hi Data Rate, Large Data Volume, Far Comm Distance
- Requires:
  - High power transponder; high gain antenna; long & frequent ground station passes; deployable antennas; stable ACS; precise knowledge of Earth direction
- Objective: Longevity (survival)
- Requires:
  - Rad hardening, redundancy, shielding

- All are critical capabilities for deep space operations

Cube Quest Challenge Architecture

Goal: to foster innovation in small spacecraft navigation, operations, and communications techniques for deep space



CubeSat limited to 6U and 14 kg

Qualify for EM-1 launch
- *or* –
get your own ride

Lunar Derby

While in lunar orbit

Achieve Lunar Orbit-
$1.5M/shared, $1M max per team

Error-free Communication

Burst Rate- $225k/25k

Total Volume- $675k/75k

Longevity

$450k/50k

Deep Space Derby

While range ≥4M km

Farthest Distance

$225k/25k

Error-free Communication

Burst Rate- $225k/25k

Total Volume- $675k/75k

Longevity

$225k/25k

Ground Tournaments (GT)

4 Rounds

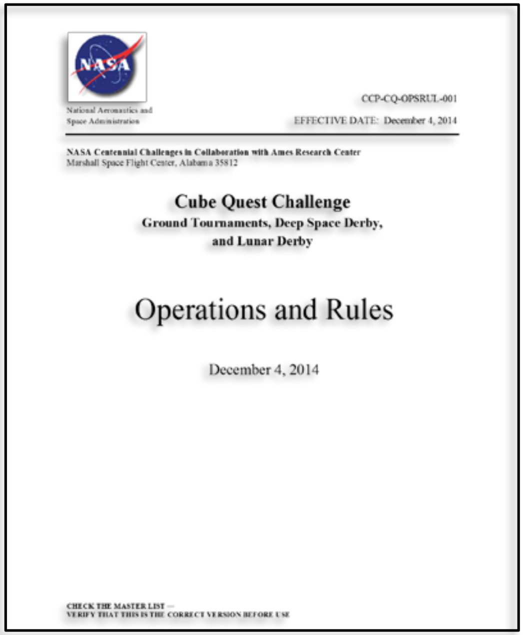
Approx every 6 months

Top 5 teams receive incremental funding (max $100k per team)

Top 3 teams launch free on EM-1

$5.0M Prize Money

Rules and Constraints



National Aeronautics and
Space Administration

CCP-CQ-OPSRUL-001

EFFECTIVE DATE: December 4, 2014

NASA Centennial Challenges in Collaboration with Ames Research Center
Marshall Space Flight Center, Alabama 35812

Cube Quest Challenge
Ground Tournaments, Deep Space Derby,
and Lunar Derby

Operations and Rules

December 4, 2014

CHECK THE MASTER LIST —
VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE

SLS Safety and Interface Requirements

- SLS Payload Safety Reviews (to fly on EM-1)
- Or equivalent, for 3rd-party launches

Any allowable part of the spectrum

- subject to FCC public freq. alloc. and licensing regs

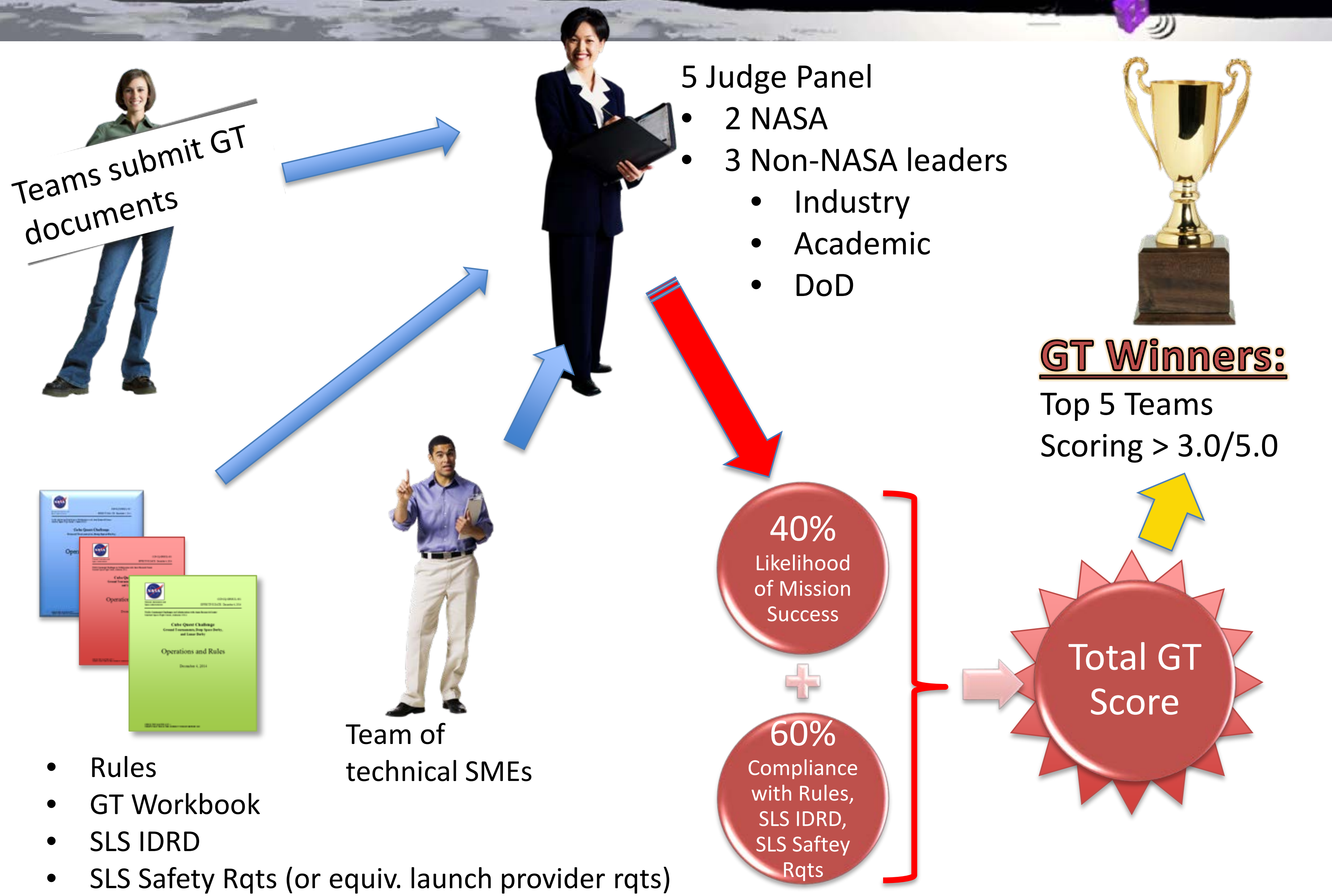
Comm data eligible for prizes

- May use NASA DSN – at your cost
- DSN tracks all trajectories; checks lunar orbit, 4M km range
- Comm data format per Rules, to qualify

Comply with Orbital Debris and Planetary Protection laws and regs

http://www.nasa.gov/cubequest/reference

Ground Tournaments



Teams submit GT documents

5 Judge Panel
- 2 NASA
- 3 Non-NASA leaders
  - Industry
  - Academic
  - DoD

GT Winners:

Top 5 Teams

Scoring > 3.0/5.0

40% Likelihood of Mission Success

\+

60% Compliance with Rules, SLS IDRD, SLS Saftey Rqts

Total GT Score

Team of technical SMEs

- Rules
- GT Workbook
- SLS IDRD
- SLS Safety Rqts (or equiv. launch provider rqts)

Ground Tournaments - 2

Top 3 qualified GT-4 Winners offered free EM-1 launch

  - Declare intent to fly EM-1
  - Be a top five winner in GT-1 and/or GT-2
  - Pass SLS payload safety reviews
  - Compete and win in GT-4

- Four Ground Tournaments (GTs)
  - GT-1 - Aug 2015 - $20k - winners announced!
  - GT-2 - Mar 2016 - $30k – winners announced!
  - GT-3 - Oct 2016 - $30k
  - GT-4 - Mar 2017 - $20k *and* chance to launch on EM-1

- Teams may compete in any or all four GTs
  - they get harder as they go!

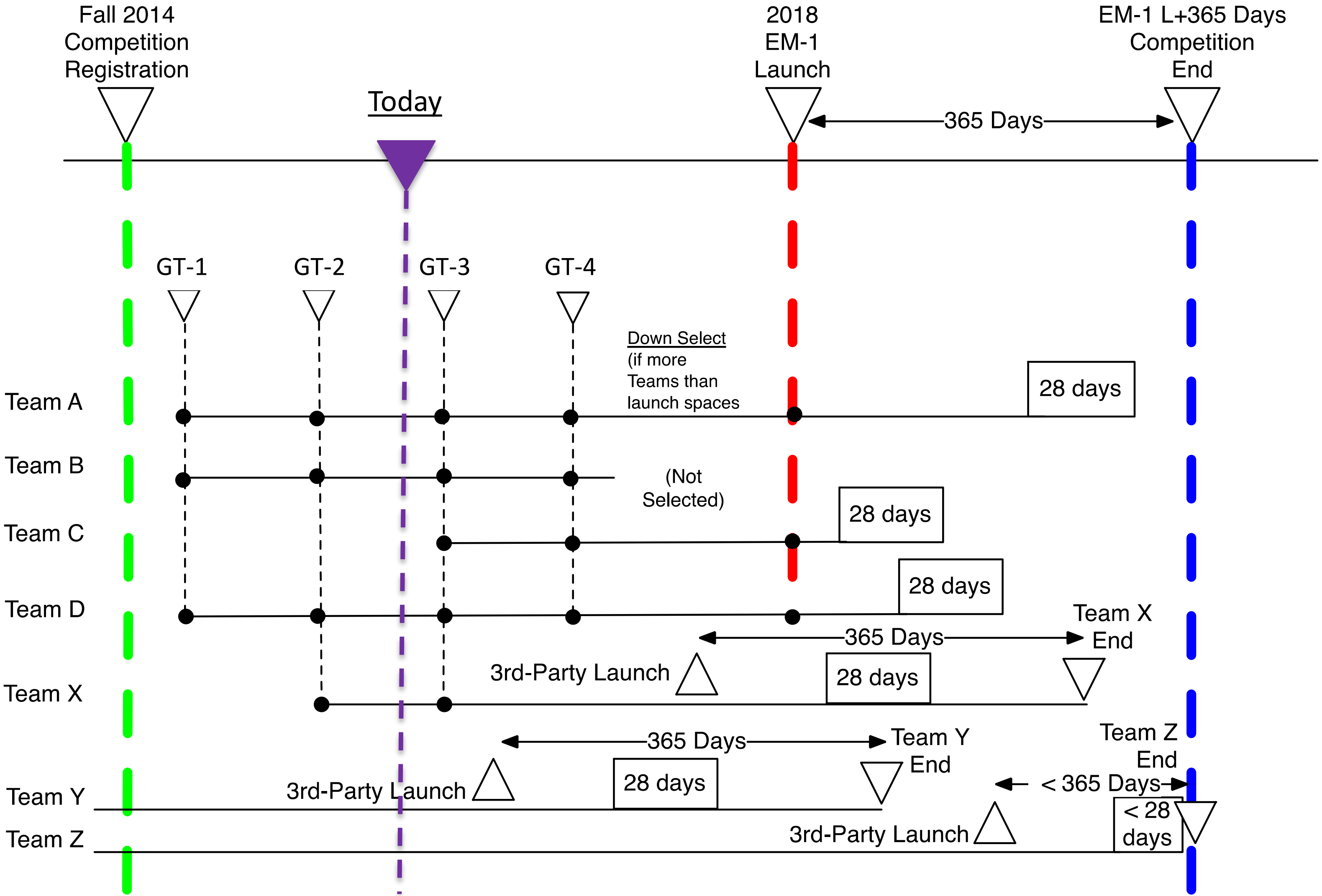
Versatility of Rules

- Challenges are structured to cover a variety of scenarios:
  - EM-1 or other launcher
    - Teams may choose to qualify for EM-1, or obtain their own launch (at their expense, and ineligibility for Ground Qualification Competition prizes)
  - Propulsion or no propulsion
    - Deep Space Challenge does not require propulsion
    - 365-day time rule should allow exotic trajectories to lunar orbit
  - With Space Communication and Navigation (SCaN) or without SCaN
    - Deep Space Network (DSN)-compatible transponders could be required by CCP for NASA ranging and authentication of comm origin
      - Cost and DSN schedule load constrain prolonged DSN use
      - Teams may propose alternatives if judges are satisfied
    - Teams are incentivized by high DSN costs to develop their own alternatives to achieve high data volumes and to control critical events over the long competition duration
- Rules avoid “hard coding” certain TBD constraints at this time:
  - EM-1 launch date
  - Final number of secondary payload slots

Challenge Firsts

- First ever government challenge in space
- Non-government individuals/entities operate spacecraft at the moon and beyond
- Demonstrate novel, TRL9 solutions to CubeSat comm, ground station, in-space propulsion, radiation tolerance

Current Status



Current Status - 2

*** - indicates EM-1 Qualifier**

Industry

Alpha CubeSat Xtraordinary
Innovative Space Partnerships, Inc.

***Heimdallr**
Ragnarok Industries, Inc

***Team Miles**
Fluid & Reason LLC

Academia

***Cislunar Explorers**
Cornell University

*** MIT KitCube**
Massachusetts Institute of Technology

*** SEDS UC San Diego**
University of California- San Diego

G.O.A.T.S.
Worchester Polytechnic Institute

*** CU-E3**
University of Colorado – Boulder

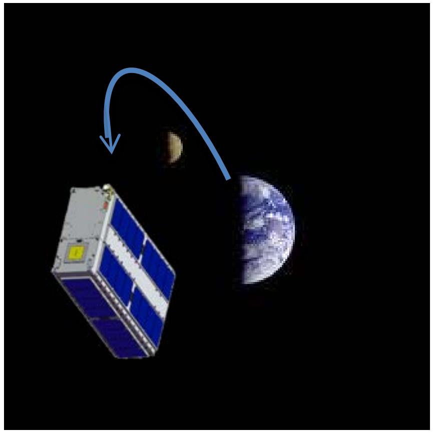
Lunar Derby

Deep Space Derby

Lunar & Deep Space Derby

What's the Status?

- **Registration is Open for GT-3**
  - Registration and Submittals due September 21, 2016
  - Winners announced October 24, 2016
- **Final Ground Tournament**
  - In-Person at Ames Research Center in March 2017
  - Down-select: 3 winners of EM-1 launch
- **Lunar and Deep Space Derbies**
  - EM-1 launch late 2018
  - In-space competition ends, winners announced, EM-1 launch +365 days (late 2019)



Emerging Technologies - Communications

- Communication Technologies
  1. RF Bands Utilized
     - S-Band
       - Commonly used but cutting-edge for CubeSats
       - Teams plan S-band for radio comm and trajectory determination
     - X-Band
       - DSN primarily uses X-band, but CubeSats haven't the power to use before
       - Teams plan X-band to commercial gnd stns or DSN
     - C-Band
       - Has some use in general sat comms; 5cm band is amateur band
       - Team plans AMSAT in C-band
     - UHF
       - Often used in CubeSats in amateur bands, to lots of amateur gnd stns
       - Team plans UHF for long distance
     - Laser Comm
       - Forefront of space comm; used on NASA's LADEE and MESSENGER; high data rates over large distances. Pointing accuratly and thermal control are significant issues
       - Team plans to use for Data Rate Prize and Aggregate Data prize achievements
  2. Antenna Design
     - Patch Antennas
       - Commonly used on CubeSats due to small size and low cost; but lacking in gain
     - Deployables
       - 1 team plans to use a reflectarray on reverse side of solar panel, fed by deployable feed horn

Emerging Technologies - Communications

- Ground Stations
  - DSN
    - NASA missions use DSN; CubeQuest judges will use DSN radiometrics to verify claimed lunar orbit and comm ranges; requires DSN compatible HW and comm protocols
    - Teams plan using DSN for trajectory determination and as primary X-band gnd stn
  - Other NASA Ground Stations
    - JPL OCTL at Table Mountain (one of 2 optical gnd stns)
    - 1 team plans to use OCTL
    - 1 team plans to use WFF UHF stn
  - Other Commercial
    - AMSAT X-band and C-band
    - Spaceflight Industries
    - ATLAS commercial ground stations
    - Arecibo for long-distance X-band
    - Their own existing UHF ground station

Emerging Technologies – Propulsion, Other

- Propulsion
    - COTS
        - Busek green monopropellant
        - ConstantQ plasma thruster (Iodine)
        - Phase Four plasma (Xenon) spin off from U of Michigan
        - Standard Micro Propulsion System from Vacco, cold gas, for attitude control
    - Custom In-House
        - 3D printed cold gas for attitude control
        - Electrolysis of water for H2 and O2, for 3D printed titanium thruster fuel and oxidizer
        - Hydrogen peroxide monopropellent for 3D printed Inconel 716
- Other Tech
    - Rad-hard components
        - deep space radiation, longer mission lifetimes intensify effect. Lunar orbit provides a proving ground for radiation-based experiments or technology demonstrations.
        - 1 team plans Resilient Affordable CubeSat Processor (RACP), a microcontroller and 3 ARM 15 SoC uPs., with a health monitoring and management system to check processors and subsystems
    - Navigation Systems
        - No GPS or magnetic field in cis-lunar space
        - Clue Canyon Technologies XACT star tracker, sun sensor and reaction wheels.
        - Or combinations of their own sun sensors, and COTS inertial sensors for ADS.
        - GEO-hard Miniature Integrated Star Tracker (MIST) from Space Micro,
        - In-house ADCS, with in-house reaction wheels, in-house star tracker and sun sensors
        - Navigate using Raspberry Pi camera to image Earth, Sun and Moon,and gyro using transformation matrix to spacecraft body from and inertial frame.

Summary

- CubeSats soon will contribute to affordable science and exploration, in deep space
- Cube Quest Challenge rewards citizen inventors to help NASA, stimulate industry, for the public good
- Competitors already breaking new ground
- Cube Quest may blaze trails for other ambitions prize challenges

Questions?

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Backups

CubeQuest Emerging Technologies

- Comm
  - UHF, S-, X-, C- and Laser
  - Mainly patch antennas – from moon and beyond
  - Deployable antennas
- Ground Stations
  - DSN
  - Table Mountain OCTL
  - WFF UHF
  - AMSAT X- and S-band
  - Commercial
  - Univ dishes
  - Arecibo
- Propulsion
  - Busek green monoprop
  - EP (Xenon and Iodine)
  - 3D printed thrusters
  - Electrolysis of water for fuel
- Other Technologies
  - Rad hardened CPU, memory, error checking and redundancy
  - Blue Canyon GNC / ADCS
  - Custom design:
    - Sun sensors
    - Star trackers
    - Reaction wheel
    - Imagers / quaternions