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

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

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

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

5a) Trajectory Correction Maneuvers (TCMs)
Orion
Outbound: 3 - 8 days

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

6a) Mission & Return to Earth
Orion

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

7) ICPS to Hello Orbit

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

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.
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
• 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”**

### Challenge Goal

- **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**

<table>
<thead>
<tr>
<th>Capabilities</th>
<th>Long-Dist Comm</th>
<th>Impactor</th>
<th>Orbiter</th>
<th>2-Sat Comm Relay</th>
<th>Prox Ops</th>
<th>Lander</th>
</tr>
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<tbody>
<tr>
<td>Propulsion</td>
<td>- No Prop Needed</td>
<td>0</td>
<td>+ Most Prop Needed</td>
<td>- No Prop Needed</td>
<td>- No Prop Needed</td>
<td>NOT FEASIBLE</td>
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<tr>
<td>Pointing</td>
<td>0</td>
<td>0</td>
<td>Hi BW Comm burst (before impact)</td>
<td>0</td>
<td>0</td>
<td>+ Most pointing</td>
</tr>
<tr>
<td>Comm</td>
<td>+ Longest range</td>
<td>+ Hi BW Comm burst (before impact)</td>
<td>0</td>
<td>+ 2-way relay</td>
<td>0</td>
<td></td>
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<tr>
<td>G&amp;NC</td>
<td>Determine Earth Direction</td>
<td>0</td>
<td>0</td>
<td>+ Determine Child’s Trajectory</td>
<td>0</td>
<td></td>
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<tr>
<td>Power</td>
<td>0</td>
<td>0</td>
<td>Shortest Mission</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Survival</td>
<td>0</td>
<td>-</td>
<td>Situation awareness</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Space Warrior</td>
<td></td>
<td>+1</td>
<td>0</td>
<td>1</td>
<td>+1</td>
<td>0</td>
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<tr>
<td>Heliophysics</td>
<td></td>
<td></td>
<td></td>
<td>√ multipoint obs</td>
<td>√ multipoint obs</td>
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<td>Lunar Exploration</td>
<td>√ comm relay?</td>
<td>√ volatile det</td>
<td>√ revisit ground tracks</td>
<td>√ landed assets comm relay</td>
<td>√ landed assets comm relay</td>
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<tr>
<td>Planetary Sci</td>
<td>√ comm</td>
<td>√ volatile det</td>
<td>√ autonomous orbit</td>
<td>√ landed assets comm relay</td>
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<tr>
<td>Earth Sci</td>
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<td>√ multipoint obs</td>
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<tr>
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<td>√ multipoint obs</td>
<td>√ multipoint obs</td>
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<tr>
<td>Exploration goals</td>
<td>√ comm</td>
<td>√ in situ recon</td>
<td>√ autonomous orbit</td>
<td>√ NEO recon</td>
<td>√ NEO recon</td>
<td>N/A</td>
</tr>
</tbody>
</table>
• 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
• **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 communications, command and control
  – Autonomy

• **Applications:**
  – NEO missions
  – Earth Science
  – Pathfinders, In-situ resource surveyors
  – Heliophysics
  – Planetary science
  – Lunar Science
• **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
Goal: to foster innovation in small spacecraft navigation, operations, and communications techniques for deep space

**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

**CubeSat limited to 6U and 14 kg**

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

$5.0M Prize Money

13 Sept 2016
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

Team of technical SMEs

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

40% Likelihood of Mission Success

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

Total GT Score
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!
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
• 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

Fall 2014 Competition Registration

GT-1              GT-2            GT-3            GT-4

Today

2018 EM-1 Launch

EM-1 L+365 Days Competition End

365 Days

Team A

GT-1

Team B

GT-2

Team C

GT-3

Team D

GT-4

Down Select (if more Teams than launch spaces)

(Not Selected)

28 days

Team X

3rd-Party Launch

365 Days

Team End

Team Y

3rd-Party Launch

28 days

Team Z

3rd-Party Launch

< 365 Days

< 28 days
**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.**
  Worcester Polytechnic Institute

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

* - indicates EM-1 Qualifier
• **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)
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 accurately 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
– 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.
• 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?

CubeQuest CHALLENGE
A NASA CENTENNIAL CHALLENGES COMPETITION

Jim Cockrell
Cube Quest Challenge Administrator
ARC-CubeQuestChallenge@mail.nasa.gov
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