Mission Design for Deep Space CubeSats

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NASA Ames’ CubeSat Missions

NASA Ames has the oldest NASA effort in CubeSats

- Peer-review Science with its CubeSat Missions since 2006
- 21 Mission flown (31 CubeSats) or in active development
- Deployed NASA’s first 1U and 3U CubeSats from ISS (2012, ’14)
- Developed the first CubeSat Science Swarms (Oct 2015, ‘16)
- Developing the first Beyond LEO Bio-nanosat (Biosentinal 2018)

Ames CubeSats have been supporting the goals of:

- Space Biology Science,
- Swarm Science, and
- Technology Development.
Current State-of-the-Practice

Domain: Low Earth Orbit
Deployment: Secondary Payload
Hosted Payload
ISS
Lifetime: Weeks to Years (limited by orbital altitude)
Trajectory: Passive
Differential Drag
Propulsion (in development but not yet routine)
Tracking: GPS
Transponders (in development)
Communications: UHF, S-band and X-band
Networked (Iridium, GlobalStar) (in development)
Optical (in development)
Applications: Education
Technology Demonstrations/Maturation
Space Biology/Life Sciences
Earth Science
The Future Need

- **Solar and space physics, Earth science and applications from space**—Exploration of Earth’s atmospheric boundary region. CubeSats are uniquely suited because of their expendability to explore the scientific processes that shape the upper atmospheric boundary using short-lifetime, low-altitude orbits.

- **Earth science and applications from space**—Multi-point, high temporal resolution of Earth processes. Satellite constellations in low Earth orbit could provide both global and diurnal observations of Earth processes that vary throughout the day, such as severe storms, and are currently under-sampled by Sun-synchronous observatories.

- **Planetary science**—In situ investigation of the physical and chemical properties of planetary surfaces or atmospheres. Deployable (daughter-ship) CubeSats could expand the scope of the motherships with complementary science or site exploration.

- **Astronomy and astrophysics, solar and space physics**—Low-frequency radio science. Interferometers made of CubeSats could explore the local space environment and also galactic and extragalactic sources with spatial resolution in ways not accessible from Earth.

- **Biological and physical sciences in space**—Investigate the survival and adaptation of organisms to space. CubeSats offer a platform to understand the effects of the environment encountered in deep space, such as microgravity and high levels of radiation.

*Committee on Achieving Science Goals with CubeSats; Space Studies Board; Division on Engineering and Physical Sciences; National Academies of Sciences, Engineering, and Medicine, 2016, Committee Chair: Thomas Zurbuchen*

The 2016 NAS/SSB report describes example science application areas for CubeSat-class missions.
Challenges of Deep Space Applications

The Deep Space environment can be much more challenging than LEO in terms of:

- Radiation
- Thermal

Deep Space Communications are much more difficult than LEO:

- Range
- Antenna Size
- Transmit Power
- Ground Networks

Power: Spacecraft are physically small, so require large area/mass SA

Deep Space Missions frequently require active trajectory control:

- Propulsion needed either: (1) to maintain the desired science orbit, or (2) to get from the secondary payload drop-off to the desired destination

- Use of propulsion implies: (1) tracking (2) orbit determination (3) scheduled communications passes, and (4) maneuver planning and execution

Deployment: Hosted payload accommodation to destination

- Transit from secondary payload drop-off to desired trajectory
  - Lots of impulsive dV or Low Thrust (high transit time in radiation belts)
Challenges of Deep Space Applications

The low-cost LEO CubeSat operations model does not apply to Deep Space

- LEO operations can utilize simpler passive operations and GPS tracking
- Deep Space operations require a more complex and active operations approach because of distance and trajectory management.

**Deep Space mission operations do not change based on the size or cost of the spacecraft!**
Mothership Concept

A larger spacecraft carries the CubeSats to their destination orbit, deploys them, and then supplies communications relay functions to Earth:

- **Propulsion is only required to maintain trajectory, not get them there**
- **Communications becomes short range to the mothership**
- **Less communications power results in smaller solar arrays**
- **Relative navigation between CubeSats and Mothership**
Mission Design Center (MDC)

Provide Mission Concept and Spacecraft Design Support for NASA, Academia, other Government agencies.

- Dedicated team of experienced SMEs in all aspects of mission design with the capability to reach out to specialized areas for specific concept requirements.
- Integrated end-to-end mission design and simulation tools with ongoing development efforts to enhance current version and create new tools.
- Extensive database of heritage flight hardware, instruments, and mission concepts to leverage for current and future concepts and spacecraft designs.
- Authors of the NASA SSTP State Satellite State of the Art Report imbedded in the concept teams to provide leading edge knowledge of spacecraft technology.
- Collaborative facilities and software tools which enhance the cooperative design environment of the MDC.
- Rapid prototyping capability with the Ames Space Shop (3D printing, CNC, laser cutting, etching, Raspberry Pi, Arduino, and other prototyping tools and systems.)
MDC provides comprehensive integrated end-to-end mission design to win proposals

- PI Concept Development
- Science Instrument Development
- Technology Development
- Constellations Designs
- Geographic Region Coverage
- Swarm Formation & Communications
Ames’ MDC supports concepts throughout development process

- Open trade space
- Frame key questions
- Analyze drivers
- Derive and assess partials

Step 1 baseline ready for proposal development

1-3 reference design options synthesized

Concept baseline engineered, costed, validated

Proposal Gate

ICE

Cost Heritage

Portfolio Gate

Concept Gate

Synthesis Gate

Trade space understood

CML 5

CML 4

CML 3

CML 2

CML 1

Salient kernel documented

Fundamental feasibility of one approach validated quantitatively

Ames’ MDC supports concepts throughout development process

JPL Innovation Foundry

CML: Concept Maturity Level

ICE: Integrated Concurrent Engineering
Proposal and Project Development Support

The MDC develops marketing material for concepts through standard products and services

- Feasibility Evaluation - for quick decision-making
- Conceptual Whitepaper - key technical considerations
- Technical Proposal – lays out credible solutions

MDC is also a shared, prioritized resource for all projects at any development phase.

Almost all spaceflight concepts are supported by the MDC at some point in planning or implementation

LCROSS, LADEE, IRIS, O/OREOS, TES 1-6, BioSentinel, NLAS, and other projects have all received MDC support

MDC Supports Missions from Proposal to Operations
Concurrent Engineering

The ARC Mission Design Center is a concurrent engineering facility

- “War Room” environment for design teams
- Similar to Team X (JPL), COMPASS (GRC), MDL (GSFC), MDF (ESA), and several in industry, such as CIEL (Boeing)
- Uses small multi-disciplinary core team augmented with support from other specific subject matter experts

Leverage IT Product Development to Space Mission Design

- Searchable database of previous mission designs
- Database of COTS hardware components and characteristics – Small Sat State of the Art Report
- Custom-built and commercial software tools comprise an Integrated Concurrent Engineering (ICE) environment
<table>
<thead>
<tr>
<th>Category</th>
<th>Item</th>
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<tr>
<td>Mission</td>
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<td>Radiation Dosage</td>
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<td>Trajectory Optimization (impulsive)</td>
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<td>Trajectory Optimization (finite/low thrust)</td>
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Legend:
- Detailed Analysis
- First-Order / Engineering Estimate
- Some Utility
- Not Applicable
- Non-Standard / Specialized

*Note: First Order software analysis is supplemented with mission design experience to produce detailed results.

Ongoing Development is Focused on Providing High Fidelity Day-in-the-life Mission Simulations
Integrated Design & Simulation Tools

Current Toolsets
- Atlas and ICEicle – Internal integrated concurrent engineering
- SharePoint – Database, project storage
- STK / SOAP – Trajectories, coverage
- Solidworks – CAD, Mechanical Designs
- Matlab/Simulink – GNC / ADCS modeling and analysis
- Thermal Desktop – Thermal Analysis
- MSC Nastran – FEA modeling

Toolsets in Progress
- Generation of xTEDS from database designs
- Integration of plug-and-play software into mission modeling
- Autocode of ConOps software
- Full simulation based design validation
- Autocoded control software
Atlas Architecture

Users
Stakeholder requirements and mission concept

Parts Database
MDC-maintained and updated pool of spacecraft components

Previous Missions
Inheritance of heritage spacecraft configuration

ATLAS
MDC concurrent engineering spacecraft design platform

External Software
MATLAB, STK...etc

Mission Phases
Payload
ADACS
CnDH
Power
Propulsion
Structures
Telecom
Thermal
### Inert Mass

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<tr>
<th>Item</th>
<th>Exists</th>
<th>Same</th>
<th>Guess</th>
<th>Override Mass</th>
<th>Uncertal Mass</th>
<th>Expendable Mass</th>
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<td>Payload</td>
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<td>5.1</td>
<td>40%</td>
<td>7.2</td>
<td>5.1</td>
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</table>

**Total Inert Mass**: 156.3 kg

### Expendable Mass

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<td>5.1</td>
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**Total Expendable Mass**: 121.5 kg

### Total Mass

**Total Mass**: 277.8 kg

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### Mass Distribution

- **Payload**: 17.0 kg (9%)
- **Power**: 26.0 kg (24%)
- **CnDH**: 5.0 kg (10%)
- **ADACS**: 6.7 kg (15%)
- **Structures**: 64.7 kg (6%)
- **Propulsion**: 42.6 kg (15%)
- **Telecom**: 6.2 kg (10%)
- **Thermal**: 5.1 kg (40%)

### Power Distribution

- **Payload**: 22%
- **ADACS**: 18%
- **CnDH**: 18%
- **Power**: 0%
- **Telecom**: 58%
- **Propulsion**: 5%
- **Structures**: 0%

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**Note**: This data is derived from the 2010 LCDE study and includes various mission components and their respective masses.
Example: Spacecraft modeling and analysis

- SolidWorks CAD model
- SolidWorks exploded view
- Thermal Desktop model
- SolidWorks Finite Element Analysis
Example: MATLAB Solar Electric Power Script

AGESS Power Analysis
• MATLAB Attitude and Top Level Parameters
• STK Power and Orbit Propagation
Example: Atlas-STK Interface

ATLAS/STK  Telecom Add-on:

• Exports ATLAS telecom design rapidly to STK
• Populates ground stations from MDC database
• Allows quick trades between ground networks
Interplanetary trajectory solver for NEOs and planets

**In-House Trajectory Tools for:**
- Solving patched conic and N-body interplanetary trajectories to NEOs and planets
- Obtaining low-energy transfers to the Moon
- Optimizing flyby encounter characteristics
- Optimizing EP thruster maneuvers and trajectories
Red Dragon Mars Sample Return Study

Demonstrated that compact and efficient use of emerging commercial capabilities to perform a high priority science mission is feasible.

Capabilities of Mission Design Division used to augment analytical work from other Ames organizations

How much mass and volume can Red Dragon deliver to Mars?

- Construct aerodynamic model of Dragon
- Include model of retro-propulsion system
- Compute EDL trajectories from entry interface down to surface
- Use in-house computational tool, TRAJ; commercially available tool, POST
- MARSGRAM atmospheric model
- Determine mass limit for successful EDL

How much mass and volume is required for Earth return rocket and related subsystems?

- Conduct parametric optimization study for Earth return rocket using in-house computational tool, HAVOC
- Determine sensitivity of design to: propellant choice, rocket motor design, staging $\Delta v$, aerodynamics, etc.
- Choose baseline design for Earth return rocket
- Perform bottom-up design of Earth return rocket and related subsystems
- Develop solutions for support equipment

Will This Fit Into This?

Yes!
- Web application for searching and assessing candidate mission trajectories
- Originally developed for internal use
- Now publicly accessible at http://trajbrowser.arc.nasa.gov
Questions?