National Aeronautics and Space Administration
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Novel Ideas for Exploring Mars with CubeSats:

Challenges and Possibilities

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Background

Ongoing study at JPL, answering two key questions:

- What science and technology demonstrations can be done with CubeSats at Mars? Some preliminary answers:
  - CubeSats can address narrowly focused science goals*
  - High science value/$
  - CubeSats may enable new investigation concepts or add significant additions to existing missions. E.g.: Spatial distributed measurements with a network of s/c, use of "disposable" sensors etc.
  - Technology missions for infrastructure support (telecom relay) and demos for future exploration (e.g. Aerocapture, Optical Comm., etc.)
- **What are the key challenges to flying CubeSats at Mars? (*main focus today*)**

Features of Mars CubeSats:

- Volume: ~6U ("U" is a 10 x 10 x 10 cm cube)
- Mass: ~10 kg
- Power: ~25-50 W at Mars
- Maintain compatibility with CubeSat avionics components
- Potential deviations from CubeSat Design Specification in the areas of propulsion & deployment

(*) Investigations and Goals are defined by Decadal Survey, Mars Exploration Program Analysis Group (MEPAG), Human Exploration Strategic Knowledge Gaps (SKG)

Potential Science Objectives

Possible mission configurations
Orbiters – Orbiter Networks – Phobos Lander CubeSats – Mars Rover Piggyback

Science Theme	Relevant MEPAG/HEO Goal	Measurement	Instrument
Weather monitoring	**MEPAG Goal II:** Understand processes of climate on Mars, characterize Mars' present climate/atmosphere **II.A.1,3:** Water & dust on all scales, volatile exchange **HEO:** Effects of dust	Presence of dust clouds and water clouds	Camera
Atmospheric profiling (T,P, etc.)	**MEPAG Goal II.A:** Characterize Mars' present atmosphere. **HEO:** Improved atmospheric modeling	Temperature, pressure , dust concentration, etc. profile vs. altitude	Atmospheric Radio Occultation
			Atmospheric Light Science
Atmospheric composition	**MEPAG Goal II.A.1,3:** Water, CO_2 on all scales, volatile exchange **HEO:** Atmospheric constituents	Atmospheric chemical composition	Mass Spectrometer
			Sub-mm wave spectrometer
		Atmospheric water vapor concentration	Microwave Radiometer
		Atmospheric dust/micro-meteorite concentration	Dust Detector
Atmospheric winds	**MEPAG Goal II.A:** Characterize Mars' present atmosphere	Atmospheric wind speed & direction vs. altitude	Lidar
			Sub-mm wave spectrometer
Cloud properties	**MEPAG Goal II.A.1,3:** Water on all scales, volatile exchange	Cloud properties	Polarimeter
Surface mineralogy	**MEPAG Goal III:** Determine evolution of surface of Mars. **HEO:** Geology/composition of Phobos and Deimos	Mineralogy	Imaging Spectrometer
Gravity field	**MEPAG Goal III.B.1:** Understand evolution of Mars' interior	Measure gravity field (high order J-terms)	Gravity Light Science Investigation
			Gravity Field Formation Flight
Lightning detection	**MEPAG Goal II.A:** Characterize Mars' present atmosphere. **HEO:** Atmospheric electricity	Radio signals from lightning	Radio detector
		Light flash from lightning	Photodiode
Magnetometry	**MEPAG Goal III.B.2,3:** Understand evolution of Mars' interior magnetic field, thermal evolution of planet	Magnetic field	Magnetometer
Radiation	**HEO:** Radiation	Radiation environment	Radiation Detector
		Total radiated dose	Dosimeter
		Solar wind	Plasma Instrument
		Neutron detection	Neutron Spectrometer

CubeSats are well suited to address narrowly focused MEPAG & Decadal Survey goals & investigations, rather than complex multifaceted questions

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CubeSats: From LEO to Mars

- Mars CubeSat development builds on:
  - Existing LEO experience
  - Current INSPIRE development
  - Future/current LEO technology testing (e.g. ISARA)
- Mars application will require:
  - Capable mother ship for MOI & communication with Earth
  - OR Improvement of current technologies to enable stand-alone CubeSat (GTO launch)

Present

LEO CubeSats

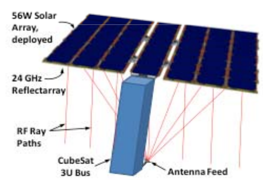
- 10 years of experience
- Well established community (Industry, Academia, NASA)
- MSU Van Allen Belt Explorer

2014

INSPIRE

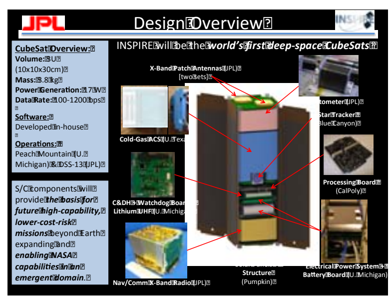
- First deep space CubeSat
- Initial steps towards Mars CubeSats
- E.g. X-Band communication, watchdog avionics, cold gas propulsion

Present – 2016



LEO Developmental Testing

- Test key technologies in earth orbit & in lab

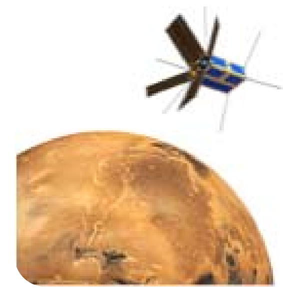


2016 – Early 2020s

Mars CubeSat *Orbiter Mother Ship*

- Mother ship provides orbital insertion and DTE comm.
- Requires additional key technology development beyond INSPIRE
- E.g.: UHF Comm., Propulsion (if necessary of separate orbits), Thermal, Power, Environment/Lifetime

2020s



Mars CubeSat *High Performance /Stand-alone*

- Either launches with Lander or launches to GTO
- Further technology development required
- E.g.: DTE Comm., High Delta-V Propulsion, Environment/Lifetime (for multi-year cruise), Navigation

Develop Solutions for Key Mars CubeSat Challenges

Top Challenges for Mars CubeSats

Mars-Specific Challenges

1. Propulsion

- Launch/Earth Departure: Assume CubeSats are secondary payload on Mars mothership. Implies high safety requirement. Other earth departure options: low thrust or solar sail
- **Mars Orbit Insertion**: Get into a suitable Mars orbit ($\Delta V \approx$ 1-2 km/s)
- Orbit Maintenance: Maintain position stability ($\Delta V \approx$ 10-50 m/s)

2. Communications

- **DTE**: Provide adequate data rates to enable quality science return
- Relay: Electra compatibility with surface assets

3. Environments/Lifetime/Radiation

- Survive cruise and **Mars radiation environments**. Current shielding technology uses precious mass resources. CubeSat propulsion techniques involving low thrust result in longer transit times.

Challenges Being Met by LEO CubeSats

4. Science Instruments

- Targeted, high-performance investigations in a low mass, low power package

5. Power Generation

- Generate sufficient power (20-50 W) for operation and communication to Earth at Mars distances

6. Thermal

- Provide adequate heat rejection given high power density

Many solutions to these challenges can be tested in the lab or on CubeSats in LEO, inexpensively and with a quick turnaround time

Propulsion: Mars Orbit Insertion

Challenges:

- Mars orbit insertion requires a ***large Delta-V (~1-2 km/s)*** to achieve a useful science or telecom orbit.
- Propulsion system must be ***safe & properly qualified*** to fly as a secondary payload on a planetary mission.

Current State of Practice:

- No propulsion on current LEO CubeSats
- Some near-term CubeSats will employ cold gas propulsion (INSPIRE - 2014)
- Current development of Low-Thrust propulsion technologies

Possible Solutions:

- Orbit insertion performed by Mars Orbiter mothership (Mars obiters are planned in 2020s)

Orbiter Mothership

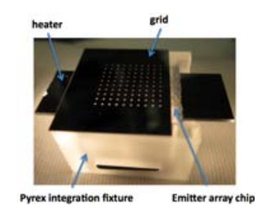
- Chemical Propulsion
  - Conventional or Restartable solid; Hybrid propulsion system
  - Requires further **development & qualification**

Solid Rocket Motor

- Aerocapture
  - Requires **precise targeting** and corridor control, **heatshield development**, and packaging in constrained volume

Aerocapture

- Low Thrust Spiral
  - Several options: JPL, Busek, etc.
  - Low thrust results in **long cruise** and increased total radiation dose



JPL Micro-Electrospray Thruster

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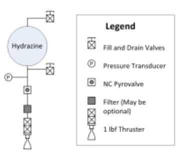
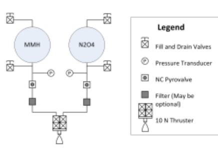
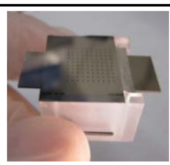
CubeSat Propulsion Technologies

	Technology	Description	Specific Impulse (Isp)	Thrust	Propulsion System Mass for 1.5 km/s Delta-V for 10 kg S/C
	Conventional Solid Rocket Motor *(Industry catalog)*	Wide range of existing solid rocket motors (e.g. ATK Star Motor)	250 – 270 s	2.5 – 5 kN	~20 kg
	Restartable Solid Rocket Motor *(In development)*	Electrically controlled solid propellant (e.g. Digital Solid State Propulsion, LLC)	~220 s	TBD	TBD
	Hybrid Propulsion System *(Larger models exist)*	Paraffin/N_2O_4	275 s*	100-500 N	~15 kg
	Monopropellant Propulsion System *(Components exist)*	Hydrazine or ADN	220 – 230 s*	5 N	~15 kg
	Bipropellant Propulsion System *(Components exist)*	Hydrazine/N_2O_4	280 s*	10 N	~15 kg
	JPL Micro-Electrospray Thruster *(In development)*	Micro-fabricated needles and liquid indium propellant	5000 s	~100 µN	~2 kg *(ΔV = 5 km/s)*

**Operates in blow-down mode*

Telecommunications

Challenges:

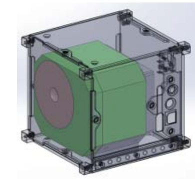
- **DTE:** Provide adequate data rates at X/Ka-band to enable quality science return at *distances up to 2.6 AU*, in a highly ***constrained power/volume*** envelope
- **Relay:** Provide ***UHF CCSDS Proximity-1*** relay capability in a highly ***constrained power/volume*** envelope (may be to surface or to other orbital assets)

Current State of Practice:

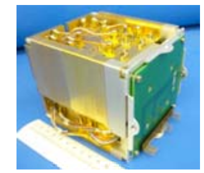
- **DTE:** DSN-compatible IRIS X-Band transponder being developed for INSPIRE, 2014 launch to 0.1 AU
  - Power amplifiers at X and Ka-Band: relatively low efficiency SSPA (~25%) or large mass/volume TWTAs
- **DTE:** Optical communications have been developed to TRL 5 (aircraft)
- **Relay:** Commercial UHF systems currently used near earth, but are not CCSDS Prox-1 compatible

Possible Solutions:

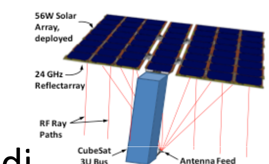
- **DTE:** Link
  - Optical Communication – may bypass some RF implementation challenges
  - Multi-band miniature radios
- **DTE:** Power Amplifier
  - High efficiency SSPAs (GaN) and miniature TWTAs
- **DTE:** Antenna
  - Reflectarray (dual-use aperture)
  - Deployable HGA
  - Fixed Offset Feed Antenna
- **Relay:** UHF CCSDS Compatible Radio
  - Based on commercial radio or IRIS



Optical Comm.



X/Ka/UHF Radio



ISARA Reflectarray

Solution Trends

Maximize antenna size
- *Data rate ~ antenna area*

Move to higher frequencies.
- *Antenna dimensions (and to some degree other components) ~ λ*
- *However: higher frequencies need better pointing*

Maximize RF/laser power efficiency
- *Data rate ~ RF/laser power output*
- *Secondary benefit: less wasted heat, better thermal balance*

Standardize
- *Use DSN for Direct-to-Earth links*
- *Electra/CCSDS for Mars proximity link*

Lifetime/Environments/Radiation

Challenges:

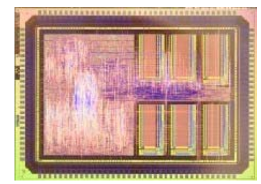
- Mars radiation environment is more hazardous than the LEO environment due to Mars' lack of a magnetosphere
- Need a cheap, lightweight method to reduce radiation hazard for avionics components at Mars
- Need radiation hardness solutions for both analog and digital parts
- Long lifetimes are required to survive cruise and perform useful science over a Mars year

Current State of Practice:

- LEO CubeSats are not typically radiation hardened and have short lifetimes
- Current trends are increasing radiation tolerance of digital parts
  - Total Integrated Dose (TID) and latch up performance improving
  - Single Event Upset (SEU) performance getting worse

Possible Solutions:

- Commercial Parts Trends
  - TID and latch up failures are being resolved by new <65nm IC technology.
  - Infant mortality, quality and reliability has radically improved
  - **SEU rates are increasing**
  - **Temperature range doesn't meet mil standards;** but automotive parts are getting close
- Error Detection And Correction/ Voting Architecture
  - Multicore or multichip voting
  - Rad-hard CubeSat avionics being pursued by several commercial companies, e.g.: SpaceMicro Proton400, Leon 3FT

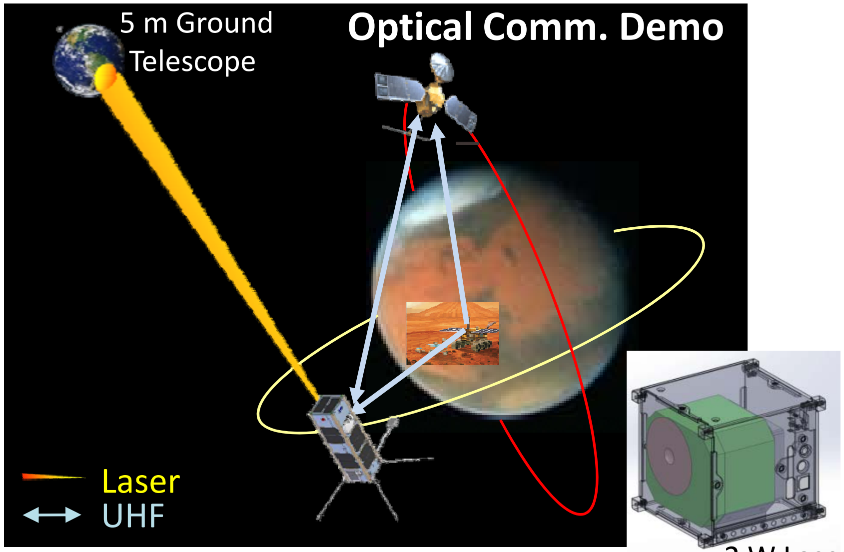


- System mitigation of SEU events
  - Repeat the same operation to detect SEU
  - Rewrite parity interrupt handler

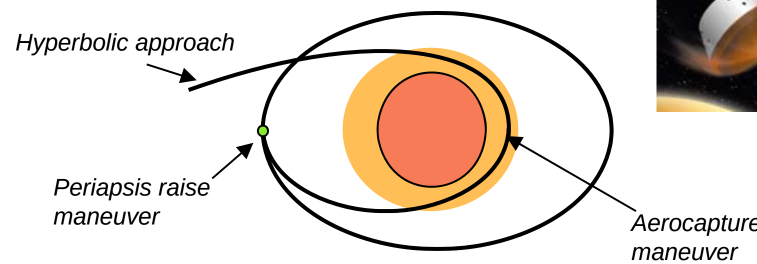
Status of Challenges for Digital Avionics

- Radiation total dose – OK with near-term technology (up to 100 krad TID – only need <10 krad)
- Latchup – OK with near-term technology (<90 nm traces)
- SEUs – Still a problem; may be addressed by EDAC or voting

Three Example Mission Concepts



Aerocapture Demo

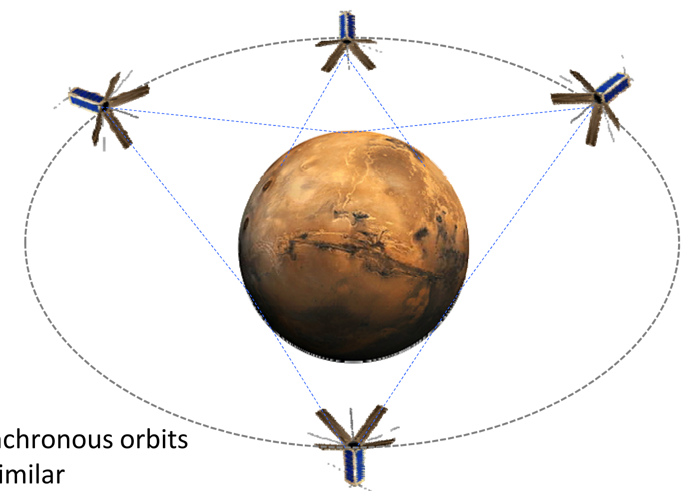


- Aerocapture replaces chemical propulsion as a method of insertion into Mars orbit
- Released on hyperbolic trajectory ~4 days prior to closest approach

- **Optical Comm. Demo:** 5 kbit/s from Mars at 2 AU
- **Aerocapture Demo:** Enables Mars orbit insertion without chemical propulsion
- **Mars CubeSat Network:** Enables spatially distributed continuous coverage for atmospheric or gravity science

Additional details in backup charts

Mars CubeSat Network



- 3 Equatorial Synchronous orbits
- 1-2 Polar sats (similar observation, lower orbit)

Conclusions

- Potential for exciting science and technology opportunities at Mars when we overcome the key technological challenges
  - Tightly focused science investigations with high value/$
  - Technology demonstrations
  - Mission enhancement for flagship missions
- Key challenges
  - **Propulsion** for Mars orbit insertion
  - Deep-space **Communication**
  - **Lifetime & Radiation**
  - *All close to resolution – need a focused technology development and lifetime/radiation testing effort to complete maturation*
- Attractive attributes of CubeSat technology development
  - Small scale lab development and test
  - Relatively modest LEO flight demonstration possibilities
  - Large and rapidly progressing existing university and industry CubeSat effort

Backup

CubeSat Propulsion Technologies

Comparison of Propulsion Technologies
For CubeSat-Class Impulsive Mars Orbit Insertion Systems

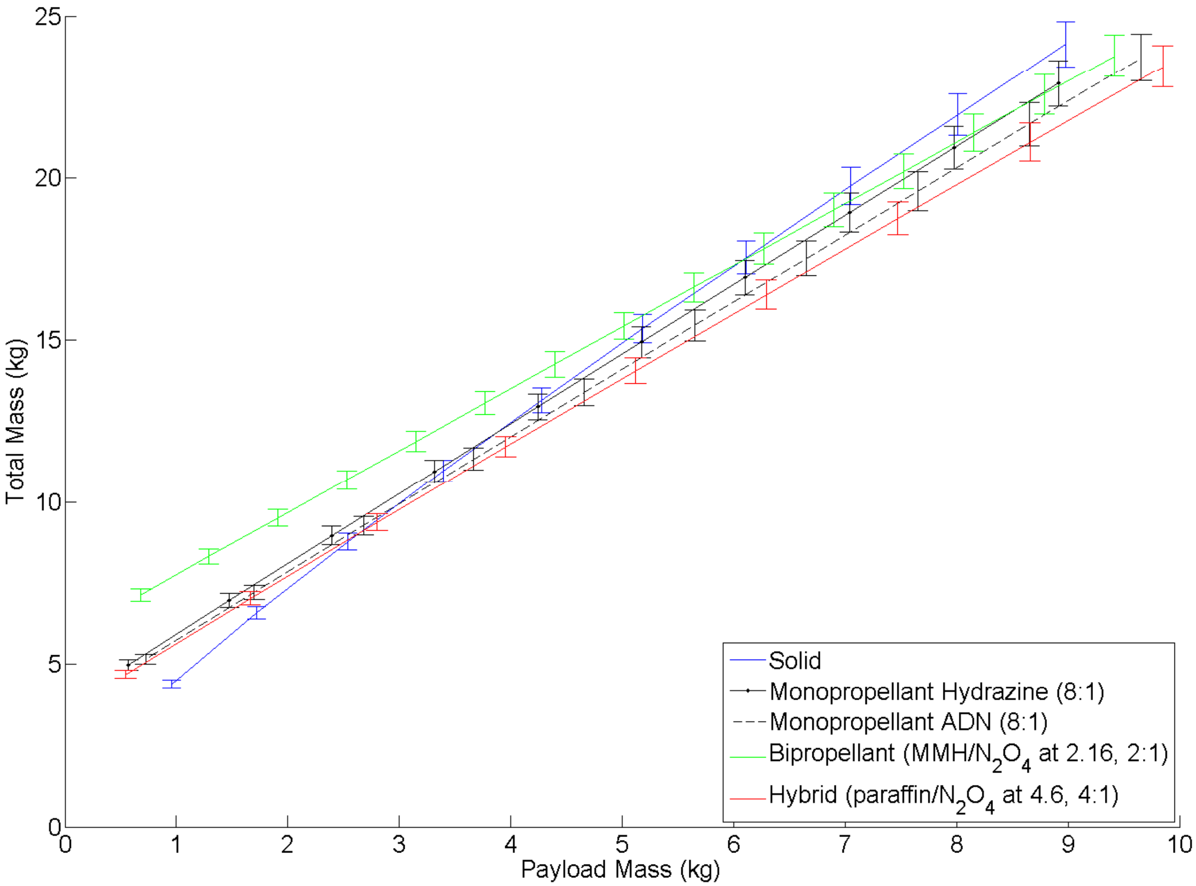


Chart Assumptions

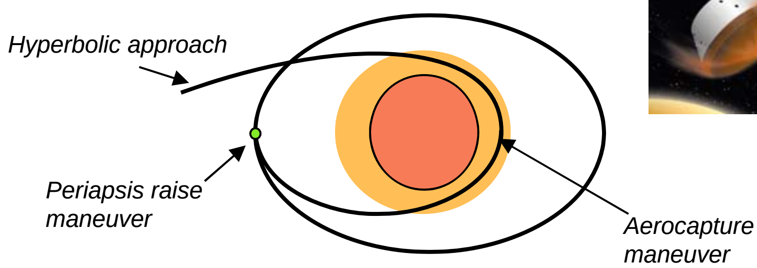
- Mars orbit insertion:
  - ΔV = 1500 m/s
- Monopropellant:
  - Isp: 220 – 230 s
  - Fixed Dry Mass: 1.6 kg
- Bipropellant:
  - Isp: 280 s
  - Fixed Dry Mass: 2.3 kg
- Hybrid:
  - Isp: 275 s
  - Fixed Dry Mass: 1.2 kg
- Solid:
  - Isp: 250 – 270 s

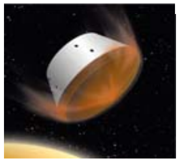
Hybrids, Solids, and Monopropellant propulsion systems are all comparable in mass performance for this class. Bipropellant systems are complex and inefficient at low mass.

Example Mission Concepts

- Three example mission concepts – many other possibilities
  - Data Relay & Aerocapture
  - Optical Comm. Data Relay
  - Network Science
- Launch with Mars 2020 Mission
  - Spinning cruise stage requires balanced mass additions
  - Twin CubeSats could provide balance and flight-system-level redundancy
  - Additional hardware required on Mars 2020 Cruise Stage to host and deploy CubeSats
  - Interface will likely deviate significantly from the CubeSat Standard

Example Mission Concept: Data Relay & Aerocapture





Background: Aerocapture is a systems technology; many of the elements have been developed for prior planetary EDL applications (e.g, MSL). The next step for aerocapture is integrate these elements and fly the vehicle in the space environment and thereby validate the design, simulation and systems engineering tools and processes

Objectives:

- Demonstrate a concept of a small inexpensive CubeSat at Mars
- Demonstrate a relay of lander data via CubeSat to the DSN
- Demonstrate system level aerocapture at Mars and validate predictive models for the atmospheric trajectory (particularly the outbound exit phase), hypersonic aerodynamics (including thruster plume interactions), and the guidance and control algorithm.

Concept:

- Twin daughter vehicles on Mars 2020 mission
- Released on hyperbolic trajectory ~4 days prior to closest approach
- Use Aerocapture to insert into Mars Orbit instead of traditional chemical propulsion
- Less than ~0.5 m heat shield, >10 U volume available
- 300 x 6000 km orbit

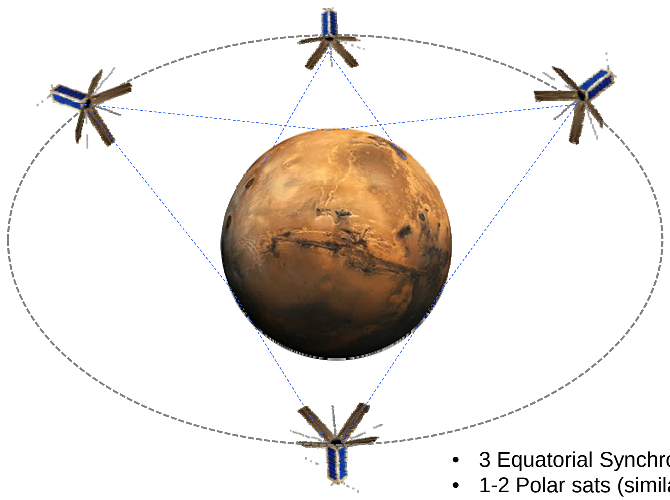
Subsystems

- MOI: Aerocapture
- Attitude Control Propulsion: Mono-prop
- DTE Telecom: X/Ka + UHF IRIS Radio, Ka SSPA, Reflector Array
- UHF Telecom: X/Ka + UHF IRIS Radio, Patch Antenna

Target System Performance

- Mass: 20 kg
- Volume: 6-9 U
- Power: 50 W @ Mars
- Data Rate: TBD
- Daily Data Volume: TBD

Example Mission Concept: Mars Weather Network



- 3 Equatorial Synchronous orbits
- 1-2 Polar sats (similar observation, lower orbit)

- Concept Description
  - Medium Res Cameras
  - Med Resolution cameras on nanosats in spaced orbits (high and/or low). "Geo" synchronous?
  - Filters to show ice/dust contrast
  - "CubeSat" class enables at affordable cost for continuous coverage

- Science Return/Technology Infusion/ Advantages
  - Continuous visual coverage of observable Mars atmosphere phenomena
    - Clouds
    - Dust
    - Polar hood, cap (when visible)
  - Surface changes

- Mission Risks/Barriers
  - Data Volume can be modulated by frame rate and onboard processors to signal change
- Technology Requirements
  - Propulsion
    - Distributed network would require the satellites to place themselves into an orbit and maintain it
  - Telecom
    - Large data sets require time and power to downlink
    - Centralized comm and timing package through mothership may allow us to build up a greater network over time

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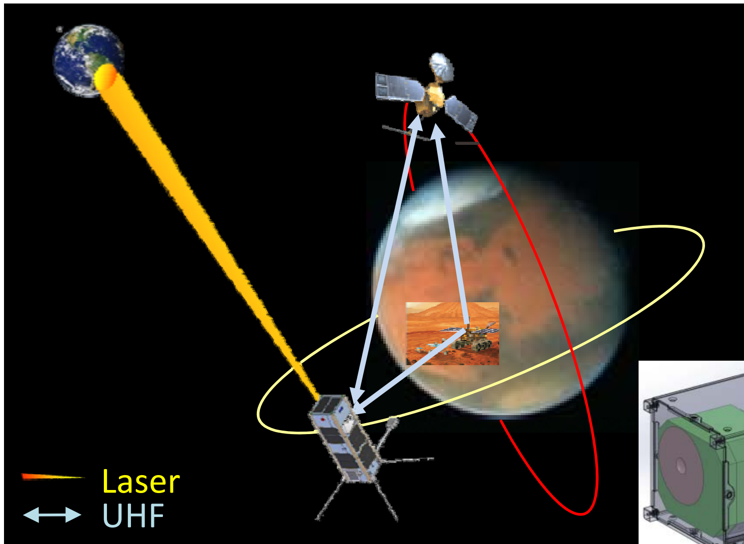
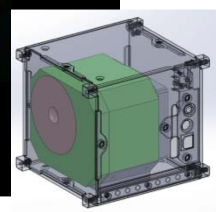
Example Mission Concept: Optical Comm. Data Relay





Objectives:

- Demonstrate a concept of a small inexpensive CubeSat at Mars
- Demonstrate optical comm from Mars to Earth (25% of ODY capability)
- Demonstrate relay of lander UHF data via a CubeSat laser link to Earth
- Use the laser carrier for Mars occultation atmospheric science

Concept

- Twin daughter vehicles delivered by Mars 2020 mission
- Mars orbit insertion with SRM
- Large elliptical orbit: 300 km x ??
- Use 5 m Hale Telescope at Palomar Observatory (Better performance possible w/ 12 m Binocular Telescope)

Subsystems

- MOI: SRM (ATK Star 9 class)
- Attitude Control Propulsion: Mono-prop
- DTE Telecom: JPL Small Optical Comm. Terminal (1U optical terminal, 4 cm mirror, ~2 kg, 2 W laser)
- UHF Telecom: UHF IRIS Radio, Patch or Helix Antenna
- Pointing: 0.2 deg

Target System Performance

- Mass: 40 kg
- Volume: 6-10 U
- Power: 50 W @ Mars
- Data Rate: 4-5 kbit/s at 2 AU to 5 m ground telescope
- Daily Data Volume: >50 Mbit/day
- Operational SEP angle: >15 deg

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CubeSat Taxonomy

Mars Formulation

Delivery Method
- Delivered to Final Orbit by another S/C
- Delivered to target by another S/C, must get to final orbit by itself
- Must fly itself to target and perform all maneuvers

Lifetime
- <1 Year
- <2 Years
- <5 Years
- >5 Years

Orbit / Destination
- Flyby
- Phobos / Deimos Orbit
- High Altitude Orbit
- Low Altitude Orbit
- Atmospheric Sampling Orbit
- Atmospheric Entry
- Landing
- Formation Flying
- Formation Flying / Multiple Units
- Other

Propulsion Capability
- No Propulsion
- Station Keeping Propulsion
- Major Maneuvers Required (MOI, Changing Orbits)

Propulsion Technology
- No Propulsion
- Cold Gas / Butane
- Micro Pulsed Plasma Thruster
- Solid Rocket Motors
- Solar Sails
- Micro Electrospray Propulsion
- Low Power SEP (Hall Thrusters)

Comm Capability
Communication
- Simple UHF Comm
- Electra Comp UHF Comm
- DTE < 1 kbps
- DTE > 1k bps

Navigation
- None
- GPS
- 1-way Doppler w/ Atomic Clock (on a chip)
- 2-way Doppler and Ranging w/ Transponder

Comm Technology
Radios / Amplifiers
- COTS radio
- COTS radio w/ Amp
- IRIS (UHF/S/X) No Amp
- IRIS (UHF/S/X) w/ Amp (SSPA)
- Ka-Band
- Optical

Antennas
- Dipole Antenna
- Patch Antenna
- Helix Antenna
- Small Fixed HGA
- 0.5m Deployable HGA

Power
Generation (@ 1AU)
- None
- RHU RPS (<1 W)
- GPHS RPS (<25 W)
- <25 W
- <50 W
- <100 W
- <150 W
- <200 W
- <250 W
- <300 W

Storage
- None
- <25 Whr
- <50 Whr
- <100 Whr
- >100 Whr

ACS Requirements
Control Type
- 3-Axis Control
- Spinning

Pointing / Stability
- >1 deg
- 1 deg
- 0.1 deg
- 0.01 deg, 2 arcsec/sec
- <0.01 deg, <0.2 arcsec/sec

ACS Technology
- COTS Sun Sensors
- COTS Star Tracker
- Upgraded Star Tracker
- Magnetorquer
- GPS
- Micro Propulsion (common w/ Prop System)
- Micro Propulsion (ACS only)
- Reaction Wheels (3 axis or 1 axis)

Structure / Thermal
- 0.5 U
- 1 U
- 2 U
- 3 U
- 6 U
- 12 U
- Custom

Avionics
- COTS Avionics (Non Rad Hard)
- COTS w/ Cascading Watchdogs (Non Rad Hard)
- COTS Radiation Hard Avionics
- Custom Boards

Enabled Instruments
- Camera
- Imaging Spec.
- Rad. Detector
- Gravity Meas.
- Neutron Spec.
- Radiometer
- Lidar
- Radar

Legend
- Exists/Planned for LEO CubeSats
- Needed for Mars Daughter CubeSats
- Needed for Mars Stand-alone CubeSats
- Not Sure

Lifetime/Radiation

- Radiation total dose – OK with near-term technology (up to 100 krad TID – only need <10 krad)
- Latchup – OK with near-term technology (<90 nm traces)
- SEUs – Still a problem; may be addressed by EDAC or RHBD