“Delivering CubeSats to the Moon and Beyond with Electric Propulsion”

Interplanetary Small Satellite Conference
Pasadena, CA
28-29 April 2014
Busek Co. Inc.

BUSEK
Space Propulsion
and Systems

Busek Co. Inc.

Busek Co. Inc. is a leader in space propulsion systems development and manufacturing

- Core expertise begins with electric propulsion thrusters for military, government, and commercial satellites
- Expertise extends to space electronics, propellant feedsystems, and systems integration and testing
- Propulsion Technologies (thruster types) include:
    - *Hall*
    - *Electrospray (colloid)*
    - *Micro pulsed plasma*
    - *RF Ion*
    - *Microresistojet*
    - *Cold gas*
    - *Chemical (green monoprop)*

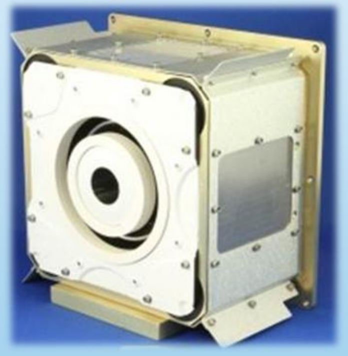
Overview

- Chemical Propulsion vs. Electric Propulsion
- Small spacecraft benefits, and limits and capability of propulsion
- CubeSat-scale spacecraft for a Lunar mission
- Propulsion-enabled ESPA-type spacecraft for Lunar and Mars CubeSat delivery
- Exposition of Busek propulsion offerings suitable for small spacecraft and ESPA missions

Chemical Propulsion vs. Electric Propulsion

Small chemical thruster (22N from AMPAC-ISP)

- Electric propulsion is much more fuel efficient than chemical propulsion
- EP has Specific impulse ~ 30X larger
- EP Results in significant spacecraft mass reduction or increase in capability



BHT-1500 Hall Thruster

Chemical Propulsion		Electric Propulsion
High thrust, low I_{sp}	vs.	Low thrust, high I_{sp}
T = Newtons and higher, typ.	vs.	T= microNewtons thru Newtons *only limited by available power*
Specific Impulse = $I_{sp} \leq 320$ sec	vs.	I_{sp} range from 500 - 10,000 sec
High propellant mass flow & low velocity	vs.	Low propellant mass flow & high velocity

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Why Small Satellites?

- Lower launch costs. Launch costs typically on a per kg basis
- Miniaturization of components and lower power requirements allow equal capability in a smaller platform
- Technological advancement allows lower cost capability, e.g. processors, solar panels
- Cheaper satellites allow for increased risk tolerance (reduced cost of losses), reduced redundancy, lowering costs further
- Lower cost = more missions.

NASA

TDRS

Small Satellites and Propulsion

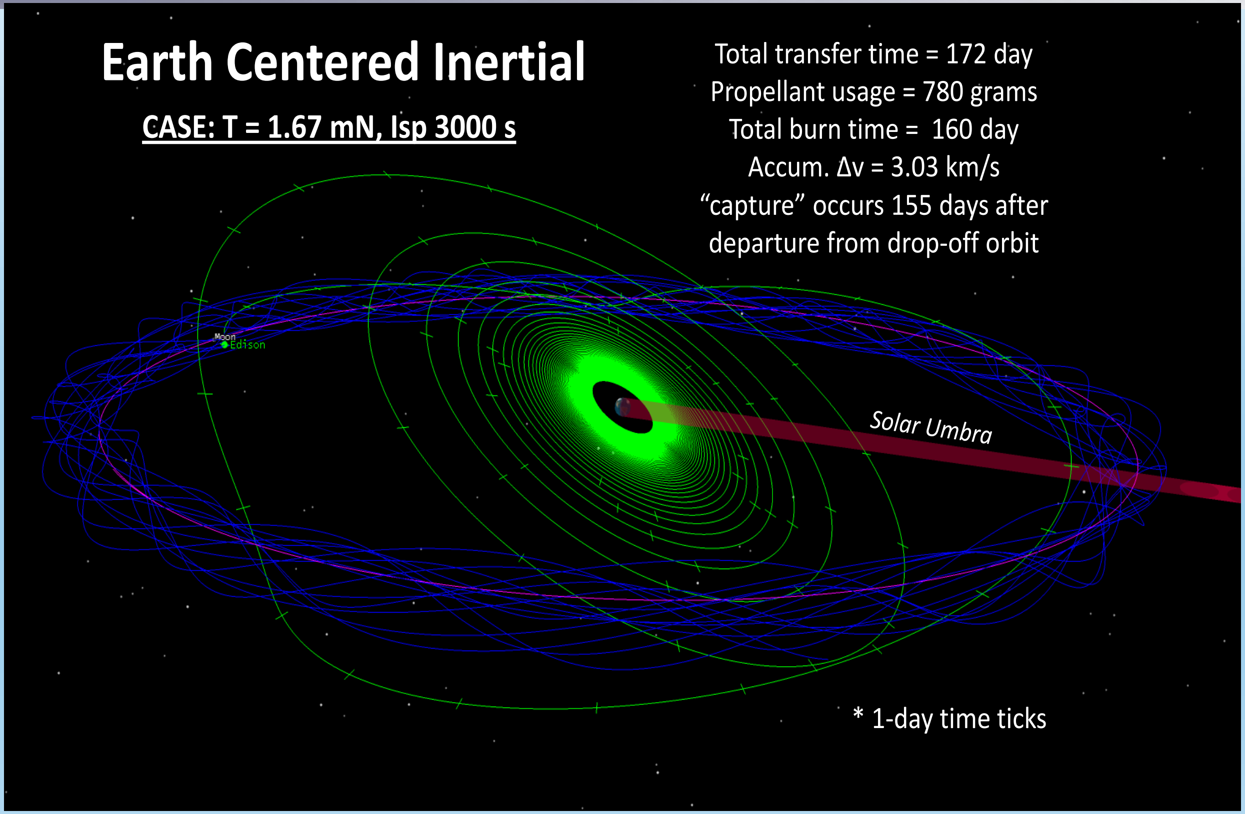
- While many satellite technologies scale favorably for small satellites, propulsion capability is limited by physics:
  - Propellant loading capacity is severely reduced
  - Mass fraction of propellant is relatively low
  - Propellant system dry mass is relatively high
  - Many thrusters cannot operate, or perform poorly, when scaled down
  - Power demands may exceed small satellite power availability
  - Inefficiencies may exacerbate thermal management challenges

Fewer propulsion technologies are suitable for small spacecraft, and selection drops off rapidly with decreasing size: Most chemical and electric propulsion limited by large dry mass. Chemical propulsion further limited by low I_{sp}*, and electric propulsion often further limited by power demands.*

Lunar Cubesat Mission

- ≈ 3km/s required to get to the moon
- Note propellant mass and I_{sp}
- Similarly, a 3kg (3U) spacecraft requires 300g propellant

Lunar missions are possible with multiple propulsion technologies with appropriate system mass vs. I_{sp} tradeoffs



Earth Centered Inertial

CASE: T = 1.67 mN, Isp 3000 s

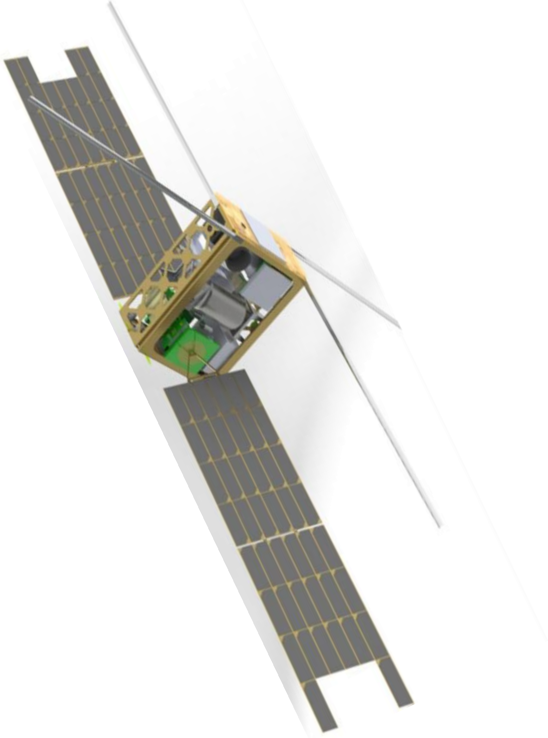
Total transfer time = 172 day
Propellant usage = 780 grams
Total burn time = 160 day
Accum. Δv = 3.03 km/s
"capture" occurs 155 days after departure from drop-off orbit

* 1-day time ticks

Lunar Cube trajectory from MEO to lunar intercept (green trace) and lunar capture/orbit (blue trace). (≈ 8kg s/c wet mass) Courtesy of JPL.

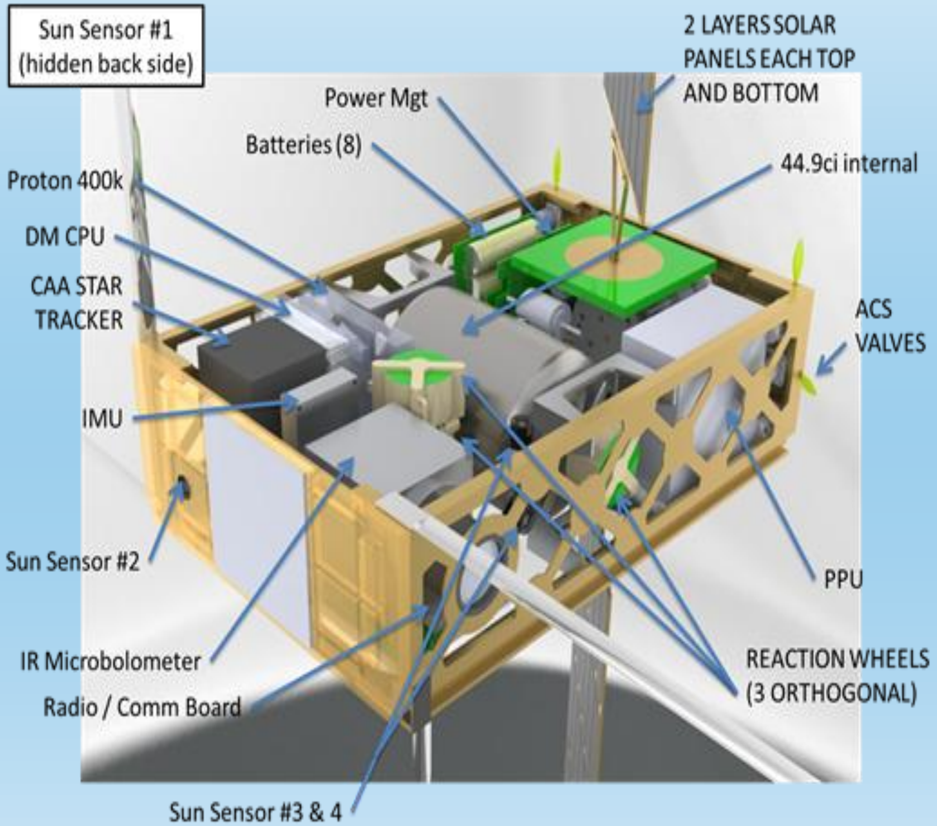
Prospective Lunar Cubesat System

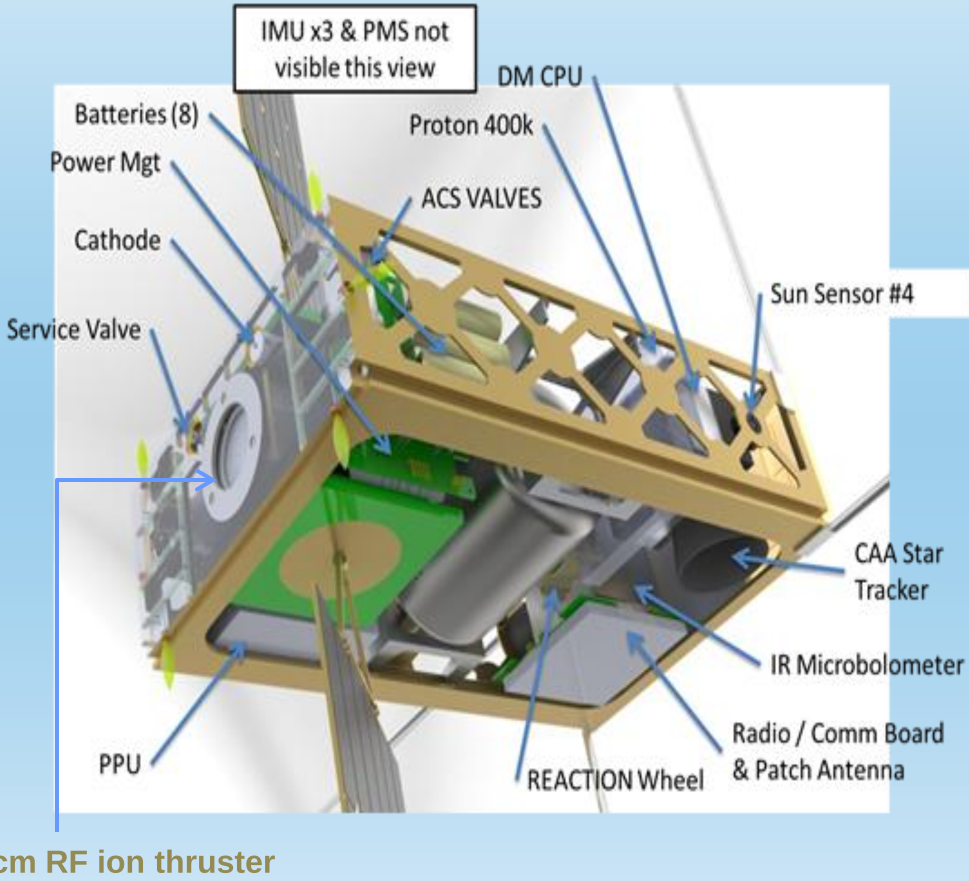
Without the use of a larger platform as a carrier, CubeSats can go from Earth to Lunar orbit using on-board propulsion and still perform valuable science when they get there



Property	Value
Mission	Demonstration of Lunar CubeSat
Initial Orbit	GPS (~20,000km)
Final Orbit	Lunar
S/C	6U CubeSat
S/C Mass	8kg
Peak Power	~96W
Propulsion	3cm RF Ion Thruster
deltaV	3.03km/s
Total transit time	~170days
Payload	Science Camera and Radiation Tolerant Computing

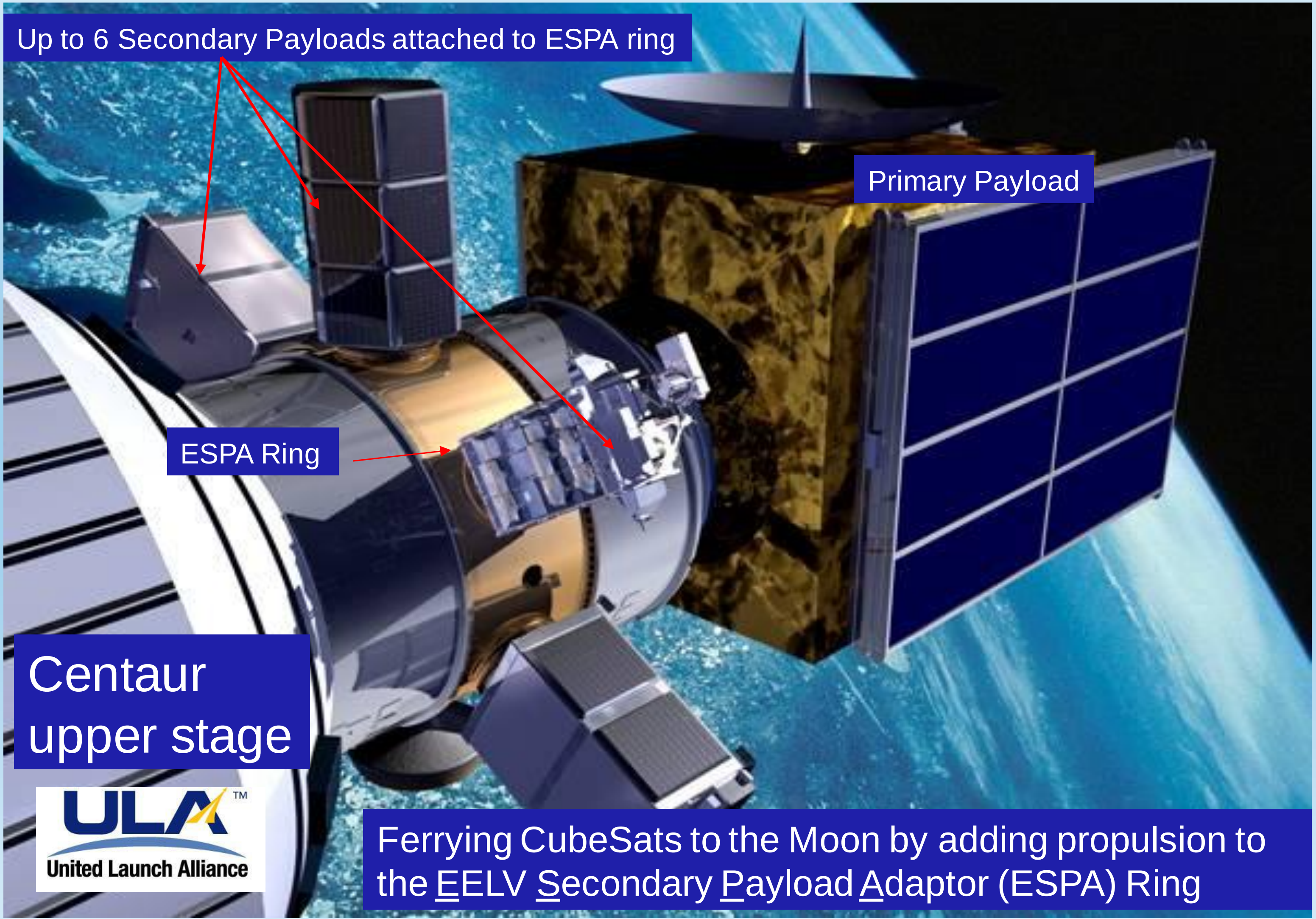
Lunar Cubesat Design Details





The 6U LunarCube concept is partially contributed by Morehead State University.

CubeSat "Lunar Ferry" via Propulsive ESPA



Up to 6 Secondary Payloads attached to ESPA ring

Primary Payload

ESPA Ring

Centaur upper stage

United Launch Alliance

Ferrying CubeSats to the Moon by adding propulsion to the EELV Secondary Payload Adaptor (ESPA) Ring

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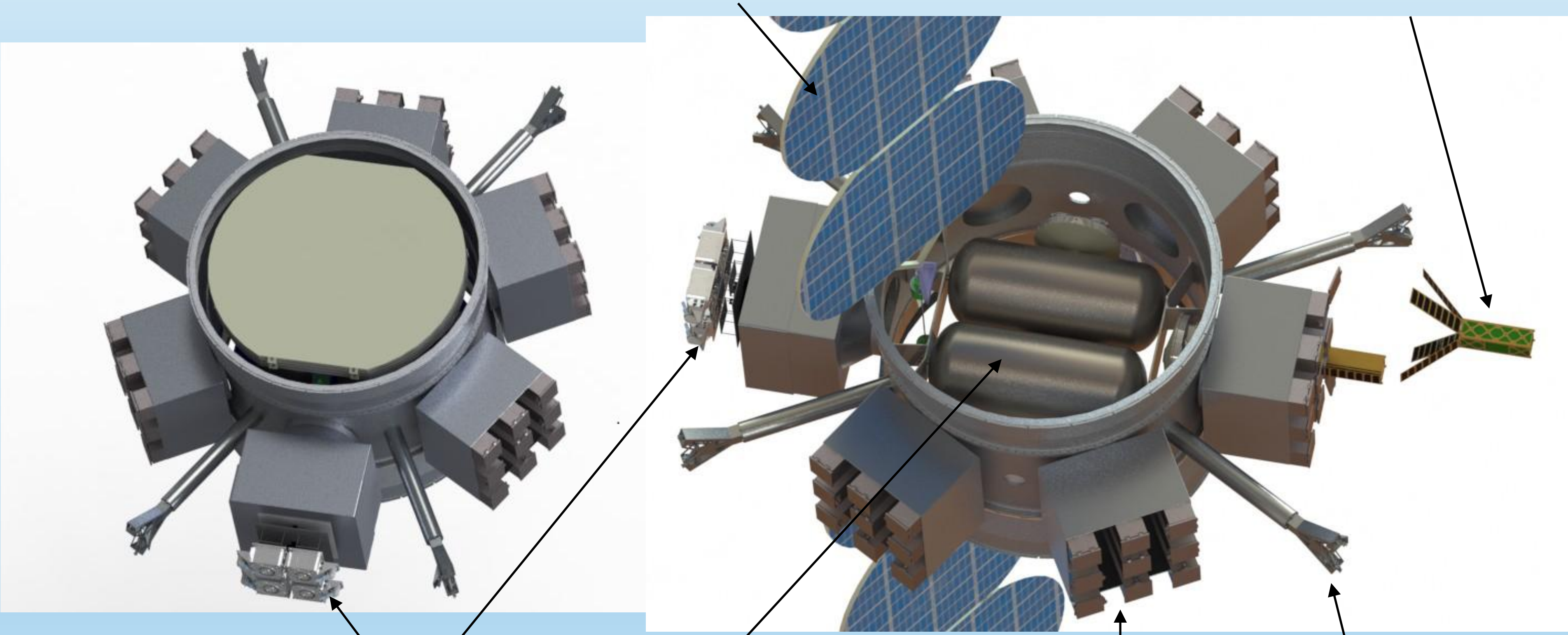
Propulsive ESPA Details



4kW Solar Array at BOL

Deployed 3U CubeSat

Propulsion Modules
Cluster of 4 BHT-1500, gimbal, PPUs, and flow control

Xenon tanks

5 Secondary Payloads
Each with 9 standard P-Pods (total 45x 3U CubeSats)

Cold-gas ACS Thrusters

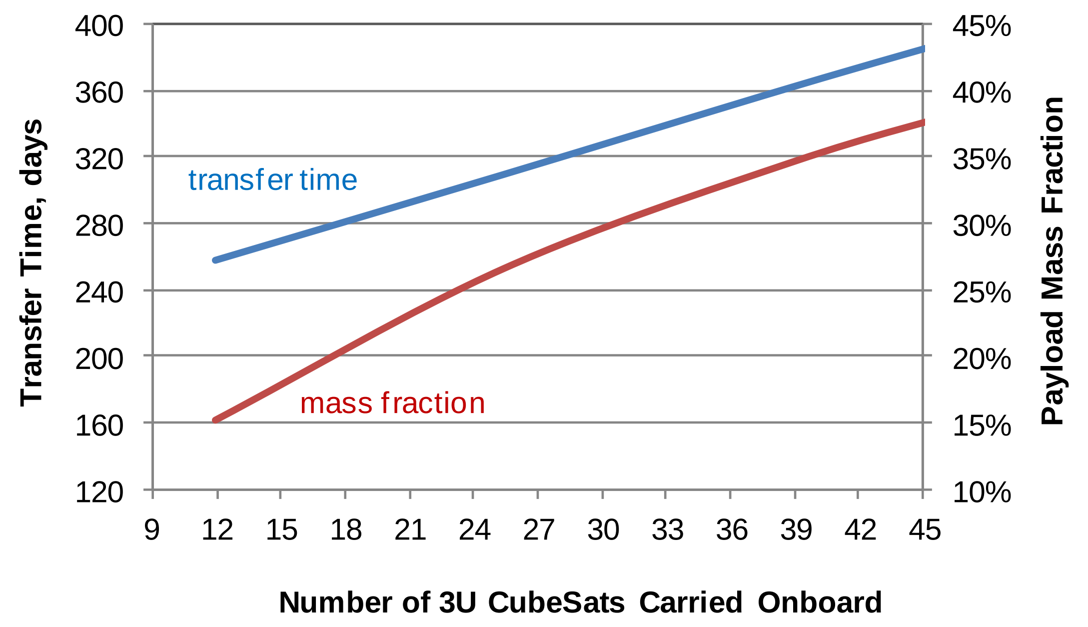
Propulsive ESPA Transfer Time

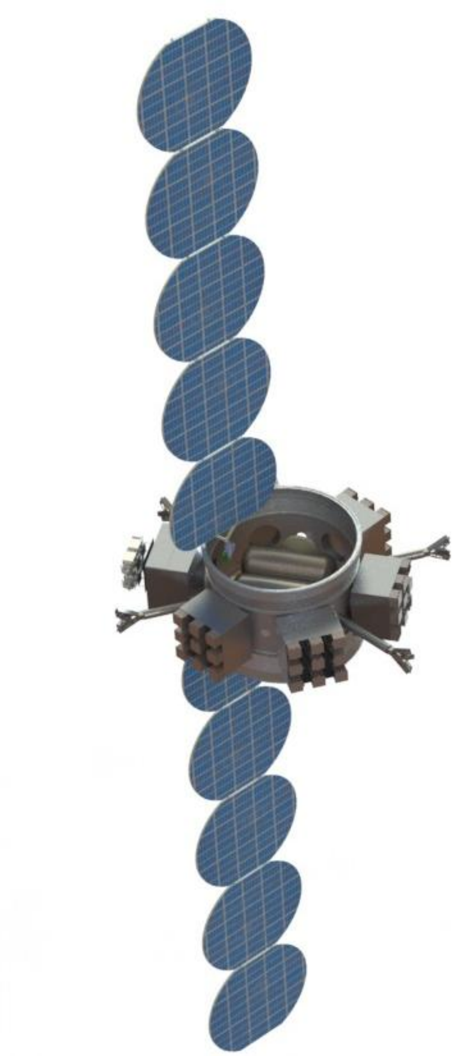
Mission:

- GTO (27^{o}, 0.74 eccentricity) to lunar capture orbit
- ~3.7 km/s delta-V required

Propulsion:

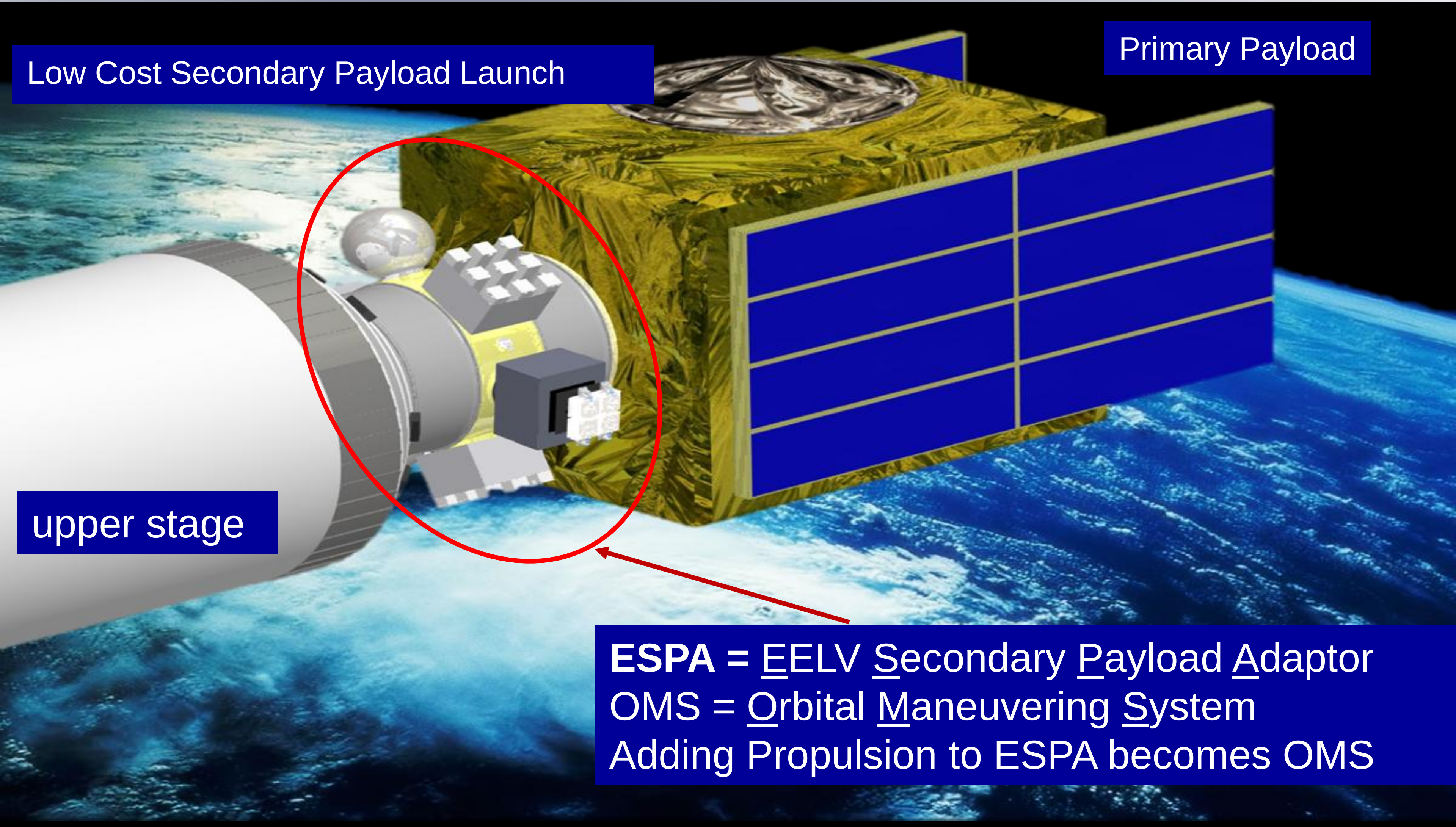
- 4 Busek BHT-1500 Hall Effect Thrusters
- 237mN total thrust at 1640sec Isp





Transfer time as function of payload mass

CubeSats to Mars carried by ESPA-OMS Carrier



Low Cost Secondary Payload Launch

Primary Payload

upper stage

ESPA = EELV Secondary Payload Adaptor
OMS = Orbital Maneuvering System
Adding Propulsion to ESPA becomes OMS

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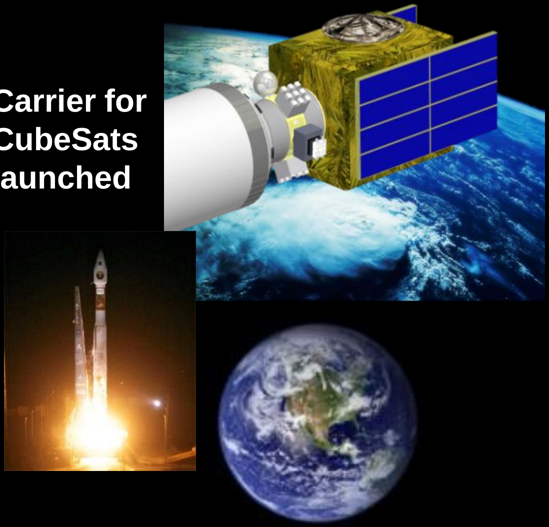
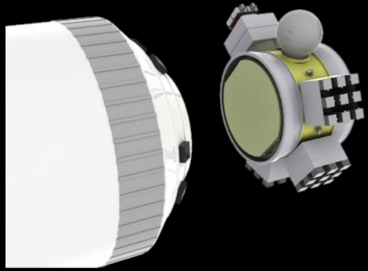
Mission Concept



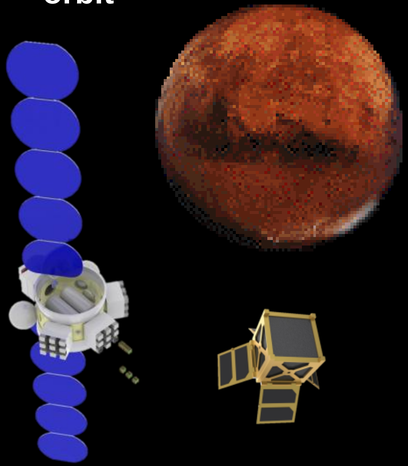
Carrier for CubeSats launched

as secondary payload with GEO primary payload



After primary payload release the CubeSat carrier released from the second stage

Solar panels are deployed and carrier begins the journey to Mars



CubeSats are deployed after entering Mars orbit

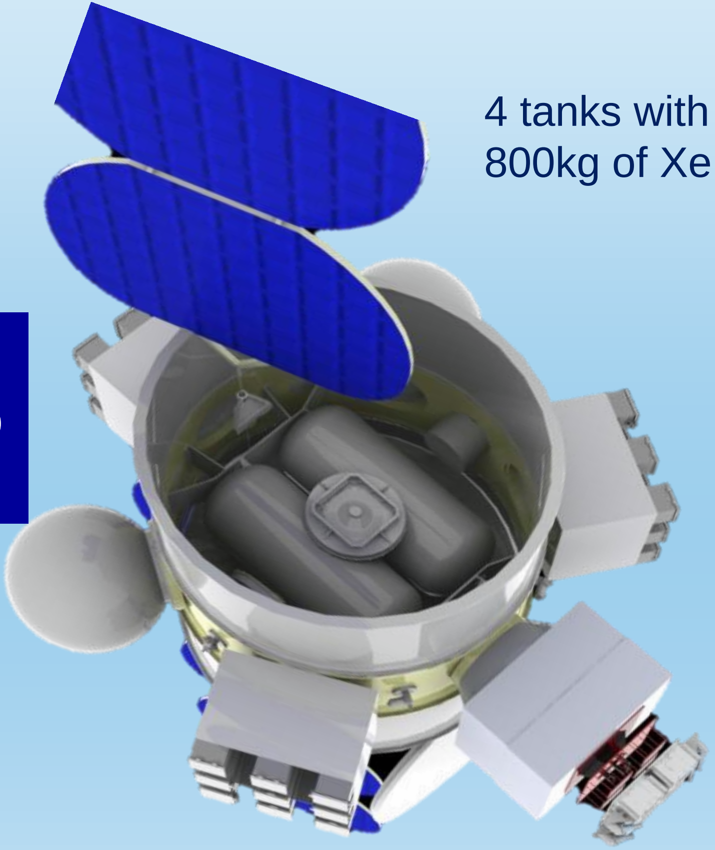
The CubeSat carrier or ESPA OMS using high efficiency propulsion can carry up to 27 – 3U CubeSats to Mars.

ESPA OMS Carrier delivers ~27 of 3U Cubesats to Mars and then serves as a communications relay back to earth

4kW array at BOL

HGA Antenna

27 P-Pods positions
Each can house up to 5U CubeSat

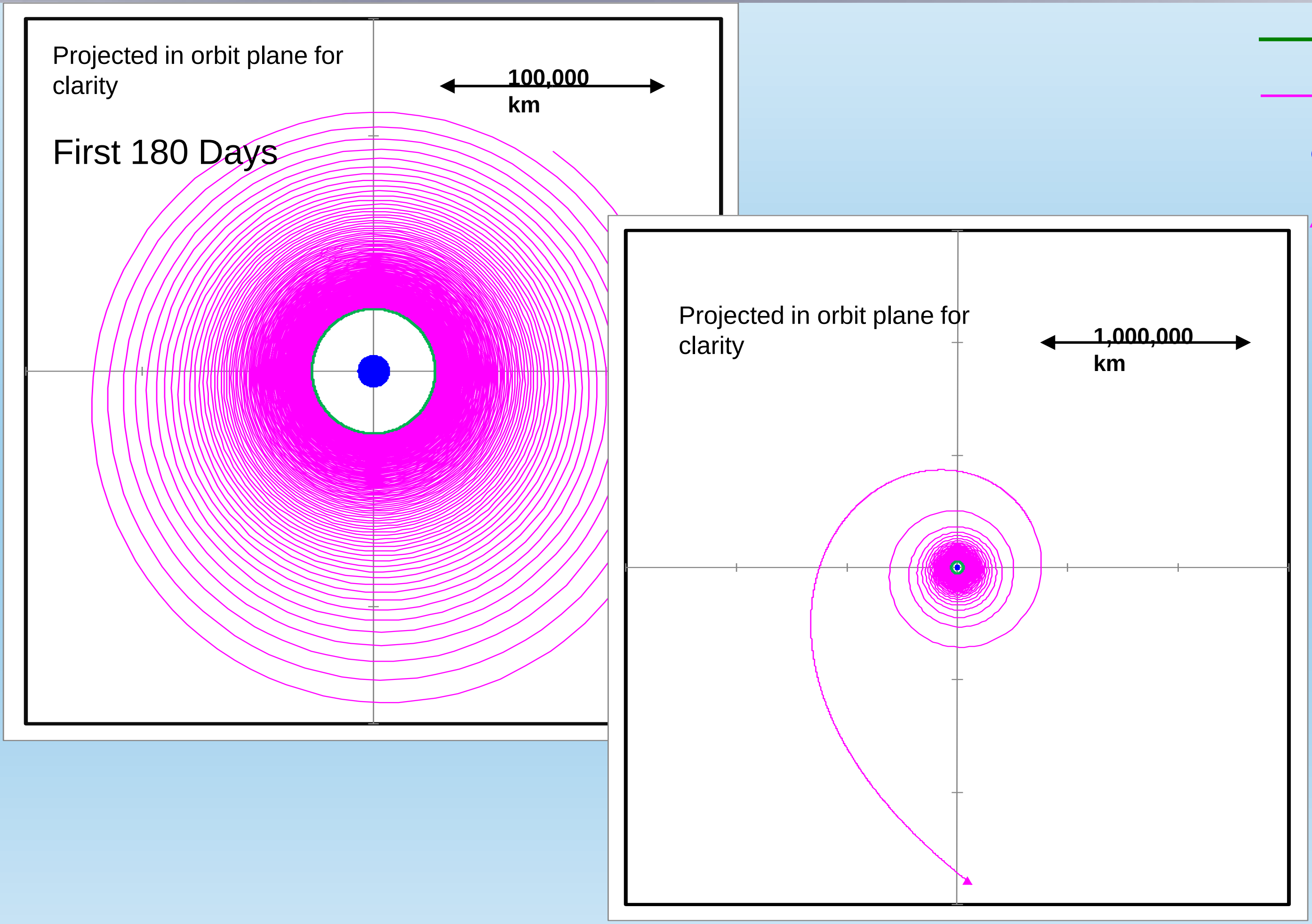


4 tanks with 800kg of Xe

Gimbaled Propulsion Module - Cluster of 4 Hall Effect Thrusters

Stimulating broad international participation, nations fly their own Cubesats to Mars

Earth Departure



GPS Orbit (plane B)

Powered Flight

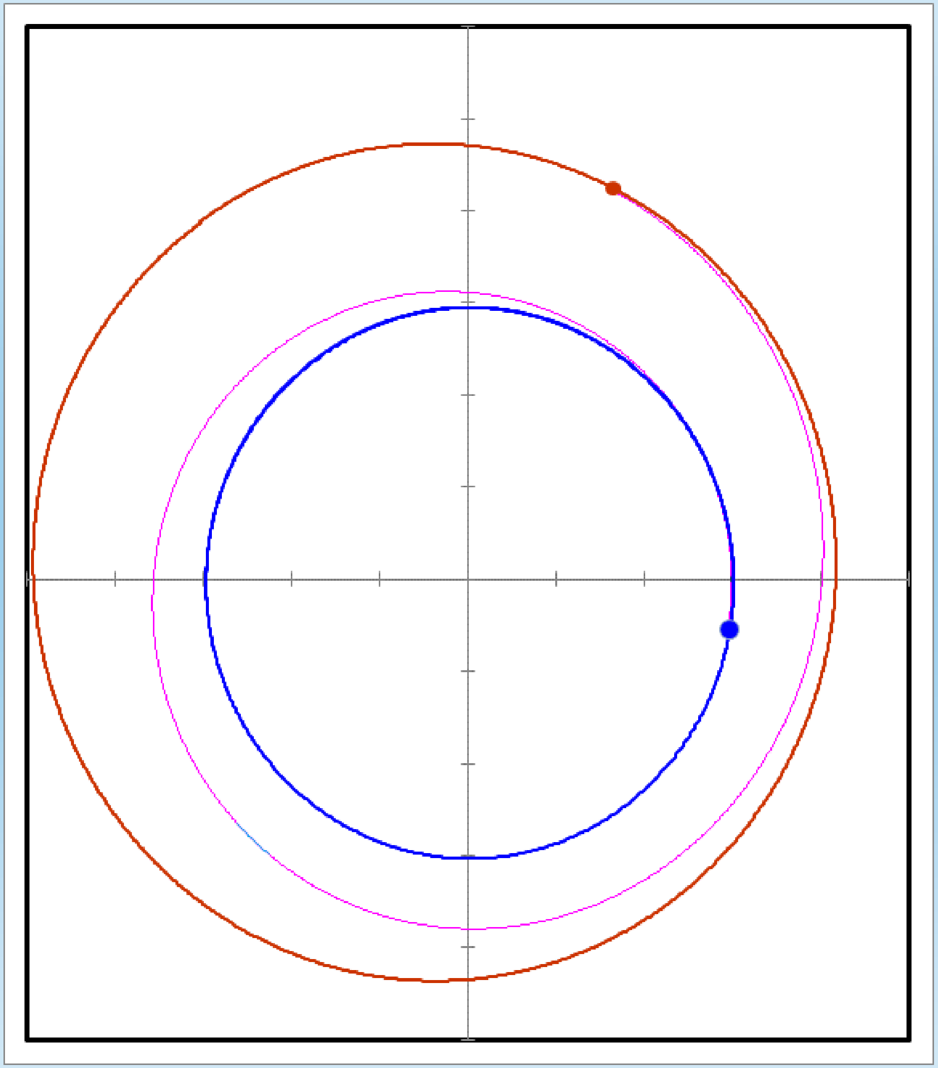
● **Earth**

▲ **Escape Point (C_3 = 0)**

- 4.35 km/s ΔV over 294 days
- Continuous low-thrust spiral orbit raise, concluding at C_3 = 0

294.1 days to Earth escape, 4.35 km/s ΔV, GPS parking orbit to C_3=0 escape

Interplanetary Trajectory



— Earth Orbit

— Mars Orbit

— Powered Flight

— Coast Flight

● Earth @ Escape

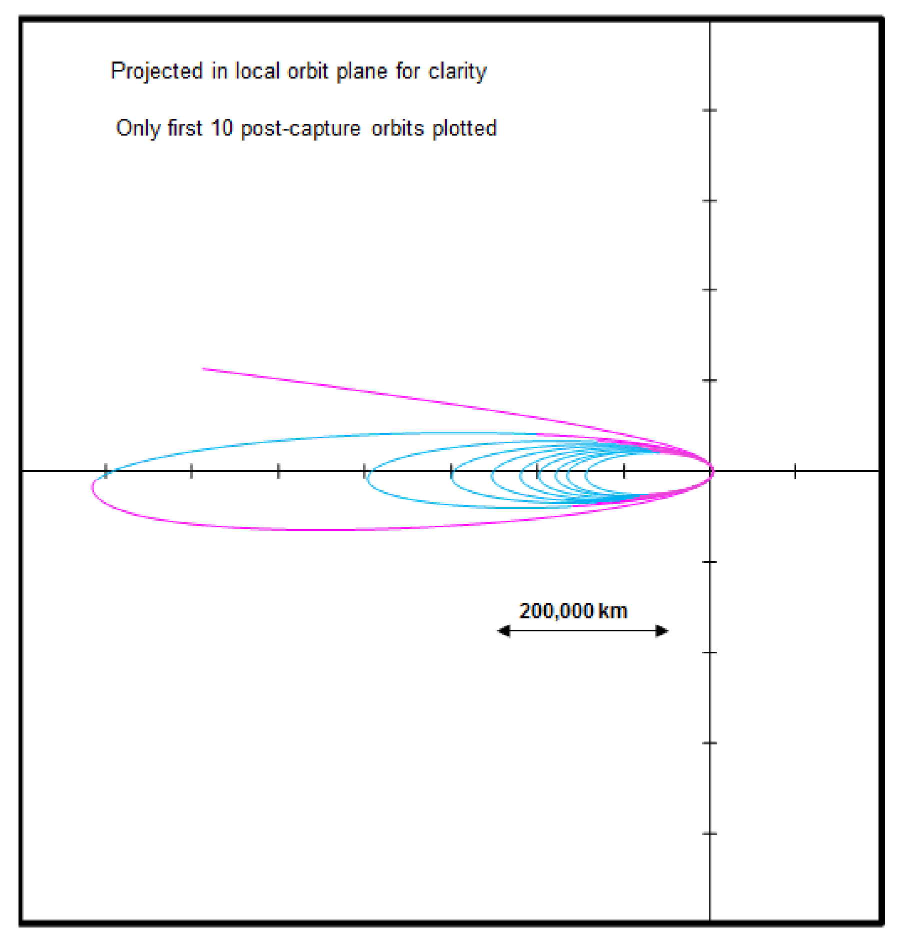
● Mars @ Capture

- **604.1 days interplanetary cruise**
- **6.46 km/s ΔV**
- **Earth escape to Mars capture**

Powered flight uses paired thrusters @ 90% overall duty cycle:

  - 10.8 hours thrusters 1/3 on
  - 1.2 hours coast
  - 10.8 hours thrusters 2/4 on
  - 1.2 hours coast

Mars Capture



- **10 m/s cold-gas capture "burn"**
  (30.5 kg xenon expended)
- **341.3 days orbit lowering**
- **0.83 km/s low-thrust ΔV**
- **Apogee reduced to 50,000 km**

Phase 6: Mars Aerobraking

Apoapsis reduced to 650 km over 500 days

Phase 7: Circularization

0.15 km/s ΔV over 16 days
400 km circular orbit

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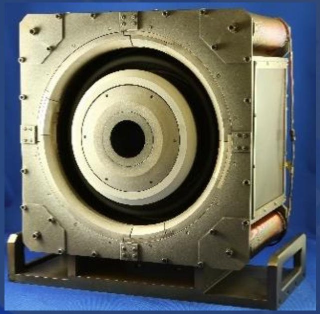
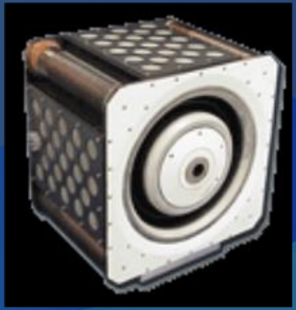
Busek Hall Thruster Technology

Busek is the Leader in Hall Effect thruster design and development technology with solutions from 100W to 20kW.

- All US Hall thrusters flown to date (BHT-200 to BPT-4000) are based on Busek technology
- Flight hardware provided for TacSat-2, FalconSat-3, LISA Pathfinder, FalconSat-5 and FalconSat-6 (current)
- Over 25 years of cutting-edge research, development and manufacture for government, academic and private customers



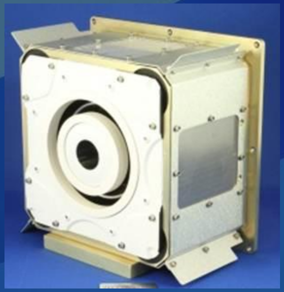
BHT-20K
Under development for NASA's Asteroid Redirect Mission



BHT-8000
Large GEO ComSats

BPT-4000 (Licensed technology)
GEO Comsats,

Hall Effect Thrusters – The ideal propulsion for orbit raising, station keeping, and de-orbit maneuvers.



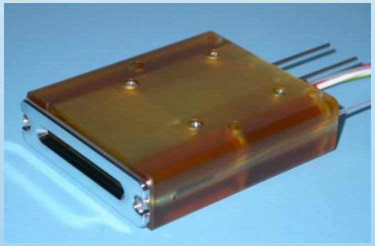
BHT-1500
Medium GEO ComSats

BHT-200
First US Hall Thruster to fly in space. TacSat-2.

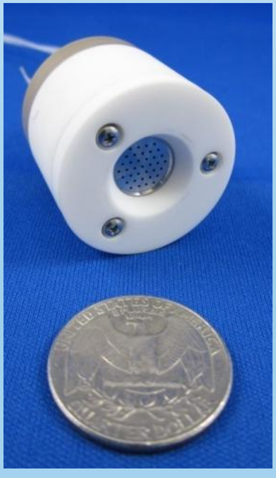
Busek's CubeSat Electric Propulsion Summary

Available 1U Package, <10W system power, ideal for missions at lunar orbit

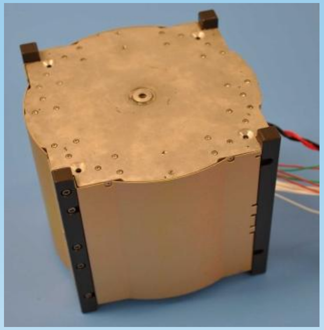
Electrospray Thruster
- ✓ High Efficiency
- ✓ Multi-emitter
- ✓ Low Risk/Technically Mature



Passive Electrospray Thruster
- ✓ No moving parts, valves
- ✓ No pressure vessel
- ✓ Low Power, high Isp



1 cm Micro RF Ion Thruster
- ✓ No internal cathode
- ✓ >2000s Isp
- ✓ FE Neutralizer is space qualified



Micro Resistojet
- ✓ Simple, ideal for prox-ops
- ✓ Higher thrust
- ✓ Integrated Primary / ACS

Micro Pulsed Plasma Thruster
- ✓ No moving parts, valves
- ✓ No pressure vessel
- ✓ Low Power
- ✓ Integrated Primary / ACS
- ✓ Prior version flown on FalconSat3

50-100W system power, Capable of earth-moon transfer for a 6U s/c

3 cm Micro RF Ion Thruster
- ✓ No internal cathode
- ✓ Tested up to 3,000s Isp
- ✓ Higher thrust
- ✓ Thermionic Neutralizer is space qualified

Summary

- ✓ **Small spacecraft deltaV limited relative to larger spacecraft, but Earth-to-Lunar missions feasible with ≈ 6U scale Cubesats with electric propulsion.**
- ✓ **Propulsive ESPA provides lower cost Lunar delivery of large quantities of Cubesats**
- ✓ **Propulsive ESPA provides interesting solution to Mars delivery of Cubesats by adding communications relay capability.**
- ✓ **Busek electric propulsion technologies are demonstrated capable of supporting such missions**

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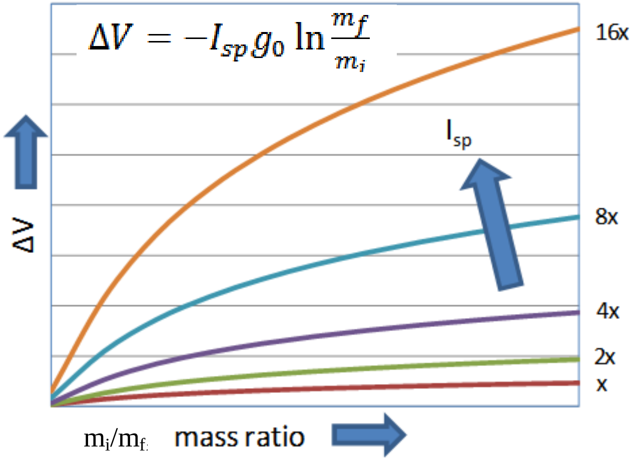
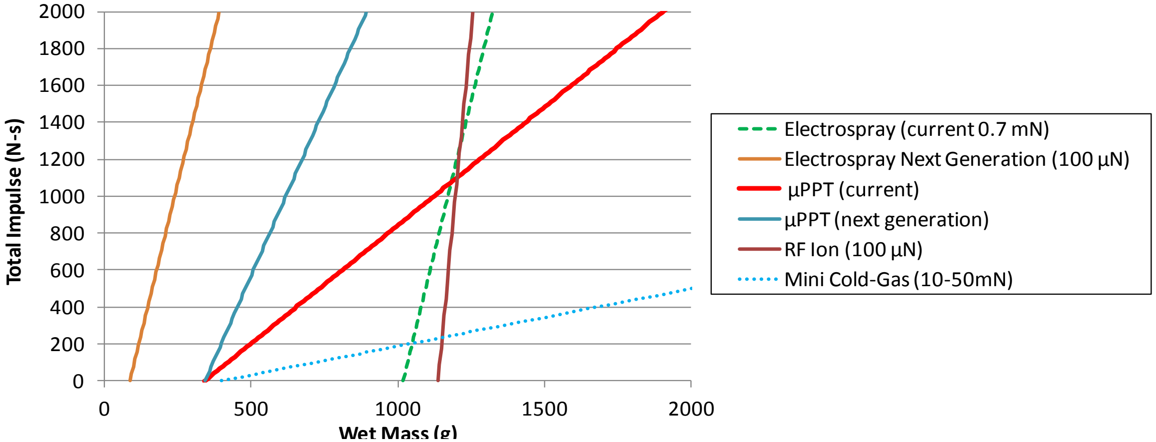
Backup Slides

Interplanetary Small Satellites Propulsion

The physical delta-V limits of small spacecraft are driven primarily by the increasingly unfavorable propellant mass fractions of small spacecraft, and secondarily by the more traditional metric of specific impulse (I_{sp}):



Comparison of Propulsion Systems by Total Impulse vs. Wet Mass



- While a large spacecraft may have a mass ratio of 5 or greater, total wet mass of a small spacecraft propulsion *system* will typically be less than 1/3 of total spacecraft mass.
- *Benefits of increased I_{sp} are often lost due to decreased mass ratio 'cost' of achieving said I_{sp}…*

(system requirements, valves, pressurized tanks, magnetics, thermal management, etc.)

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