Small Satellite Mars Missions Using Electric Propulsion

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Presentation Overview

• Electric propulsion (EP) background
  – History
  – Principles
  – Current position

• Application to Small Interplanetary Missions
  – Advantages
  – Limitations

• Example of Small Mars Missions with science payloads by:
  – M-GAS, Univeristy of Oxford, Prof Fred Taylor
  – M-SIS, University of Leicester, Mark Sims
  – M-PADS, Open Univeristy, Andrew Ball, John Zarnecki
Background - Electric Propulsion

- Electric Propulsion developed over many years, from 1960s on..
- Now over 100 engines launched and operated, US, FSU, UK, Japan…
- Mostly on low altitude and geostationary platforms
- A growing list of interplanetary science missions
  - Deep Space One, SMART-1, Muses-C/Hyabusa, GOCE
  - Bepi-Colombo, DAWN, Prometheus

- Current developments in QinetiQ for a variety of missions
  - GOCE: ESA science mission, T5 drag compensation for low altitude ops
  - Bepi Columbo: ESA science mission to Mercury by solar EP
  - AlphaBus: GEO communications platform using EP for station keeping
Background - Electric Propulsion Principles

- Xenon propellant forms a plasma with Xe ions accelerated out by kV fields
- Ion velocity typically 30-50km/s, depending on accelerating field
- Beam is neutralised
- Thrust can be throttled by controlling flowrate, plasma density, anode I

Neutralised beam of $\text{Xenon}^+$ and $e^-$

Travelling at 30 to 50km/s (SI of 3000 to 5000s)

Chemical plume typically 3km/s (SI of 300s)
Background - Current Engines (QinetiQ)

T5 (GOCE)
- 10cm beam diameter
- 1-20mN thrust
- 1.6kg
- GOCE launch 2006
- T5 build complete 2005
- SI 4500s

T6 (Bepi-Colombo, AlphaBus)
- 22cm beam diameter
- 30-200mN thrust
- 7.5kg
- Undergoing 5000 hour life test
- SI 4600s
Application of EP to Small Interplanetary Spacecraft

• **Advantages**
  – fuel mass for baseline mission to large captured orbit
  – need less energy from launcher, larger launch mass
  – low cost of additional orbit changes at destination
  – e.g. small circular orbit without aerobraking
  – timeline (in some cases)

• **Disadvantages**
  – power requirement
  – low thrust, so takes time to perform manoeuvres
  – timeline (in some cases)
Application of EP to Small Interplanetary Spacecraft

Reduced Fuel mass fraction

- e.g. 2km/s
  - chemical propulsion requires 50% of launch mass
  - EP around 5%
Application of EP to Small Interplanetary Spacecraft

Increased launcher capability

- Usually most efficient for launcher to provide velocity for transfer orbit
- For EP mission, more efficient still to use on-board propulsion, requiring less energy from launcher, allowing larger launch mass

- Rockot/Breeze for Mars transfer
  - chemical propulsion allows ~270kg
  - EP allows ~350kg

* Courtesy of Y Viertal EUROCOKOT Launch Services, GmbH
Mars Micro Mission Study

- Define “Micro” Mars Missions making use of mass saving capability of current electric propulsion technology

- QinetiQ led the study and was responsible for the spacecraft engineering*, launcher selection and low thrust trajectory designs

- Prof. Fred Taylor, University of Oxford, led the science and instruments aspects of M-GAS Global Atmosphere Survey

- Dr. Mark Sims, University of Leicester, led the science and instruments aspects of M-SIS Subsurface Ice Survey

- Prof. John Zarnecki and Dr. Andrew Ball, Open University, led the science and instruments aspects of M-PADS Phobos and Deimos Survey

* One of the platforms is based on a Saab Ericsson Space concept
Mission design

- **Launch**: Direct Earth escape with small 0.5-1km/s excess velocity, or large Earth bound launch, lunar flyby etc.
- **Transfer**: 2 long burn arcs of a few months separated by a coast arc
- **Mars orbit insertion**: retrograde burn allows Weak Stability Boundary capture by Mars gravity followed by orbit size reduction
- **Final Orbit**: low thrust orbit insertion and low cost of additional dV allows low mass cost of different final orbits.
- e.g. small circular orbit readily available, different planes from same launcher, visiting both moons with single craft
Mars Global Atmosphere Survey (M-GAS)

MGAS Spacecraft design

ASAP-compatible s/c shown

Dnepr fairing

ADU booster

Stowed solar array
HG A
Payload bay
PPU
Star camera
T5

Stowed HGA feed
LGA
RF subsystem
Central thrust tube
Xe tank
Launcher interface adapter
## Mars Global Atmosphere Survey (M-GAS)

### Instrument requirements & examples

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Weight (kg)</th>
</tr>
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<tbody>
<tr>
<td>Ultra Stable Oscillator</td>
<td>2</td>
</tr>
<tr>
<td>Digital Signal Processing package</td>
<td>3</td>
</tr>
<tr>
<td>IR dust sensor</td>
<td>3</td>
</tr>
<tr>
<td>Camera</td>
<td>2</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>10</strong></td>
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</tbody>
</table>

- **C** = core
- **H** = high priority

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Cassini USO (APL)

AMIE (CSEM)
Mars Global Atmosphere Survey (M-GAS)

MGAS Mission

• Payload accommodation
  - modest resource requirements
  - power, data, thermal microsat OK

• Multi-spacecraft constellation at Mars
  - Very costly, unless lower cost microsatellites are used
  - All the microsatellites be launched together
  - 4 spacecraft, 3 orthogonal plane constellation
  - based on previous bus design (SIMONE)
Mars Global Atmosphere Survey (M-GAS)

**MGAS Mission** - Constellation in 3 orthogonal planes at Mars

Mars Inertial Axes
9 Aug 2007 14:00:00 Time Ste
Mars Global Atmosphere Survey (M-GAS)

Spacecraft - design summary

- **Launch mass:** ~120kg (maximum available: ~200kg)
- **Platform dimensions:** 0.6x0.6mx0.7(h) cuboid shape (could be taller)
- **Propulsion:** 25mN thrust at Earth, 15mN at Mars (single T5 ion engine)
- **Power:** 1170W BoL at Earth, 460-500W EoL at Mars (two 0.7x3.3m semi-rigid solar array wings with 28% efficient GaAs cells)
- **Comms:** 1.4kbps X-band downlink to EDSN at 2AU range from 0.5m HGA
- **Attitude control:** 3-axis stabilised by wheels & Hollow Cathode Thrusters,
- **Attitude knowledge:** sensing by star trackers, sun sensors & gyros
- **Propellant:** 25kg Xe (all s/c) to low periapsis Mars orbits (different inclinations)
- **Payload:** 11kg
Mars Phobos And Deimos Survey (M-PADS)

M-PADS Spacecraft design

Gas system
Inter-s/c separation system
Launch adapter

HGA
Xe tank (2 of 4)
Stowed solar array wing
SADM

radiator
Thermal baffle
T6 thruster
HGA
UK M-PADS Current Hardware Maturity

- DEBIE (OU / Finavitec)
- FONEMA (MSSL)
- Ptolemy (OU / RAL)
- CAPS-ELS (MSSL)
- FGM (ICSTM)
- D-CIXS (RAL)
Mars Phobos And Deimos Survey (M-PADS)

Mission design

• **Direct Earth escape launch:** Dnepr with 0.8km/s excess velocity, s/c separation

• **Transfer:** 6-month burn + 4.5 month coast + 4.5-month burn to approach Mars with 0.5km/s excess velocity

• **Mars orbit insertion:** 5.5-week retrograde burn into 100,000km, 0.25 eccentricity Mars orbit

• **Deimos orbit acquisition:** sequence of long/short burns to spiral down to co-orbit Deimos at 20,000km circular (4 months), Orbiter measurements (1 month)

• **Phobos orbit acquisition:** Orbiter spiral down to co-orbit Phobos at 6,000km circular (2 months), Orbiter measurements (1 month)

• **Lander deployment:** targeted site on Deimos/Phobos from Orbiter data

28 months total mission duration; 6.75km/s total ∆V
Mars Phobos And Deimos Survey (M-PADS)

Spacecraft - Performance summary

- **Launch mass**: ~330kg (low excess velocity Earth Escape launch)
- **Platform dimensions**: 0.6x1.72m irregular octagon shape, composite design
- **Propulsion**: 75mN thrust at Earth, 36-39mN at Mars (single T6 ion engine)
- **Power**: 2200W BoL at Earth, 1100W EoL at Mars (two 1.1x4.0m wings)
- **Comms**: 16kbps Ka-band downlink to EDSN at 2AU range (0.8m HGA top panel)
- **Attitude control**: 3-axis stabilised by wheels & Hollow Cathode Thrusters
- **Attitude knowledge**: sensing by star trackers, sun sensors & gyros
- **Propellant**: 50kg Xe stored in 4 small spherical tanks
- **Payload**: 60kg
### MMM Mission Summary

<table>
<thead>
<tr>
<th></th>
<th>M-GAS</th>
<th>M-PADS</th>
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<tr>
<td><strong>Mass (kg)</strong></td>
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<tr>
<td>Launch Mass (kg)</td>
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<td>Fuel Mass (kg)</td>
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<td>Payload Mass (kg)</td>
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<td><strong>Transfer Time (months)</strong></td>
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<td>Operational Orbit</td>
<td>500km circular</td>
<td>Deimos co-orbit</td>
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<tr>
<td>Launch to Operational Mars Orbit</td>
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<td>20</td>
</tr>
</tbody>
</table>

- Launch to large captured orbit in ~15 months for quoted mass/thrust ratios
- Small EP enables small interplanetary missions with useful payload mass
- Allows orbit flexibility at Mars. e.g. small circular orbit or both moons
- Potential for constellation from single launcher e.g. 4 or 6 M-GAS spacecraft on DNEPR
- Timelines longer but typically <2 years to low Mars orbit
Small Satellite Mars Missions with EP Study Conclusions

• Two feasible mission concepts for low-cost Small Mars Missions were identified and studied in some detail

• Both missions highly challenging with chemical propulsion
  – MGAS, require constellation in different planes from single launch
  – MPADS, require higher dV for moon rendezvous than for Mars orbit

• Each offers useful scientific return and addresses key outstanding questions concerning the Martian system

• Both concepts demonstrate the capability of small vehicles, with ion propulsion and miniaturised avionics, to perform high value deep space missions
Application of EP to Small Interplanetary Spacecraft

Conclusions

- Some missions will benefit more than others
- Enables high dV missions
  
  e.g. asteroids, Mercury, low planetary orbits, sample return
- Small missions to Mars, Venus, asteroids, Lagrange points…. have increased potential
- Allows more flexibility of orbit at destination
- High power a requirement, but will also allow higher data rates
- Timelines longer, but will be acceptable in many cases in return for savings elsewhere. e.g. mass