Identification of New Orbits to Enable Future Mission for the Exploration of the Martian Moon Phobos

Mattia Zamaro

space@strath.ac.uk

www.strath.ac.uk/space
Overview of the project
Overview of the project

<table>
<thead>
<tr>
<th>Inspiration</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESA and NASA current interest in developing future missions to the moons of Mars, as a paramount stepping stone in the long-term goal to bring humans to Mars</td>
</tr>
</tbody>
</table>
Overview of the project

Inspiration

Current interest in developing future missions to the moons of Mars, as a paramount stepping stone in the long-term goal to bring humans to Mars.
## Overview of the project

### Inspiration

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Who</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Where</strong></td>
<td></td>
</tr>
</tbody>
</table>

- ESA and NASA current interest in developing future missions to the moons of Mars, as a paramount stepping stone in the long-term goal to bring humans to Mars.
Overview of the project

<table>
<thead>
<tr>
<th>Inspiration</th>
</tr>
</thead>
<tbody>
<tr>
<td>current interest in developing future missions to the moons of Mars, as a paramount stepping stone in the long-term goal to bring humans to Mars</td>
</tr>
</tbody>
</table>

Who

Where

When
Overview of the project

Inspiration

Current interest in developing future missions to the moons of Mars, as a paramount stepping stone in the long-term goal to bring humans to Mars

Specific objective

Identify new space mission opportunities in the Mars-Phobos system
Overview of the project

Inspiration

Current interest in developing future missions to the moons of Mars, as a paramount stepping stone in the long-term goal to bring humans to Mars

Specific objective

Identify new space mission opportunities in the Mars-Phobos system

Targets: Dynamical Objects

Points
Orbits
Trajectories
Overview of the project

**Inspiration**

 ESA and NASA's current interest in developing future missions to the moons of Mars, as a paramount stepping stone in the long-term goal to bring humans to Mars.

**Specific objective**

Identify new space mission opportunities in the Mars-Phobos system.

**Targets: Dynamical Objects**

- Points
- Orbits
- Trajectories

**Performances: Low Cost**

- Low Energy: exploitation of natural dynamics with advanced models and nonlinear techniques (DST)
- Low Thrust: SEP implementations (SK cost, optimal control for added requirements)
Overview of the project

Inspiration

Current interest in developing future missions to the moons of Mars, as a paramount stepping stone in the long-term goal to bring humans to Mars

Specific objective

Identify new space mission opportunities in the Mars-Phobos system

Targets: Dynamical Objects

Points
Orbits
Trajectories

Performances: Low Cost

Low Energy: exploitation of natural dynamics with advanced models and nonlinear techniques (DST)

Low Thrust: SEP implementations (SK cost, optimal control for added requirements)

Aims: Missions

Unique positions for probing unmanned observation missions and manned flights for undertaking real-time robotic investigations of Phobos and Mars, while reducing human exposure to space radiation
Overview of the project

Inspiration

- Established current interest in developing future missions to the moons of Mars, as a paramount stepping stone in the long-term goal to bring humans to Mars

Specific objective

- Identify new space mission opportunities in the Mars-Phobos system

Targets: Dynamical Objects

- Points
- Orbits
- Trajectories

Performances: Low Cost

- Low Energy: exploitation of natural dynamics with advanced models and nonlinear techniques (DST)
- Low Thrust: SEP implementations (SK cost, optimal control for added requirements)

Aims: Missions

- Unique positions for probing unmanned observation missions and manned flights for undertaking real-time robotic investigations of Phobos and Mars, while reducing human exposure to space radiation

Who
- University of Strathclyde
- Advanced Space Concepts Laboratory

Where

When

My Research

What

How

Why

Outcome

15/06/2015
Mattia Zamaro
Overview of the project

**Inspiration**
- Current interest in developing future missions to the moons of Mars, as a paramount stepping stone in the long-term goal to bring humans to Mars

**Specific objective**
- Identify new space mission opportunities in the Mars-Phobos system

**Targets: Dynamical Objects**
- Points
- Orbits
- Trajectories

**Performances: Low Cost**
- Low Energy: exploitation of natural dynamics with advanced models and nonlinear techniques (DST)
- Low Thrust: SEP implementations (SK cost, optimal control for added requirements)

**Aims: Missions**
- Unique positions for probing unmanned observation missions and manned flights for undertaking real-time robotic investigations of Phobos and Mars, while reducing human exposure to space radiation

**Who**

**Where**

**When**

**My Research**

**What**

**How**

**Why**

**Outcome**

15/06/2015

Mattia Zamaro
Overview of the project

Inspiration

ESA and NASA, current interest in developing future missions to the moons of Mars, as a paramount stepping stone in the long-term goal to bring humans to Mars

Specific objective

Identify new space mission opportunities in the Mars-Phobos system

Targets: Dynamical Objects

- Points (EP, AEP)
- Orbits
- Trajectories

Performances: Low Cost

- Low Energy: exploitation of natural dynamics with advanced models and nonlinear techniques (DST)
- Low Thrust: SEP implementations (SK cost, optimal control for added requirements)

Aims: Missions

Unique positions for probing unmanned observation missions and manned flights for undertaking real-time robotic investigations of Phobos and Mars, while reducing human exposure to space radiation

University of Strathclyde
Advanced Concepts Laboratory

My Research

What

How

Why

Outcome

15/06/2015

Mattia Zamaro
Overview of the project

Who

Inspiration

And current interest in developing future missions to the moons of Mars, as a paramount stepping stone in the long-term goal to bring humans to Mars

Where

Specific objective

Identify new space mission opportunities in the Mars-Phobos system

When

My Research

What

Targets: Dynamical Objects

Points (EP, AEP)

Orbits (VDCO, LPO, QSO, FF)

Trajectories

How

Performances: Low Cost

Low Energy: exploitation of natural dynamics with advanced models and nonlinear techniques (DST)

Low Thrust: SEP implementations (SK cost, optimal control for added requirements)

Why

Aims: Missions

Unique positions for probing unmanned observation missions and manned flights for undertaking real-time robotic investigations of Phobos and Mars, while reducing human exposure to space radiation

Outcome

15/06/2015

Mattia Zamaro
Overview of the project

Inspiration

Current interest in developing future missions to the moons of Mars, as a paramount stepping stone in the long-term goal to bring humans to Mars.

Specific objective

Identify new space mission opportunities in the Mars-Phobos system.

Targets: Dynamical Objects

Points (EP, AEP)
Orbits (VDCO, LPO, QSO, FF)
Trajectories (IM, HOC/HEC, I, T)

Performances: Low Cost

Low Energy: exploitation of natural dynamics with advanced models and nonlinear techniques (DST)
Low Thrust: SEP implementations (SK cost, optimal control for added requirements)

Aims: Missions

Unique positions for probing unmanned observation missions and manned flights for undertaking real-time robotic investigations of Phobos and Mars, while reducing human exposure to space radiation.
Overview of the project

Inspiration

and current interest in developing future missions to the moons of Mars, as a paramount stepping stone in the long-term goal to bring humans to Mars

Specific objective

Identify new space mission opportunities in the Mars-Phobos system

Targets: Dynamical Objects

Points (EP, AEP)
Orbits (VDCO, LPO, QSO, FF)
Trajectories (IM, HOC/HEC, I, T)

Performances: Low Cost

Low Energy: exploitation of natural dynamics with advanced models and nonlinear techniques (DST)
Low Thrust: SEP implementations (SK cost, optimal control for added requirements)

Aims: Missions

Unique positions for probing unmanned observation missions and manned flights for undertaking real-time robotic investigations of Phobos and Mars, while reducing human exposure to space radiation
Overview of the project

Inspiration

current interest in developing future missions to the moons of Mars, as a paramount stepping stone in the long-term goal to bring humans to Mars

Specific objective

Identify new space mission opportunities in the Mars-Phobos system

What

Targets: Dynamical Objects
- Points (EP, AEP)
- Orbits (VDCO, LPO, QSO, FF)
- Trajectories (IM, HOC/HEC, I, T)

How

Performances: Low Cost
- Low Energy: exploitation of natural dynamics with advanced models and nonlinear techniques (DST)
- Low Thrust: SEP implementations (SK cost, optimal control for added requirements)

Why

Aims: Missions
- Unique positions for probing unmanned observation missions and manned flights for undertaking real-time robotic investigations of Phobos and Mars, while reducing human exposure to space radiation

Outcome

15/06/2015

Mattia Zamaro
Overview of the project

**Inspiration**
- ESA and NASA current interest in developing future missions to the moons of Mars, as a paramount stepping stone in the long-term goal to bring humans to Mars

**Specific objective**
- Identify new space mission opportunities in the Mars-Phobos system

**Targets: Dynamical Objects**
- Points (EP,AEP)
- Orbits (VDCO,LPO,QSO,FF)
- Trajectories (IM,HOC/HEC,I,T)

**Performances: Low Cost**
- Low Energy: exploitation of natural dynamics with advanced models and nonlinear techniques (DST)
- Low Thrust: SEP implementations (SK cost, optimal control for added requirements)

**Aims: Missions**
- Unique positions for probing unmanned observation missions and manned flights for undertaking real-time robotic investigations of Phobos and Mars, while reducing human exposure to space radiation
- Exploitation of Phobos as a natural radiation shield

**My Research**

**What**
- Targets: Dynamical Objects
- Performances: Low Cost
- Aims: Missions

**How**
- My Research

**Why**
- Overview of the project

**Who**

**Where**

**When**

15/06/2015 Mattia Zamaro
Phobos

Characteristics and Interests

- Both the two Martian moons are very similar: they are **small** and **irregular** shaped, their orbits around Mars are almost **circular** and **equatorial**, and they rotate with **synchronous** period and **zero-tilt**.
- Phobos is bigger (x2) and closer (x2) to Mars than Deimos.

---

**Deimos**: 23,460 km orbit radius, 30 hr period
- $1.48 \cdot 10^{15}$ kg mass
- $7.5 \times 6.1 \times 5.2$ km rad dims

**Mars**: 6.42 $\cdot 10^{23}$ kg mass
- 3,390 km radius

**Phobos**: 9,377 km orbit radius
- 7.7 hr period
- $1.07 \cdot 10^{16}$ kg mass
- $13.1 \times 11.1 \times 9.3$ km rad dims
Phobos
Characteristics and Interests

- Both the two Martian moons are very similar: they are small and irregular shaped, their orbits around Mars are almost circular and equatorial, and they rotate with synchronous period and zero-tilt.
- Phobos is bigger (x2) and closer (x2) to Mars than Deimos.
- Scientific interest about origin (asteroid capture, proto-SS material coalescence, Mars ejecta) and evolution (planetary crash or ring).
Stepping Stones
Exploring a series of increasingly challenging destinations on the way to Mars...

2016
Asteroid survey

2017
Asteroid scout

2017
SLS test flight

2023
Phobos/Deimos Scout

2031-2035
Red Rocks: explore Mars from Phobos/Deimos

2024, 2025, 2029
Plymouth Rock: Humans explore asteroids like 1999 AO10 and 2000 SG344

2018-2023
Fastnet: Explore the Moon’s far side from Earth-Moon L2 region

2013-2020
Human systems tests on ISS
Phobos

Characteristics and Interests

- Engineering interest: exploration of Martian moons is one of the stepping stones of the long term goal to bring humans to Mars
  - Exploitation of Phobos proximity for comms (access times), transfer of robotic scouts (the absence of atmosphere makes manned landing more suitable than do that directly on Mars), passive shielding protection from directional Solar radiation (shadow's wake) and isotropic cosmic rays (bulk's occultation)
Phobos

Characteristics and Interests

- Engineering interest: exploration of Martian moons is one of the stepping stones of the long term goal to bring humans to Mars.
- Exploitation of Phobos proximity for comms (access times), transfer of robotic scouts (the absence of atmosphere makes manned landing more suitable than do that directly on Mars), passive shielding protection from directional Solar radiation (shadow's wake) and isotropic cosmic rays (bulk's occultation).

<table>
<thead>
<tr>
<th>Age at exposure</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>1.5Sv</td>
<td>1.0Sv</td>
</tr>
<tr>
<td>35</td>
<td>2.5Sv</td>
<td>1.75Sv</td>
</tr>
<tr>
<td>45</td>
<td>3.2Sv</td>
<td>2.5Sv</td>
</tr>
<tr>
<td>55</td>
<td>4.0Sv</td>
<td>3.0Sv</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SEPEs ( p )</td>
<td>125(\mu)Sv/h</td>
<td>834(\mu)Sv/h</td>
</tr>
<tr>
<td></td>
<td>3.0mSv/day</td>
<td>20.0mSv/h</td>
</tr>
<tr>
<td></td>
<td>1.1Sv/y</td>
<td>7.3(Sv/y)</td>
</tr>
<tr>
<td>GCRs ( p &amp; \alpha )</td>
<td>90(\mu)Sv/h</td>
<td>19(\mu)Sv/h</td>
</tr>
<tr>
<td></td>
<td>2.2mSv/day</td>
<td>0.5mSv/h</td>
</tr>
<tr>
<td></td>
<td>0.8Sv/y</td>
<td>0.2(Sv/y)</td>
</tr>
<tr>
<td>Total</td>
<td>215(\mu)Sv/h</td>
<td>853(\mu)Sv/h</td>
</tr>
<tr>
<td></td>
<td>5.2mSv/day</td>
<td>20.5mSv/h</td>
</tr>
<tr>
<td></td>
<td>1.9Sv/y</td>
<td>7.5(Sv/y)</td>
</tr>
</tbody>
</table>
Phobos
Characteristics and Interests

- Engineering interest: exploration of Martian moons is one of the stepping stones of the long term goal to bring humans to Mars
- Exploitation of Phobos proximity for comms (access times), transfer of robotic scouts (the absence of atmosphere makes manned landing more suitable than do that directly on Mars), passive shielding protection from directional Solar radiation (shadow's wake) and isotropic cosmic rays (bulk's occultation)
- As part of the Mars Robotic Exploration Programme (MREP-2), ESA Phootprint mission aims to obtain and return a sample from Phobos
Phobos

Characteristics and Interests

- Engineering interest: exploration of Martian moons is one of the stepping stones of the long term goal to bring humans to Mars.
- Exploitation of Phobos proximity for comms (access times), transfer of robotic scouts (the absence of atmosphere makes manned landing more suitable than do that directly on Mars), passive shielding protection from directional Solar radiation (shadow's wake) and isotropic cosmic rays (bulk's occultation).
- As part of the Mars Robotic Exploration Programme (MREP-2), ESA Phootprint mission aims to obtain and return a sample from Phobos.
- NASA aims to develop a new rover concept for exploration of minor bodies: Phobos is the target chosen to test a swarm of robotic hedgehogs.
The Three-Body Model (Phobos neighbourhood)

- Application to the Mars-Phobos system: circular orbit approximation and short-term analysis in a classical CR3BP
The Three-Body Model (Phobos neighbourhood)

- Application to the Mars-Phobos system: circular orbit approximation and short-term analysis in a classical CR3BP
- Peculiarities of this system:
  \[ \mu = 1.66059511088139 \times 10^{-8} \]
  \[ R_1/L = 36\% \]
  Very low mass parameter
  Very low length scaling factor
The Three-Body Model (Phobos neighbourhood)

- Application to the Mars-Phobos system: circular orbit approximation and short-term analysis in a classical CR3BP
- Peculiarities of this system:
  \[ \mu = 1.66059511088139 \cdot 10^{-8} \]  
  Very low mass parameter
  \[ R_1/L = 36\% \]  
  Very low length scaling factor
- The Phobos region of influence collapses very close to its surface, making impossible to orbit it with a classical Keplerian motion
The Three-Body Model (Phobos neighbourhood)

- Application to the Mars-Phobos system: circular orbit approximation and short-term analysis in a classical CR3BP
- Peculiarities of this system:
  \[ \mu = 1.66059511088139 \times 10^{-8} \]
  \[ R_1/L = 36\% \]
  Very low mass parameter
  Very low length scaling factor
- The Phobos region of influence collapses very close to its surface, making impossible to orbit it with a classical Keplerian motion
The Three-Body Model
(Phobos neighbourhood)

- Orbital differential perturbations analysis (Phobos orbit is highly non-keplerian by Mars J2): inside the Phobos realm, Phobos real gravity field and orbital eccentricity are relevant, then Mars J2
Shadowing Effects & Occultation

- Sun 4B attraction and RP are not relevant, but a 4B coupled analysis (Sun/Mars eclipses at Phobos, Sun/Phobos and Mars/Phobos eclipses) displays the lighting conditions.
Shadowing Effects & Occultation

- Sun 4B attraction and RP are not relevant, but a 4B coupled analysis (Sun/Mars eclipses at Phobos, Sun/Phobos and Mars/Phobos eclipses) displays the lighting conditions
- Phobos shadowing wake follows the anti-Sun orbit (Vertical Displaced Circular Orbit), plus short Mars eclipse blackouts
Shadowing Effects & Occultation

- Sun 4B attraction and RP are not relevant, but a 4B coupled analysis (Sun/Mars eclipses at Phobos, Sun/Phobos and Mars/Phobos eclipses) displays the lighting conditions.
- Phobos shadowing wake follows the anti-Sun orbit (Vertical Displaced Circular Orbit), plus short Mars eclipse blackouts.
- Integral analysis of the light field provides the opportunities:
  - seasonal (complete shadowing by close points/orbits over Polar zones).
Shadowing Effects & Occultation

- Sun 4B attraction and RP are not relevant, but a 4B coupled analysis (Sun/Mars eclipses at Phobos, Sun/Phobos and Mars/Phobos eclipses) displays the lighting conditions.
- Phobos shadowing wake follows the anti-Sun orbit (Vertical Displaced Circular Orbit), plus short Mars eclipse blackouts.
- Integral analysis of the light field provides the opportunities:
  - seasonal (complete shadowing by close points/orbits over Polar zones)
  - long-time (limitation of Sun FOV by close points on the Mars-side, fixed conditions by orbits on the Solar plane synchronous with the Sun)
Shadowing Effects & Occultation

- Sun 4B attraction and RP are not relevant, but a 4B coupled analysis (Sun/Mars eclipses at Phobos, Sun/Phobos and Mars/Phobos eclipses) displays the lighting conditions
- Phobos shadowing wake follows the anti-Sun orbit (Vertical Displaced Circular Orbit), plus short Mars eclipse blackouts
- Integral analysis of the light field provides the opportunities
- Sky occultation by 3B coupled analysis: filling fraction of bulks of Phobos and Mars would limit the isotropic radiation hazards (points/orbits inside the sphere of influence and on the Mars-side)
Artificial EPs with Low Thrust

- Addition of a constant acceleration to EoM of CR3BP
Artificial EPs with Low Thrust

- Addition of a constant acceleration to EoM of CR3BP
- Hovering by displacement of natural EPs: AEPs (i.e. Trailing orbits)
Artificial EPs with Low Thrust

- Addition of a constant acceleration to EoM of CR3BP
- **Hovering** by displacement of natural EPs: AEPs (i.e. Trailing orbits)
- Trade-Off consumption/stability/lighting/shielding:
Artificial EPs with Low Thrust

- Addition of a constant acceleration to EoM of CR3BP
- **Hovering** by displacement of natural EPs: AEPs (i.e. Trailing orbits)
- Trade-Off consumption/stability/lighting/shielding:
Artificial EPs with Low Thrust

- Addition of a constant acceleration to EoM of CR3BP
- **Hovering** by displacement of natural EPs: AEPs (i.e. Trailing orbits)
- Trade-Off consumption/stability/lighting/shielding:
  - Far (r>80km): cheap, stable (long phases), light, no shielding
Artificial EPs with Low Thrust

- Addition of a constant acceleration to EoM of CR3BP
- **Hovering** by displacement of natural EPs: AEPs (i.e. Trailing orbits)
- Trade-Off consumption/stability/lighting/shielding:
  - Far (r>80km): cheap, stable (long phases), light, no shielding
  - Close to enhance shielding: thrust too high for SEP, very unstable (short phases)
Artificial EPs with Low Thrust

- Addition of a constant acceleration to EoM of CR3BP
- **Hovering** by displacement of natural EPs: AEPs (i.e. Trailing orbits)
- Trade-Off consumption/stability/lighting/shielding:
  - Far (r>80km): cheap, stable (long phases), light, no shielding
  - Close to enhance shielding: thrust too high for SEP, very unstable (short phases)
  - Identification of suitable minimum-distance (1.9\(\text{mm/s}^2\)) and minimum-control (0.4\(\text{mm/s}^2\)) stable AEPs, but without shielding
Artificial EPs with Low Thrust

- Addition of a constant acceleration to EoM of CR3BP
- **Hovering** by displacement of natural EPs: AEPs (i.e. Trailing orbits)
- Trade-Off consumption/stability/lighting/shielding:
  - Far (r>80km): cheap, stable (long phases), light, no shielding
  - Close to enhance shielding: thrust too high for SEP, very unstable (short phases)
  - Identification of suitable minimum-distance (1.9mm/s²) and minimum-control (0.4mm/s²) stable AEPs, but without shielding
- Generalization of AEPs to any rotational frame: **SS-VDCOs** to provide constant lighting/shadowing conditions
Artificial EPs with Low Thrust

- Addition of a constant acceleration to EoM of CR3BP
- **Hovering** by displacement of natural EPs: AEPs (i.e. Trailing orbits)
- Trade-Off consumption/stability/lighting/shielding:
  - Far ($r>80\text{km}$): cheap, stable (long phases), light, no shielding
  - Close to enhance shielding: thrust too high for SEP, very unstable (short phases)
  - Identification of suitable minimum-distance ($1.9\text{mm/s}^2$) and minimum-control ($0.4\text{mm/s}^2$) stable AEPs, but without shielding
- Generalization of AEPs to any rotational frame: **SS-VDCOs** to provide constant lighting/shadowing conditions
- Keplerian stable solution for entire year has $\Delta v$ cost unsustainable in the 3BP

---

**Graphs**

- Vertical Displaced Circular Orbits: $|a_p| [\text{m/s}^2]$ on the left.
- Vertical Displaced Circular Orbits: stability on the right.
Artificial EPs with Low Thrust

- Addition of a constant acceleration to EoM of CR3BP
- **Hovering** by displacement of natural EPs: AEPs (i.e. Trailing orbits)
- Trade-Off consumption/stability/lighting/shielding:
  - Far ($r > 80\text{km}$): cheap, stable (long phases), light, no shielding
  - Close to enhance shielding: thrust too high for SEP, very unstable (short phases)
  - Identification of suitable minimum-distance ($1.9\text{mm/s}^2$) and minimum-control ($0.4\text{mm/s}^2$) stable AEPs, but without shielding
- Generalization of AEPs to any rotational frame: **SS-VDCOs** to provide constant lighting/shadowing conditions
- Keplerian stable solution for entire year has $\Delta v$ cost unsustainable in the 3BP

Horizontal Displaced Circular Orbits: $1T \Delta v [\text{m/s}]$
Libration Point Orbits

- Invariant solutions of the CR3BP about the collinear EPs: LPO
Libration Point Orbits

- Invariant solutions of the CR3BP about the collinear EPs: LPO
- Families of planar and vertical Lyapunov orbits and their 2-phases tori of Lissajous orbits, and bifurcated family of N/S Halo orbits
Libration Point Orbits

- Invariant solutions of the CR3BP about the collinear EPs: LPO
- Families of planar and vertical Lyapunov orbits and their 2-phases tori of Lissajous orbits, and bifurcated family of N/S Halo orbits
Libration Point Orbits

- Invariant solutions of the CR3BP about the collinear EPs: **LPO**
- Families of planar and vertical Lyapunov orbits and their 2-phases tori of Lissajous orbits, and bifurcated family of N/S Halo orbits
Libration Point Orbits

- Invariant solutions of the CR3BP about the collinear EPs: **LPO**
- Families of planar and vertical Lyapunov orbits and their 2-phases tori of Lissajous orbits, and bifurcated family of N/S Halo orbits
- **Invariant Manifolds** of LPOs: application as natural gateway trajectories for landing and take-off to/from Phobos
Libration Point Orbits

- Invariant solutions of the CR3BP about the collinear EPs: **LPO**
- Families of planar and vertical Lyapunov orbits and their 2-phases tori of Lissajous orbits, and bifurcated family of N/S Halo orbits
- **Invariant Manifolds** of LPOs: application as natural gateway trajectories for landing and take-off to/from Phobos
- Tracking LPOs in the real world would require a high SK cost: computation of their **dynamical substitutes** in ER3BP-GH by numerical continuation of the CR3BP solutions
Libration Point Orbits

- Continuation w.r.t. GHs ($J_2=0.1051$): drift, distortion and tilt
Libration Point Orbits

- Continuation w.r.t. GHs ($J_2=0.1051$): drift, distortion and tilt
- Four new families of periodic LPOs in the CR3BP-GH
Libration Point Orbits

- Continuation w.r.t. GHs ($J_2=0.1051$): drift, distortion and tilt
- Four new families of periodic LPOs in the CR3BP-GH
Libration Point Orbits

- Continuation w.r.t. GHs ($J_2=0.1051$): drift, distortion and tilt
  - Four new families of periodic LPOs in the CR3BP-GH
  - Related families of quasi-periodic tori around them
Libration Point Orbits

- Continuation w.r.t. GHs ($J_2=0.1051$): drift, distortion and tilt
  - Four new families of periodic LPOs in the CR3BP-GH
  - Related families of quasi-periodic tori around them
Libration Point Orbits

- Continuation w.r.t. GHs ($J_2=0.1051$): drift, distortion and tilt
  - Four new families of periodic LPOs in the CR3BP-GH
  - Related families of quasi-periodic tori around them
  - Convergence analysis on degree-order GHs included
Libration Point Orbits

- Continuation w.r.t. GHs ($J_2=0.1051$): drift, distortion and tilt
  - Four new families of periodic LPOs in the CR3BP-GH
  - Related families of quasi-periodic tori around them
  - Convergence analysis on degree-order GHs included
  - Phobos shape fills Hill's SOI with GHs: accretion origin
Libration Point Orbits

- Continuation w.r.t. GHs ($J_2=0.1051$): drift, distortion and tilt
- Continuation w.r.t. eccentricity ($e=0.0156$): increment of the phase-space by Mars-Phobos orbital frequency (oscillation of $\sim260m$)
Libration Point Orbits

- Continuation w.r.t. GHs ($J_2=0.1051$): drift, distortion and tilt
- Continuation w.r.t. eccentricity ($e=0.0156$): increment of the phase-space by Mars-Phobos orbital frequency (oscillation of ~260m)
  - Resonant periodic orbits: comms-bridge on all Phobos faces
Libration Point Orbits

- Continuation w.r.t. GHs ($J_2=0.1051$): drift, distortion and tilt
- Continuation w.r.t. eccentricity ($e=0.0156$): increment of the phase-space by Mars-Phobos orbital frequency (oscillation of ~260m)
  - Resonant periodic orbits: comms-bridge on all Phobos faces
  - Quasi-periodic orbits: four families of 2-tori, and 3-tori around them
Libration Point Orbits

- Continuation w.r.t. GHs ($J_2=0.1051$): drift, distortion and tilt
- Continuation w.r.t. eccentricity ($e=0.0156$): increment of the phase-space by Mars-Phobos orbital frequency (oscillation of $\sim 260m$)
  - Resonant periodic orbits: comms-bridge on all Phobos faces
  - Quasi-periodic orbits: four families of 2-tori, and 3-tori around them
Libration Point Orbits

- Continuation w.r.t. GHs ($J_2=0.1051$): drift, distortion and tilt
- Continuation w.r.t. eccentricity ($e=0.0156$): increment of the phase-space by Mars-Phobos orbital frequency (oscillation of $\sim 260 m$)
  - Resonant periodic orbits: comms-bridge on all Phobos faces
  - Quasi-periodic orbits: four families of 2-tori, and 3-tori around them
  - Natural shielding for reduction of isotropic space radiation
Libration Point Orbits

- Continuation w.r.t. GHs ($J_2=0.1051$): drift, distortion and tilt
- Continuation w.r.t. eccentricity ($e=0.0156$): increment of the phase-space by Mars-Phobos orbital frequency (oscillation of $260m$)
  - Resonant periodic orbits: comms-bridge on all Phobos faces
  - Quasi-periodic orbits: four families of 2-tori, and 3-tori around them
  - Natural shielding for reduction of isotropic space radiation
  - LPOs of ER3BP-GH provide SK savings up to 95%
Libration Point Orbits

- Continuation w.r.t. GHs ($J_2=0.1051$): drift, distortion and tilt
- Continuation w.r.t. eccentricity ($e=0.0156$): increment of the phase-space by Mars-Phobos orbital frequency (oscillation of $\sim 260m$)
  - Resonant periodic orbits: comms-bridge on all Phobos faces
  - Quasi-periodic orbits: four families of 2-tori, and 3-tori around them
  - Natural shielding for reduction of isotropic space radiation
  - LPOs of ER3BP-GH provide SK savings up to 95%
- GNC assessment: LPOs feasible only with auto-abs navigation, not ground-based
Libration Point Orbits

- Continuation w.r.t. GHs ($J_2=0.1051$): drift, distortion and tilt
- Continuation w.r.t. eccentricity (e=0.0156): increment of the phase-space by Mars-Phobos orbital frequency (oscillation of $\sim260m$)
  - Resonant periodic orbits: comms-bridge on all Phobos faces
  - Quasi-periodic orbits: four families of 2-tori, and 3-tori around them
  - Natural shielding for reduction of isotropic space radiation
  - LPOs of ER3BP-GH provide SK savings up to 95%
- GNC assessment: LPOs feasible only with auto-abs navigation, not ground-based

<table>
<thead>
<tr>
<th>Frequency SK Inaccuracy pos-vel-$\Delta v$</th>
<th>0.5h</th>
<th>1h</th>
<th>1.5h</th>
<th>&gt;2h</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1m-0.1mm/s-0.1mm/s</td>
<td>0.1 m/s/day</td>
<td>0.1 m/s/day</td>
<td>0.3 m/s/day</td>
<td>&gt;0.5 m/s/day</td>
</tr>
<tr>
<td></td>
<td>3 m</td>
<td>3 mm/s</td>
<td>10 mm/s</td>
<td>&gt;50 m</td>
</tr>
<tr>
<td></td>
<td>1 m</td>
<td>6 mm/s</td>
<td>10 mm/s</td>
<td>&gt;30 mm/s</td>
</tr>
<tr>
<td>1m-1mm/s-1mm/s</td>
<td>0.2 m/s/day</td>
<td>0.2 m/s/day</td>
<td>0.5 m/s/day</td>
<td>&gt;1 m/s/day</td>
</tr>
<tr>
<td></td>
<td>4 m</td>
<td>4 mm/s</td>
<td>12 m</td>
<td>&gt;100 m</td>
</tr>
<tr>
<td></td>
<td>20 m</td>
<td>20 mm/s</td>
<td>60 m</td>
<td>&gt;50 mm/s</td>
</tr>
<tr>
<td>10m-10mm/s-10mm/s</td>
<td>1 m/s/day</td>
<td>1 m/s/day</td>
<td>3 m/s/day</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>20 m</td>
<td>20 mm/s</td>
<td>60 m</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>100 m</td>
<td>100 mm/s</td>
<td>300 m</td>
<td>N/A</td>
</tr>
<tr>
<td>100m-100mm/s-100mm/s</td>
<td>200 mm/s</td>
<td>200 mm/s</td>
<td>500 mm/s</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Libration Point Orbits

- Continuation w.r.t. GHs ($J_2=0.1051$): drift, distortion and tilt
- Continuation w.r.t. eccentricity ($e=0.0156$): increment of the phase-space by Mars-Phobos orbital frequency (oscillation of $\sim 260m$)
- Performance analysis of the Invariant Manifolds of the LPOs in the ER3BP-GH: natural trajectories for low incidence/escape velocity in function of the topographical landing/departure sites on Phobos, valid down to $\sim 10\mu m$ (natural impacts with IMs, dust clouds LPOs)
Libration Point Orbits

- Continuation w.r.t. GHs ($J_2=0.1051$): drift, distortion and tilt
- Continuation w.r.t. eccentricity ($e=0.0156$): increment of the phase-space by Mars-Phobos orbital frequency (oscillation of ~260m)
- Performance analysis of the Invariant Manifolds of the LPOs in the ER3BP-GH: natural trajectories for low incidence/escape velocity in function of the topographical landing/departure sites on Phobos, valid down to ~10μm (natural impacts with IMs, dust clouds LPOs)
Libration Point Orbits

- Continuation w.r.t. GHs ($J_2=0.1051$): drift, distortion and tilt
- Continuation w.r.t. eccentricity ($e=0.0156$): increment of the phase-space by Mars-Phobos orbital frequency (oscillation of $\sim260m$)
- Performance analysis of the Invariant Manifolds of the LPOs in the ER3BP-GH: natural trajectories for low incidence/escape velocity in function of the topographical landing/departure sites on Phobos, valid down to $\sim10\mu m$ (natural impacts with IMs, dust clouds LPOs)
Libration Point Orbits

- Continuation w.r.t. GHs ($J_2 = 0.1051$): drift, distortion and tilt
- Continuation w.r.t. eccentricity ($e = 0.0156$): increment of the phase-space by Mars-Phobos orbital frequency (oscillation of $\sim 260m$)
- Performance analysis of the Invariant Manifolds of the LPOs in the ER3BP-GH: natural trajectories for low incidence/escape velocity in function of the topographical landing/departure sites on Phobos, valid down to $\sim 10\mu m$ (natural impacts with IMs, dust clouds LPOs)
- Addition of constant low-thrust: displacement of LPOs from Phobos
Libration Point Orbits

- Continuation w.r.t. GHs ($J_2=0.1051$): drift, distortion and tilt
- Continuation w.r.t. eccentricity ($e=0.0156$): increment of the phase-space by Mars-Phobos orbital frequency (oscillation of $\sim 260m$)
- Performance analysis of the Invariant Manifolds of the LPOs in the ER3BP-GH: natural trajectories for **low incidence/escape velocity** in function of the topographical landing/departure sites on Phobos, valid down to $\sim 10\mu m$ (natural impacts with IMs, dust clouds LPOs)
- Addition of constant low-thrust: displacement of LPOs from Phobos **reduces accuracy of GHs model** for convergence of the LPOs computation and their instability, and enables orbital resonance and **whole coverage** of IMs + HCs
Libration Point Orbits

- Continuation w.r.t. GHs ($J_2=0.1051$): drift, distortion and tilt
- Continuation w.r.t. eccentricity ($e=0.0156$): increment of the phase-space by Mars-Phobos orbital frequency (oscillation of $\sim 260m$)
- Performance analysis of the Invariant Manifolds of the LPOs in the ER3BP-GH: natural trajectories for low incidence/escape velocity in function of the topographical landing/departure sites on Phobos, valid down to $\sim 10\mu m$ (natural impacts with IMs, dust clouds LPOs)
- Addition of constant low-thrust: displacement of LPOs from Phobos reduces accuracy of GHs model for convergence of the LPOs computation and their instability, and enables orbital resonance and whole coverage of IMs + HCs
Libration Point Orbits

- Continuation w.r.t. GHs ($J_2=0.1051$): drift, distortion and tilt
- Continuation w.r.t. eccentricity ($e=0.0156$): increment of the phase-space by Mars-Phobos orbital frequency (oscillation of $\sim 260m$)
- Performance analysis of the Invariant Manifolds of the LPOs in the ER3BP-GH: natural trajectories for low incidence/escape velocity in function of the topographical landing/departure sites on Phobos, valid down to $\sim 10\mu m$ (natural impacts with IMs, dust clouds LPOs)
- Addition of constant low-thrust: displacement of LPOs from Phobos reduces accuracy of GHs model for convergence of the LPOs computation and their instability, and enables orbital resonance and whole coverage of IMs + HCs
Quasi-Satellite Orbits

- Far beyond LPs, Keplerian FF becomes suitable dynamical model
Quasi-Satellite Orbits

- Far beyond LPs, Keplerian FF becomes suitable dynamical model
- Artificial FF by compensation of Phobos gravity: low-thrust feasible but configuration is locked and additional manoeuvres are needed
Quasi-Satellite Orbits

- Far beyond LPs, Keplerian FF becomes suitable dynamical model
- Artificial FF by compensation of Phobos gravity: low-thrust feasible but configuration is locked and additional manoeuvres are needed
- J2-invariant configuration to enable natural precession: time too long for \( \Delta v \)
Quasi-Satellite Orbits

- Far beyond LPs, Keplerian FF becomes suitable dynamical model
- Artificial FF by compensation of Phobos gravity: low-thrust feasible but configuration is locked and additional manoeuvres are needed
- J2-invariant configuration to enable natural precession: time too long for Δv
- Artificial-J2 amplification to speed up precession: fast full coverage but high cost still contrained by illumination and pointing requirements
Quasi-Satellite Orbits

- Far beyond LPs, Keplerian FF becomes suitable dynamical model
- Artificial FF by compensation of Phobos gravity: low-thrust feasible but configuration is locked and additional manoeuvres are needed
- J2-invariant configuration to enable natural precession: time too long for Δv
- Artificial-J2 amplification to speed up precession: fast full coverage but high cost still constrained by illumination and pointing requirements
Quasi-Satellite Orbits

- Far beyond LPs, Keplerian FF becomes suitable dynamical model
- Artificial FF by compensation of Phobos gravity: low-thrust feasible but configuration is locked and additional maneuvers are needed
- J2-invariant configuration to enable natural precession: time too long for $\Delta v$
- Artificial-J2 amplification to speed up precession: fast full coverage but high cost still constrained by illumination and pointing requirements
- Natural dynamics: moving closer, relative orbits in ER3BP become QSOs
Quasi-Satellite Orbits

- Far beyond LPs, Keplerian FF becomes suitable dynamical model
- Artificial FF by compensation of Phobos gravity: low-thrust feasible but configuration is locked and additional manoeuvres are needed
- J2-invariant configuration to enable natural precession: time too long for $\Delta v$
- Artificial-J2 amplification to speed up precession: fast full coverage but high cost still constrained by illumination and pointing requirements
- Natural dynamics: moving closer, relative orbits in ER3BP become QSOs
- ESA Phootprint choice for Phobos mission segment (Phase 0/A) to observe the surface and identify the landing site
Quasi-Satellite Orbits

- Linear self-stability mechanism: precession eventually rotates 3D QSO to unstable attitude (rel-LoN along the r-axis) when inclined enough ($\Delta i > \Delta e$)
Quasi-Satellite Orbits

- Linear self-stability mechanism: precession eventually rotates 3D QSO to unstable attitude (rel-LoN along the r-axis) when inclined enough ($\Delta i > \Delta e$)
- Long-period true-life simulations to identify the region of reliable QSOs around Phobos, where select the one that will optimize future constraints ($\Delta v$ of insertion manoeuver from previous segment, Trailing configuration)
Quasi-Satellite Orbits

- Linear **self-stability** mechanism: precession eventually rotates 3D QSO to **unstable attitude** (rel-LoN along the r-axis) when inclined enough \(\sim \Delta \alpha > \Delta \epsilon\)
- Long-period true-life simulations to identify the region of reliable QSOs around Phobos, where select the one that will optimize future constraints (\(\Delta v\) of insertion manoeuvre from previous segment, Trailing configuration)
Quasi-Satellite Orbits

- Linear **self-stability** mechanism: precession eventually rotates 3D QSO to **unstable attitude** (rel-LoN along the r-axis) when inclined enough ($\sim \Delta i > \Delta e$)
- Long-period true-life simulations to identify the region of reliable QSOs around Phobos, where select the one that will optimize future constraints ($\Delta v$ of insertion manoeuvre from previous segment, Trailing configuration)
- Precession of close QSOs overcomes the 1:1 resonance to provide a fast complete coverage of Phobos surface for identification of the landing site
Quasi-Satellite Orbits

- Linear self-stability mechanism: precession eventually rotates 3D QSO to unstable attitude (rel-LoN along the r-axis) when inclined enough (∆i > ∆e)
- Long-period true-life simulations to identify the region of reliable QSOs around Phobos, where select the one that will optimize future constraints (∆v of insertion manoeuver from previous segment, Trailing configuration)
- Precession of close QSOs overcomes the 1:1 resonance to provide a fast complete coverage of Phobos surface for identification of the landing site
- Distant QSOs could be exploited for constant lighting/shadowing constraints
Quasi-Satellite Orbits

- Linear **self-stability** mechanism: precession eventually rotates 3D QSO to **unstable attitude** (rel-LoN along the r-axis) when inclined enough ($\Delta i > \Delta e$)
- Long-period true-life simulations to identify the region of reliable QSOs around Phobos, where select the one that will optimize future constraints ($\Delta v$ of insertion manoeuver from previous segment, Trailing configuration)
- Precession of close QSOs overcomes the 1:1 resonance to provide a fast complete coverage of Phobos surface for identification of the landing site
- Distant QSOs could be exploited for constant lighting/shadowing constraints
- QSO is low altitude “orbital garage” to park modules and stockpiles in advance without orbital SK costs for planned pit-stops in Mars exploration
### Mission Opportunities to Phobos: Summary

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Altitude</th>
<th>Model</th>
<th>Propulsion</th>
<th>Station-Keeping</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEP</td>
<td>&lt;70km</td>
<td>C3B</td>
<td>HT</td>
<td>high GNC load</td>
<td>dedicated operations</td>
</tr>
<tr>
<td></td>
<td>&gt;70 km y</td>
<td>E3B</td>
<td>SEP</td>
<td>cheap</td>
<td>long observation</td>
</tr>
<tr>
<td>SS-VDCO</td>
<td>&lt;10km</td>
<td>C3B</td>
<td>HT</td>
<td>expensive</td>
<td>fixed lighting conditions</td>
</tr>
<tr>
<td>LPO</td>
<td>&lt;10km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate GH and NAV</td>
<td>close observation, comm-bridge, radiation protection</td>
</tr>
<tr>
<td>ALPO</td>
<td>&gt;10km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>approach, measurements</td>
</tr>
<tr>
<td>IM-LPO</td>
<td>0-10-500km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate GH and NAV</td>
<td>soft landing / cheap take-off (s&amp;r)</td>
</tr>
<tr>
<td>IM-ALPO</td>
<td>0-70-500km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>enhanced landing / take-off sites, fly-bys</td>
</tr>
<tr>
<td>AFF</td>
<td>50-200km</td>
<td>2B-P</td>
<td>LT-HT</td>
<td>expensive</td>
<td>fast coverage</td>
</tr>
<tr>
<td>QSO</td>
<td>25-200km</td>
<td>2B-P</td>
<td>no</td>
<td>no</td>
<td>long parking, mapping, comms-relay</td>
</tr>
</tbody>
</table>
## Mission Opportunities to Phobos: Summary

### Mission Scenario

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Altitude</th>
<th>Model</th>
<th>Propulsion</th>
<th>Station-Keeping</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEP</td>
<td>&lt;70 km</td>
<td>C3B</td>
<td>HT</td>
<td>high GNC load</td>
<td>dedicated operations</td>
</tr>
<tr>
<td></td>
<td>&gt;70 km y</td>
<td>E3B</td>
<td>SEP</td>
<td>cheap</td>
<td>long observation</td>
</tr>
<tr>
<td>SS-VDCO</td>
<td>&lt;10 km</td>
<td>C3B</td>
<td>HT</td>
<td>expensive</td>
<td>fixed lighting conditions</td>
</tr>
<tr>
<td>LPO</td>
<td>&lt;10 km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate GH and NAV</td>
<td>close observation, comm-bridge, radiation protection</td>
</tr>
<tr>
<td>ALPO</td>
<td>&gt;10 km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>approach, measurements</td>
</tr>
<tr>
<td>IM-LPO</td>
<td>0-10-500km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate GH and NAV</td>
<td>soft landing / cheap take-off (s&amp;r)</td>
</tr>
<tr>
<td>IM-ALPO</td>
<td>0-70-500km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>enhanced landing / take-off sites, fly-byes</td>
</tr>
<tr>
<td>AFF</td>
<td>50-200km</td>
<td>2B-P</td>
<td>LT-HT</td>
<td>expensive</td>
<td>fast coverage</td>
</tr>
<tr>
<td>QSO</td>
<td>25-200km</td>
<td>2B-P</td>
<td>no</td>
<td>no</td>
<td>long parking, mapping, comms-relay</td>
</tr>
</tbody>
</table>

**Footer:**

15/06/2015
Mattia Zamaro
### Mission Opportunities to Phobos: Summary

**Mission Scenario**

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Altitude</th>
<th>Model</th>
<th>Propulsion</th>
<th>Station-Keeping</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEP</td>
<td>&lt;70 km</td>
<td>C3B</td>
<td>HT</td>
<td>high GNC load</td>
<td>dedicated operations</td>
</tr>
<tr>
<td></td>
<td>&gt;70 km</td>
<td>E3B</td>
<td>SEP</td>
<td>cheap</td>
<td>long observation</td>
</tr>
<tr>
<td>SS-VDCO</td>
<td>&lt;10 km</td>
<td>C3B</td>
<td>HT</td>
<td>expensive</td>
<td>fixed lighting conditions</td>
</tr>
<tr>
<td>LPO</td>
<td>&lt;10 km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate GH and NAV</td>
<td>close observation, comm-bridge, radiation protection</td>
</tr>
<tr>
<td>ALPO</td>
<td>&gt;10 km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>approach, measurements</td>
</tr>
<tr>
<td>IM-LPO</td>
<td>0-10-500km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate GH and NAV</td>
<td>soft landing / cheap take-off (s&amp;r)</td>
</tr>
<tr>
<td>IM-ALPO</td>
<td>0-70-500km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>enhanced landing / take-off sites, fly-byes</td>
</tr>
<tr>
<td>AFF</td>
<td>50-200km</td>
<td>2B-P</td>
<td>LT-HT</td>
<td>expensive</td>
<td>fast coverage</td>
</tr>
<tr>
<td>QSO</td>
<td>25-200km</td>
<td>2B-P</td>
<td>no</td>
<td>no</td>
<td>long parking, mapping, comms-relay</td>
</tr>
</tbody>
</table>

**Phobostack&GM**
## Mission Opportunities to Phobos:

### Summary

#### Mission Scenario

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Altitude</th>
<th>Model</th>
<th>Propulsion</th>
<th>Station-Keeping</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEP</td>
<td>&lt;70 km</td>
<td>C3B</td>
<td>HT</td>
<td>high GNC load</td>
<td>dedicated operations</td>
</tr>
<tr>
<td></td>
<td>&gt;70 km y</td>
<td>E3B</td>
<td>SEP</td>
<td>cheap</td>
<td>long observation</td>
</tr>
<tr>
<td>SS-VDCO</td>
<td>&lt;10 km</td>
<td>C3B</td>
<td>HT</td>
<td>expensive</td>
<td>fixed lighting conditions</td>
</tr>
<tr>
<td>LPO</td>
<td>&lt;10 km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate</td>
<td>close observation, comm-bridge, radiation protection</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>GH and NAV</td>
<td></td>
</tr>
<tr>
<td>ALPO</td>
<td>&gt;10 km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>approach, measurements</td>
</tr>
<tr>
<td>IM-LPO</td>
<td>0-10-500 km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate</td>
<td>soft landing / cheap take-off (s&amp;r)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>GH and NAV</td>
<td>enhanced landing / take-off sites, fly-byes</td>
</tr>
<tr>
<td>IM-ALPO</td>
<td>0-70-500 km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>fast coverage</td>
</tr>
<tr>
<td>AFF</td>
<td>50-200 km</td>
<td>2B-P</td>
<td>LT-HT</td>
<td>expensive</td>
<td>long parking, mapping, comms-relay</td>
</tr>
<tr>
<td>QSO</td>
<td>25-200 km</td>
<td>2B-P</td>
<td>no</td>
<td>no</td>
<td></td>
</tr>
</tbody>
</table>

---

15/06/2015  Mattia Zamaro
## Mission Opportunities to Phobos: Summary

### Mission Scenario

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Altitude</th>
<th>Model</th>
<th>Propulsion</th>
<th>Station-Keeping</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEP</td>
<td>&lt;70 km</td>
<td>C3B</td>
<td>HT</td>
<td>high GNC load</td>
<td>dedicated operations</td>
</tr>
<tr>
<td></td>
<td>&gt;70 km y</td>
<td>E3B</td>
<td>SEP</td>
<td>cheap</td>
<td>long observation</td>
</tr>
<tr>
<td>SS-VDCO</td>
<td>&lt;10 km</td>
<td>C3B</td>
<td>HT</td>
<td>expensive</td>
<td>fixed lighting conditions</td>
</tr>
<tr>
<td>LPO</td>
<td>&lt;10 km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate</td>
<td>close observation, comm-bridge, radiation protection</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>GH and NAV</td>
<td>approach, measurements</td>
</tr>
<tr>
<td>ALPO</td>
<td>&gt;10 km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>soft landing / cheap take-off (s&amp;r)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>enhanced landing / take-off sites, fly-byes</td>
</tr>
<tr>
<td>IM-LPO</td>
<td>0-10-500km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate</td>
<td>fast coverage</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>GH and NAV</td>
<td>long parking, mapping, comms-relay</td>
</tr>
<tr>
<td>IM-ALPO</td>
<td>0-70-500km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td></td>
</tr>
<tr>
<td>AFF</td>
<td>50-200km</td>
<td>2B-P</td>
<td>LT-HT</td>
<td>expensive</td>
<td></td>
</tr>
<tr>
<td>QSO</td>
<td>25-200km</td>
<td>2B-P</td>
<td>no</td>
<td>no</td>
<td></td>
</tr>
</tbody>
</table>
## Mission Opportunities to Phobos: Summary

### Mission Scenario

<table>
<thead>
<tr>
<th>Phobos track &amp; GM</th>
<th>Orbit</th>
<th>Altitude</th>
<th>Model</th>
<th>Propulsion</th>
<th>Station-Keeping</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEP</td>
<td>&lt;70 km</td>
<td>C3B</td>
<td>HT</td>
<td>HT</td>
<td>high GNC load</td>
<td>dedicated operations</td>
</tr>
<tr>
<td></td>
<td>&gt;70 km</td>
<td>E3B</td>
<td>SEP</td>
<td></td>
<td>cheap</td>
<td>long observation</td>
</tr>
<tr>
<td>SS-VDCO</td>
<td>&lt;10 km</td>
<td>C3B</td>
<td>HT</td>
<td></td>
<td>expensive</td>
<td>fixed lighting conditions</td>
</tr>
<tr>
<td>LPO</td>
<td>&lt;10 km</td>
<td>E3B-GH</td>
<td>no</td>
<td></td>
<td>cheap, accurate</td>
<td>close observation, communication, radiation protection</td>
</tr>
<tr>
<td>ALPO</td>
<td>&gt;10 km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>soft landing / cheap take-off (s&amp;r)</td>
<td></td>
</tr>
<tr>
<td>IM-LPO</td>
<td>0-10-500 km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate GH and NAV</td>
<td>enhanced landing / take-off sites, fly-byes</td>
<td></td>
</tr>
<tr>
<td>IM-ALPO</td>
<td>0-70-500 km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AFF</td>
<td>50-200 km</td>
<td>2B-P</td>
<td>LT-HT</td>
<td>expensive</td>
<td></td>
<td>fast coverage</td>
</tr>
<tr>
<td>QSO</td>
<td>25-200 km</td>
<td>2B-P</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>long parking, mapping, comms-relay</td>
</tr>
</tbody>
</table>
## Mission Opportunities to Phobos: Summary

### Mission Scenario

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Altitude</th>
<th>Model</th>
<th>Propulsion</th>
<th>Station-Keeping</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phobostrack&amp;GM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AEP</td>
<td>&lt;70 km</td>
<td>C3B</td>
<td>HT</td>
<td>high GNC load</td>
<td>dedicated operations</td>
</tr>
<tr>
<td></td>
<td>&gt;70 km</td>
<td>E3B</td>
<td>SEP</td>
<td>cheap</td>
<td>long observation</td>
</tr>
<tr>
<td>SS-VDCO</td>
<td>&lt;10 km</td>
<td>C3B</td>
<td>HT</td>
<td>expensive</td>
<td>fixed lighting conditions</td>
</tr>
<tr>
<td>LPO</td>
<td>&lt;10 km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate GH and NAV</td>
<td>close observation, comm-bridge, radiation protection</td>
</tr>
<tr>
<td>ALPO</td>
<td>&gt;10 km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>approach, measurements</td>
</tr>
<tr>
<td>IM-LPO</td>
<td>0-10-500km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate GH and NAV</td>
<td>soft landing / cheap take-off (s&amp;r)</td>
</tr>
<tr>
<td>IM-ALPO</td>
<td>0-70-500km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>enhanced landing / take-off sites, fly-byes</td>
</tr>
<tr>
<td>AFF</td>
<td>50-200km</td>
<td>2B-P</td>
<td>LT-HT</td>
<td>expensive</td>
<td>fast coverage</td>
</tr>
<tr>
<td>QSO</td>
<td>25-200km</td>
<td>2B-P</td>
<td>no</td>
<td>no</td>
<td>long parking, mapping, comms-relay</td>
</tr>
</tbody>
</table>

**mapping & GH measurements**
## Mission Opportunities to Phobos: Summary

### Mission Scenario

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Altitude</th>
<th>Model</th>
<th>Propulsion</th>
<th>Station-Keeping</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEP</td>
<td>&lt;70 km</td>
<td>C3B</td>
<td>HT</td>
<td>high GNC load</td>
<td>dedicated operations</td>
</tr>
<tr>
<td></td>
<td>&gt;70 km</td>
<td>E3B</td>
<td>SEP</td>
<td>cheap</td>
<td>long observation</td>
</tr>
<tr>
<td>SS-VDCO</td>
<td>&lt;10 km</td>
<td>C3B</td>
<td>HT</td>
<td>expensive</td>
<td>fixed lighting conditions</td>
</tr>
<tr>
<td>LPO</td>
<td>&lt;10 km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate</td>
<td>close observation, comm-bridge,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>GH and NAV</td>
<td>radiation protection</td>
</tr>
<tr>
<td>ALPO</td>
<td>&gt;10 km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>approach, measurements</td>
</tr>
<tr>
<td>IM-LPO</td>
<td>0-10-500 km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate</td>
<td>soft landing / cheap take-off (s&amp;r)</td>
</tr>
<tr>
<td>IM-ALPO</td>
<td>0-70-500 km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>enhanced landing / take-off sites, fly-byes</td>
</tr>
<tr>
<td>AFF</td>
<td>50-200 km</td>
<td>2B-P</td>
<td>LT-HT</td>
<td>expensive</td>
<td>fast coverage</td>
</tr>
<tr>
<td>QSO</td>
<td>25-200 km</td>
<td>2B-P</td>
<td>no</td>
<td>no</td>
<td>long parking, mapping, comms-relay</td>
</tr>
</tbody>
</table>
# Mission Opportunities to Phobos: Summary

## Mission Scenario

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Altitude</th>
<th>Model</th>
<th>Propulsion</th>
<th>Station-Keeping</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phobostrack&amp;GM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AEP</td>
<td>&lt;70km</td>
<td>C3B</td>
<td>HT</td>
<td>high GNC load</td>
<td>dedicated operations, long observation</td>
</tr>
<tr>
<td></td>
<td>&gt;70 km y</td>
<td>E3B</td>
<td>SEP</td>
<td>cheap</td>
<td></td>
</tr>
<tr>
<td>SS-VDCO</td>
<td>&lt;10km</td>
<td>C3B</td>
<td>HT</td>
<td>expensive</td>
<td>fixed lighting conditions, close observation</td>
</tr>
<tr>
<td>LPO</td>
<td>&lt;10km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate GH and NAV</td>
<td>comm-bridge, radiation protection, approach</td>
</tr>
<tr>
<td>ALPO</td>
<td>&gt;10km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>measurements, soft landing, cheap take-off (s&amp;n)</td>
</tr>
<tr>
<td>IM-LPO</td>
<td>0-10-500km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate GH and NAV</td>
<td>enhanced landing/take-off sites, fly-byes</td>
</tr>
<tr>
<td>IM-ALPO</td>
<td>0-70-500km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td></td>
</tr>
<tr>
<td>AFF</td>
<td>50-200km</td>
<td>2B-P</td>
<td>LT-HT</td>
<td>expensive</td>
<td>fast coverage, long parking, mapping, comms-relay</td>
</tr>
<tr>
<td>QSO</td>
<td>25-200km</td>
<td>2B-P</td>
<td>no</td>
<td>no</td>
<td></td>
</tr>
</tbody>
</table>
## Mission Opportunities to Phobos: Summary

### Mission Scenario

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Altitude</th>
<th>Model</th>
<th>Propulsion</th>
<th>Station-Keeping</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Phobos track &amp; GM</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AEP</td>
<td>&lt;70km</td>
<td>C3B</td>
<td>HT</td>
<td>high GNC load</td>
<td>dedicated operations</td>
</tr>
<tr>
<td></td>
<td>&gt;70 km y</td>
<td>E3B</td>
<td>SEP</td>
<td>cheap</td>
<td>long observation</td>
</tr>
<tr>
<td>SS-VDCO</td>
<td>&lt;10km</td>
<td>C3B</td>
<td>HT</td>
<td>expensive</td>
<td>fixed lighting conditions</td>
</tr>
<tr>
<td>LPO</td>
<td>&lt;10km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate GH and NAV</td>
<td>close observation, comm-bridge, radiation protection</td>
</tr>
<tr>
<td>ALPO</td>
<td>&gt;10km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>approach, measurements</td>
</tr>
<tr>
<td>IM-LPO</td>
<td>0-10-500km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate GH and NAV</td>
<td>soft landing / cheap take-off (s&amp;r)</td>
</tr>
<tr>
<td>IM-ALPO</td>
<td>0-70-500km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>enhanced landing / take-off sites, fly-byes</td>
</tr>
<tr>
<td>AFF</td>
<td>50-200km</td>
<td>2B-P</td>
<td>LT-HT</td>
<td>expensive</td>
<td>fast coverage</td>
</tr>
<tr>
<td>QSO</td>
<td>25-200km</td>
<td>2B-P</td>
<td>no</td>
<td>no</td>
<td>long parking, mapping, comms-relay</td>
</tr>
</tbody>
</table>

---

**15/06/2015**

Mattia Zamaro
## Mission Opportunities to Phobos: Summary

### Mission Scenario

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Altitude</th>
<th>Model</th>
<th>Propulsion</th>
<th>Station-Keeping</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phobos track&amp;GM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AEP</td>
<td>&lt;70 km</td>
<td>C3B</td>
<td>HT</td>
<td>high GNC load</td>
<td>dedicated operations</td>
</tr>
<tr>
<td></td>
<td>&gt;70 km</td>
<td>E3B</td>
<td>SEP</td>
<td>cheap</td>
<td>long observation</td>
</tr>
<tr>
<td>SS-VDCO</td>
<td>&lt;10 km</td>
<td>C3B</td>
<td>HT</td>
<td>expensive</td>
<td>fixed lighting conditions</td>
</tr>
<tr>
<td>LPO</td>
<td>&lt;10 km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate</td>
<td>close observation, comm-bridge, radiation protection</td>
</tr>
<tr>
<td>ALPO</td>
<td>&gt;10 km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>approach, measurements</td>
</tr>
<tr>
<td>IM-LPO</td>
<td>0-10-500km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate</td>
<td>soft landing / cheap take-off (s&amp;r)</td>
</tr>
<tr>
<td>IM-ALPO</td>
<td>0-70-500km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>enhanced landing / take-off sites, fly-byes</td>
</tr>
<tr>
<td>descent&amp;landing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mapping &amp; GH measurements</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AFF</td>
<td>50-200km</td>
<td>2B-P</td>
<td>LT-HT</td>
<td>expensive</td>
<td>fast coverage</td>
</tr>
<tr>
<td>QSO</td>
<td>25-200km</td>
<td>2B-P</td>
<td>no</td>
<td>no</td>
<td>long parking, mapping, comms-relay</td>
</tr>
</tbody>
</table>

15/06/2015
Mattia Zamaro
# Mission Opportunities to Phobos: Summary

## Mission Scenario

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Altitude</th>
<th>Model</th>
<th>Propulsion</th>
<th>Station-Keeping</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Phobostack&amp;GM</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AEP</td>
<td>&lt;70km</td>
<td>C3B</td>
<td>HT</td>
<td>high GNC load</td>
<td>dedicated operations</td>
</tr>
<tr>
<td></td>
<td>&gt;70 km</td>
<td>E3B</td>
<td>SEP</td>
<td>cheap</td>
<td>long observation</td>
</tr>
<tr>
<td>SS-VDCO</td>
<td>&lt;10km</td>
<td>C3B</td>
<td>HT</td>
<td>expensive</td>
<td>fixed lighting conditions</td>
</tr>
<tr>
<td><strong>Observation&amp;Relay</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LPO</td>
<td>&lt;10km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate GH and NAV</td>
<td>close observation, comm-bridge, radiation protection</td>
</tr>
<tr>
<td>ALPO</td>
<td>&gt;10km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>approach, measurements</td>
</tr>
<tr>
<td>IM-LPO</td>
<td>0-10-500km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate GH and NAV</td>
<td>soft landing / cheap take-off (s&amp;r)</td>
</tr>
<tr>
<td>IM-ALPO</td>
<td>0-70-500km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>enhanced landing/take-off sites, fly-byes</td>
</tr>
<tr>
<td><strong>Descent&amp;Landing</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AFF</td>
<td>50-200km</td>
<td>2B-P</td>
<td>LT-HT</td>
<td>expensive</td>
<td>fast coverage</td>
</tr>
<tr>
<td>QSO</td>
<td>25-200km</td>
<td>2B-P</td>
<td>no</td>
<td>no</td>
<td>long parking, mapping, comms-relay</td>
</tr>
</tbody>
</table>

15/06/2015
Mattia Zamaro
## Mission Opportunities to Phobos: Summary

### Mission Scenario

<table>
<thead>
<tr>
<th></th>
<th>Orbit</th>
<th>Altitude</th>
<th>Model</th>
<th>Propulsion</th>
<th>Station-Keeping</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Phobos track &amp; GM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>AEP</td>
<td>&lt;70 km</td>
<td>C3B</td>
<td>HT</td>
<td>high GNC load</td>
<td>dedicated operations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;70 km</td>
<td>E3B</td>
<td>SEP</td>
<td>cheap</td>
<td>long observation</td>
</tr>
<tr>
<td></td>
<td>SS-VDCO</td>
<td>&lt;10 km</td>
<td>C3B</td>
<td>HT</td>
<td>expensive</td>
<td>fixed lighting conditions</td>
</tr>
<tr>
<td></td>
<td>observation &amp; relay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LPO</td>
<td>&lt;10 km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate</td>
<td>close observation, comm-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>GH and NAV</td>
<td>bridge, radiation protection</td>
</tr>
<tr>
<td></td>
<td>ALPO</td>
<td>&gt;10 km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>approach, measurements</td>
</tr>
<tr>
<td></td>
<td>IM-LPO</td>
<td>0-10-500 km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate GH and NAV</td>
<td>soft landing / cheap take-off (s&amp;r)</td>
</tr>
<tr>
<td></td>
<td>IM-ALPO</td>
<td>0-70-500 km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>enhanced landing/ take-off sites, fly-byes</td>
</tr>
<tr>
<td></td>
<td>descent &amp; landing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>AFF</td>
<td>50-200 km</td>
<td>2B-P</td>
<td>LT-HT</td>
<td>expensive</td>
<td>fast coverage</td>
</tr>
<tr>
<td></td>
<td>QSO</td>
<td>25-200 km</td>
<td>2B-P</td>
<td>no</td>
<td>no</td>
<td>long parking, mapping, comms-relay</td>
</tr>
</tbody>
</table>

15/06/2015

Mattia Zamaro
Mission Opportunities to Phobos: Summary

<table>
<thead>
<tr>
<th>Mission Scenario</th>
<th>Orbit</th>
<th>Altitude</th>
<th>Model</th>
<th>Propulsion</th>
<th>Station-Keeping</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phobos track&amp;GM</td>
<td>AEP</td>
<td>&lt;70 km</td>
<td>C3B</td>
<td>HT</td>
<td>high GNC load</td>
<td>dedicated operations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;70 km</td>
<td>E3B</td>
<td>SEP</td>
<td>cheap</td>
<td>long observation</td>
</tr>
<tr>
<td></td>
<td>SS-VDCO</td>
<td>&lt;10 km</td>
<td>C3B</td>
<td>HT</td>
<td>expensive</td>
<td>fixed lighting conditions</td>
</tr>
<tr>
<td>observation&amp;relay</td>
<td>LPO</td>
<td>&lt;10 km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate</td>
<td>close observation, comm-bridge, radiation protection</td>
</tr>
<tr>
<td></td>
<td>ALPO</td>
<td>&gt;10 km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>approach, measurements</td>
</tr>
<tr>
<td>descent&amp;landing</td>
<td>IM-LPO</td>
<td>0-10-500km</td>
<td>E3B-GH</td>
<td>no</td>
<td>cheap, accurate</td>
<td>soft landing / cheap take-off (s&amp;r)</td>
</tr>
<tr>
<td></td>
<td>IM-ALPO</td>
<td>0-70-500km</td>
<td>E3B-GH</td>
<td>LT-HT</td>
<td>light GH and NAV</td>
<td>enhanced landing/take-off sites, fly-byes</td>
</tr>
<tr>
<td>mapping &amp; GH measurements</td>
<td>AFF</td>
<td>50-200km</td>
<td>2B-P</td>
<td>LT-HT</td>
<td>expensive</td>
<td>fast coverage</td>
</tr>
<tr>
<td></td>
<td>QSO</td>
<td>25-200km</td>
<td>2B-P</td>
<td>no</td>
<td>no</td>
<td>long parking, mapping, comms-relay</td>
</tr>
</tbody>
</table>