Optimal Operational Planning Applied to a Small Phobos Lander

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Motivation

- Interplanetary missions: very constrained (energy, comms, etc.)
- CubeSats: very constrained (size, mass, etc.)
- Interplanetary CubeSats: Are they feasible? How to optimize?
- Problem: Heuristics and budgets are not sufficient for these complex, highly-constrained missions!
- Solution: Model-based approaches that consider constraints, operations, and dynamics for mission and vehicle optimization

RAX-1 CubeSat, launched 2010
[Image Credit: MXL Website]

Deep Space Exploration
[Image Credit: National Geographic]
Contributions
What’s covered in this talk

- Analytical model framework
  - Goal, Decisions, Constraints, Dynamics
  - Enables assessment, optimization, sensitivity analysis
- Optimization of interplanetary mission (Phobos lander)
  - Compare two communication architectures
  - Variable vs. constant rate communication
  - Design space exploration- data rates, power, antenna gains
Framework Elements:

- **Goal**: maximize data downloaded
- **Decisions**: payload and communication operations
- **Constraints**: opportunities, storage capacity
- **Dynamics**:
  - Orbital- Simulation Tool Kit (STK)
  - Energy Acquisition- solar trends, panel design
  - Energy Consumption- nominal, payload, download ops
  - Link Budget- distances, communication systems

![Diagram showing the interaction of energy and data dynamics]

- **Payload** (instruments)
- **Communication** (radios, antennae)
- **Power system** (solar panels, battery)
Phobos-Lander Mission
An example interplanetary mission application

- **Mission Objectives (motivated by *Decadel Survey, 2011*)**
  - Primary: Collect soil samples for composition analysis
  - Secondary: Radiation, thermal, and seismic analysis
- **Science Instruments**: penetrator, mass spectrometer, seismometer, heat probe, docimeter
- **Subsystems**: power, ADCS, thermal, propulsion
- **Location**: $\phi = 0^\circ$, $\lambda = 0^\circ$ on Phobos (facing Mars)

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*Schematic of Phobos CubeSat*

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1 The Decadel Survey emphasized exploring small bodies such as Phobos to investigate how the chemical and physical properties and processes shaped the origins and evolution of the solar system.
Eclipse Assessment
Energy generation potential is a function of eclipse times

Individual eclipse durations
(Epoch: January 2016)

- Eclipse due to rotation of Mars about Sun and Martian eclipse
- Dynamic eclipse durations: challenging for operational planning!
Communication Architectures
Proximity: Phobos-Lander via ExoMars orbiter
ExoMars orbit: perigee of 255 km, apogee of 320 km, and inclination of 92.7°
Communication Architectures
Long-distance: Phobos-Lander Directly to DSN
Using three 34 meter DSN Dishes
Access Time
Time available for downlink

**Duration of ExoMars passes**

- Durations are dynamic and periodic
- Access times every sol (sol = 24.66 hours):
  - Phobos lander to ExoMars: average 6.6 hours/sol
  - Phobos lander to DSN: average 9.7 hours/sol

**Duration of DSN passes**
Short-term range trends due to ExoMars and Phobos orbits

Range has significant impact on data rate (factor of five)

Range from lander to ExoMars Orbiter

UHF data rate as a function of range
Communication to ExoMars Orbiter
Optimal solutions for dynamic and constant-rate communication (48 hours)
• Long duration range variance due to Martian and Earth years
• Data rate is very low, highly dependent on transmit antenna gain

**Range from lander to DSN**

**X-band data rate as a function of range**
Communication to Earth DSN
Optimal solutions: dynamic rate, variable transmit antenna gain (48 hours)

- Variable rate similar to constant rate due to constant distance
- 20% of time spent communicating to DSN
- Logistical, financial challenges associated with DSN
Effect of Variable Power Collection
Communication to Mars Orbiter (48 hours)

<table>
<thead>
<tr>
<th>Planet</th>
<th>Units</th>
<th>Mercury</th>
<th>Venus</th>
<th>Earth</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Solar Radiation</td>
<td>W/m²</td>
<td>10,359</td>
<td>2,611.5</td>
<td>1,367</td>
<td>603.5</td>
</tr>
<tr>
<td>Collected Power</td>
<td>W</td>
<td>161.6004</td>
<td>40.74</td>
<td>21.33</td>
<td>9.41</td>
</tr>
</tbody>
</table>

\( \text{Collected Power} \approx \frac{161.6004}{A} \)\(^2 \quad (1) \)

\( A = 0.06cm^2 \)

\( \text{Dynamic Rate} \)
\( \text{Constant Rate, 128 kbps} \)

\( \text{Data Downloaded, MBytes} \)
\( \text{Collected Power, Watts} \)

\( 10^1 \quad 10^2 \)
Conclusions
.. and Extensions

- Analytic modeling framework for analysis and optimization
- Applied model to assess feasibility, optimize, compare
- Demonstrated advantages of variable rate and proximity communications for Phobos lander

Extensions:
- Longer duration scenarios (address computational issues)
- More complex networks (i.e. all ExoMars/DSN transmitters/receivers)
- Realistic stochastic communication efficiencies
- Vehicle and network design optimization
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- Dr. Amy Cohn, Kyle Gilson, Derek Dalle
- University of Michigan RAX Team for their input and support.
- CubeSat and amateur radio community
Analytic Optimization Formulation

\[
\begin{align*}
\max & \sum_{i \in I} \sum_{o \in O_i} \eta_{io} q_{io} \\
\text{s.t.} & \\
\sum_{o \in O_i} x_{io} & \leq 1 \quad \forall i \in I \\
q_{io} & \leq \Delta t_i \phi_o x_{io} \quad \forall i \in I, o \in O_i \\
e_0 & = e_{\text{start}} \\
e_{\text{min}} \leq e_i & \leq e_{\text{max}} \quad \forall i \in I \\
e_{i+1} & = e_i - \beta_i^e y_i + \delta_i^{e+} - \delta_i^{e-} - \sum_{o \in O_i} \alpha_{io} q_{io} - h_i^e \\
d_0 & = d_{\text{start}} \\
d_{\text{min}} \leq d_i & \leq d_{\text{max}} \quad \forall i \in I \\
d_{i+1} & = d_i + \beta_i^d y_i + \delta_i^{d+} - \delta_i^{d-} + \sum_{o \in O_i} q_{io} - h_i^d \
\end{align*}
\]
Phobos Lander Mission Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Battery Capacity</td>
<td>336</td>
<td>kJ</td>
</tr>
<tr>
<td>Maximum Depth of Discharge</td>
<td>20</td>
<td>%</td>
</tr>
<tr>
<td>Maximum Data Capacity</td>
<td>25</td>
<td>MBytes</td>
</tr>
<tr>
<td>Power Collected in Sun on Phobos</td>
<td>9.4</td>
<td>W</td>
</tr>
<tr>
<td>Power Required for Nominal Operations</td>
<td>2.8</td>
<td>W</td>
</tr>
<tr>
<td>Power Required During Experiments</td>
<td>7.5</td>
<td>W</td>
</tr>
<tr>
<td>Data Collection Rate for Nominal Operations</td>
<td>0.5</td>
<td>kbps</td>
</tr>
<tr>
<td>Data Collection Rate During Experiments</td>
<td>400</td>
<td>kbps</td>
</tr>
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# Link Budget Analysis

<table>
<thead>
<tr>
<th>Link Budget Parameter</th>
<th>Symbol</th>
<th>UHF to ExoMars TGO</th>
<th>X-Band to DSN</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>$f$</td>
<td>401</td>
<td>8,425</td>
<td>MHz</td>
</tr>
<tr>
<td>Propagation Path Distance</td>
<td>$S$</td>
<td>$8 \cdot 10^3$</td>
<td>$1 \cdot 10^8$</td>
<td>km</td>
</tr>
<tr>
<td>Transmitter Power</td>
<td>$P_t$</td>
<td>10</td>
<td>12</td>
<td>dBW</td>
</tr>
<tr>
<td>Transmit Antenna Gain</td>
<td>$G_t$</td>
<td>0</td>
<td>0</td>
<td>dBi</td>
</tr>
<tr>
<td>Transmit Line Losses</td>
<td>$L_t$</td>
<td>2</td>
<td>1</td>
<td>dBi</td>
</tr>
<tr>
<td>Equivalent Isotropic Radiated Power</td>
<td>EIRP</td>
<td>8</td>
<td>9.8</td>
<td>dBW</td>
</tr>
<tr>
<td>Receive Antenna Gain</td>
<td>$G_r$</td>
<td>12</td>
<td>66.8</td>
<td>dBi</td>
</tr>
<tr>
<td>Pointing Error Loss</td>
<td>$L_e$</td>
<td>1</td>
<td>1</td>
<td>dB</td>
</tr>
<tr>
<td>Polarization losses</td>
<td>$L_p$</td>
<td>1</td>
<td>1</td>
<td>dB</td>
</tr>
<tr>
<td>Receive Line Losses</td>
<td>$L_r$</td>
<td>2</td>
<td>0.4</td>
<td>dBi</td>
</tr>
<tr>
<td>Space Loss</td>
<td>$L_s$</td>
<td>162.6</td>
<td>270.9</td>
<td>dB</td>
</tr>
<tr>
<td>Received Power</td>
<td>$P_r$</td>
<td>-144.6</td>
<td>-196.4</td>
<td>dBW</td>
</tr>
<tr>
<td>System Noise Temperature</td>
<td>$T_s$</td>
<td>500</td>
<td>500</td>
<td>K</td>
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<tr>
<td>Carrier-to-Noise Spectral Power Density Ratio</td>
<td>$C/N_0$</td>
<td>57.0</td>
<td>5.2</td>
<td>dB</td>
</tr>
<tr>
<td>Minimum $E_b/N_0$</td>
<td>$E_b/N_0,\text{min}$</td>
<td>2.7</td>
<td>1.24</td>
<td>dB</td>
</tr>
<tr>
<td>Link Margin</td>
<td>$M$</td>
<td>3</td>
<td>3</td>
<td>dB</td>
</tr>
<tr>
<td>Feasible Data Rate</td>
<td>$r$</td>
<td>136,239</td>
<td>1.3</td>
<td>bits/sec</td>
</tr>
</tbody>
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