Using Automated Scheduling for Analysis of the EMIT Mission

Amruta Yelamanchili, Steve Chien, Christopher Wells, Joseph Russino, Robert Green, Bogdan Oaida, David R. Thompson
Jet Propulsion Laboratory, California Institute of Technology
Mission Background

- **Earth Surface Mineral Dust Source Investigation**¹
- Scheduled for launch to the International Space Station in 2022
- Spectrometer in the visible and shortwave-infrared (VSWIR)
- Goal is to map the surface mineralogy of dust source regions to improve atmospheric models

---

CLASP Background

- **Compressed Large-scale Activity Scheduling and Planning System**
- Chooses orientation and on/off times of space-based instruments that can be modeled as pushbrooms
- Uses the NAIF SPICE toolkit for geometric reasoning
- Squeaky wheel optimization built in but custom schedulers can be plugged in

---

CLASP Inputs

- Spacecraft ephemeris in the form of spice kernels
- Instrument field of view/pointing capability
- Campaigns
  - Point or polygon on surface of planet
  - Geometric/illumination Constraints

CLASP for Mission Analysis

- Automated Scheduling by CLASP has been used to analyze the effects of variety of factors on EMIT mission success:
  - Observation policy design
  - Hardware configurations
  - Effect of clouds on coverage
Observation Policy

• In earlier mission planning phase, EMIT instrument had pointing capability
• How to prioritize observations according to pointing and sun angle?
• Highest quality data taken sun is closer to zenith, and instrument is pointed closer to nadir
Hardware Configuration: Pointing Mirror

- Examined impact of removing pointing capability on coverage
- Found coverage with:
  - theoretical upperbound with wide swath
  - pointing capability with narrow swath
  - no pointing capability with narrow swath
- Found that with impact of clouds and ISS orbit, pointing capability does not achieve much higher coverage
Effects of Clouds

- Onboard cloud screening software will excise cloudy observations
- Analysed effects on coverage achievable and onboard data volume using mask of cloud probabilities

MODIS Cloud Probability Mask
Darker regions have lower probability of clouds

Coverage Success Criteria

• Given a base target mask, abstract the mask into 100 km x 100 km “bins” with a resolution of 5 km target points within each region.

• Analysis regarding two criteria was done:
  • How much of each bin should be covered with cloud free acquisitions to be considered successful.
  • Which bins contained enough of the target mask to be of value in the coverage success metric.
100 km regions overlaid on initial target mask
Probability of Covering a single 5 km gridpoint

- CLASP produced a schedule over a year, observing each target point whenever illumination conditions met
- Given some 5 km grid point
  - with $N$ observations
  - with a cloud probability of $C$ obtained from the MODIS cloud mask
  - the probability $P$ that the grid point will have at least one non-cloudy observation is
    - $P = 1.0 - C^N$
    - i.e. for grid point with 0.30 cloud probability and 4 observations, $P = 1.0 - 0.30^4 = 0.9919 = 99.19\%$
5 x 5km grid point

4 observations

0.30 cloud probability

From cloud probability mask

0.9919 probability of having at least one non-cloudy observation

100 x 100km bin
Probability of covering a given percentage of a 100 km region

- Given a 100 x 100 km bin
  - with 400 contained 5 x 5 km grid points
  - with each grid point $g$ having some probability $P_g$ of having at least one non-cloudy observation
- Given some threshold $T$ of percentage of covered grid points in a bin needed to satisfy the bin
  - The bin has some probability $Q$ that $T$ or more of its contained grid points have at least one non-cloudy observation
    - $Q = \sum_{i=T}^{400} EXACT(i)$
      - Where $EXACT(i)$ is the probability that exactly $i$ of the grid points in the bin will have at least one non-cloudy observation
      - Calculated as the $(400 - i)\text{'th coefficient of } \prod(P_gx + (1 - P_g))\text{ for all grid points } g \text{ in the bin}$
Probabilities for each 5 x 5 grid point

Threshold of 80% bin coverage needed

Probability of the 100 x 100km bin having at least 80% of grid points covered

ex. 0.93

<table>
<thead>
<tr>
<th>0.99</th>
<th>0.82</th>
<th>0.83</th>
<th>0.74</th>
<th>0.21</th>
<th>...</th>
<th>...</th>
<th>...</th>
<th>...</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.59</td>
<td>0.61</td>
<td>0.72</td>
<td>0.61</td>
<td>0.37</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>0.71</td>
<td>0.65</td>
<td>0.63</td>
<td>0.91</td>
<td>0.50</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Each 5 x 5km grid point has some probability of having at least one non-cloudy observation
Cloud cover probabilities (overall coverage)

- Given a set $M$ of 100 x 100km bins, it has some probability $R$ of having exactly $V$ percent coverage (given some threshold $T$)
  - Where $V$ (percent coverage) can be any portion of the number of bins
  - Ex. For 600 bins $V$ could be 0/600, 1/600, … 599/600, or 600/600
Confirming Probability Propagation

• To confirm that our propagation of the cloud cover probabilities is correct, we compared it to a realization of the schedule
  • For each scheduled observation, lookup its cloud probability and with that chance remove it from the schedule
  • For several different threshold values
    • For each 5 x 5km grid point check if at least one observation is remaining
    • For each 100 x 100km bin check if at least the threshold number of grid points have at least one observation
    • See what percentage of the 100 x 100km bins are satisfied
  • Plot realization results against propagated probabilities
5 x 5km grid point

4 observations

0.30 cloud probability

From `cloudprobs.csv` grid of 1° x 1° squares

<table>
<thead>
<tr>
<th>Observation 1</th>
<th>0.3 chance to be cloudy</th>
<th>Not cloudy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observation 2</td>
<td>0.3 chance to be cloudy</td>
<td>Cloudy</td>
</tr>
<tr>
<td>Observation 3</td>
<td>0.3 chance to be cloudy</td>
<td>Not cloudy</td>
</tr>
<tr>
<td>Observation 4</td>
<td>0.3 chance to be cloudy</td>
<td>Not cloudy</td>
</tr>
</tbody>
</table>

At least one non-cloudy observation (3)

100 x 100km bin

...
Number of 5 x 5 grid points with at least one non-cloudy observation

Threshold of 80% bin coverage needed

The bin is covered above 80%

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>X</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Each 5 x 5km grid point either has at least one non-cloudy observation or not
Propagated Probabilities vs Realization Results

Dashed line indicates the coverage percentage achieved in the realization, for the same threshold values as the propagated probabilities
Bin Inclusion Threshold

This bin contains only a few target grid points.

This bin contains a lot of target grid points.
Comparison of different bin inclusion thresholds

Each line is a realization of a schedule using a different threshold for the number of 5 x 5km grids in the original target map need to be in a 100 x 100km bin to consider the bin
Conclusion

• Automated Scheduling used to aid in many aspects of mission design for EMIT
  • Observation Design
  • Hardware configurations
  • Effect of Clouds on Coverage