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• Planned launch in December 2020: Arrival at EV5 in October 2022: Return to Earth (with boulder) in late 2025
• Light times necessitate autonomous landing, boulder retrieval and ascent
Transition from the 5 km hold point to 200 m waypoint on pre-defined burn
- 200 m waypoint to 50 m also performed on a pre-defined burn
- 50 m to 20 m descent and asteroid spin rate matching performed with closed loop control
- No thrusting towards surface after 20 m
Overview

M. Shoemaker et al., AAS/AIAA Space Flight Mechanics Meeting, Napa, CA, 2016
Ground-based Mapping

- Using higher altitude narrow-FOV survey images.
- Stereophotoclinometry (SPC) generates digital elevation maps.
- Process has mission heritage over ~25 years.
Landmark and Maplet Definitions

Terminology:
• Maplets – small maps that tile the surface
• Landmark – origin of a maplet
Onboard Landmark Measurements

- Uses wide-FOV images during descent.
- Also based on SPC-heritage ground-based methods.
- Our goal is to implement in flight SW onboard.
Step 1:
- Transform subset of image pixels that contain the maplet into maplet-space
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Step 2:
- Illuminate the onboard maplet in maplet space, using an illumination model and maplet heights (slopes) and albedo.
Landmark Measurement Process

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- Illuminate the onboard maplet in maplet space, using an illumination model and maplet heights (slopes) and albedo.
Step 3:
• 2D search in maplet-space to find shift that maximizes correlation between these two

Step 4:
• Transform solved-for shift from maplet space to image space, becomes the new $(s, l)$ measurements to the landmark
Performance Characterization

- How do errors in these parameters affect the errors in the landmark \((s, l)\) measurements?
- These errors represent onboard navigation error, camera model errors, and asteroid model errors.

<table>
<thead>
<tr>
<th>Parameter or state to perturb</th>
<th>1-σ std applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asteroid-relative spacecraft position (r_{sc}), each component</td>
<td>0.1667 m</td>
</tr>
<tr>
<td>Asteroid-relative spacecraft attitude, each component</td>
<td>0.05 deg</td>
</tr>
<tr>
<td>Asteroid-relative landmark position (r_{lm}), each component</td>
<td>3.33 cm</td>
</tr>
<tr>
<td>Maplet terrain height (z(x, y))</td>
<td>3.33 mm</td>
</tr>
<tr>
<td>Maplet terrain albedo (a(x, y))</td>
<td>0.047</td>
</tr>
<tr>
<td>Camera model pixel skew (K_{yx})</td>
<td>(1 \times 10^{-5})</td>
</tr>
<tr>
<td>Camera model principle coordinates ((s_0, l_0))</td>
<td>0.1667 pixels</td>
</tr>
<tr>
<td>Camera model focal length (f)</td>
<td>0.004 mm</td>
</tr>
<tr>
<td>Camera model distortion coefficients (\epsilon)</td>
<td>((1 \times 10^{-5}, 1 \times 10^{-7}, 1 \times 10^{-5}, 1 \times 10^{-5}, 0, 0))</td>
</tr>
<tr>
<td>Asteroid-relative sun vector direction, RA and DEC</td>
<td>0.3 deg</td>
</tr>
</tbody>
</table>
Performance Characterization

- Selected 12 landmarks and tested at 50-m altitude

- Camera and Detector Parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector horiz. resolution</td>
<td>2592 pixels</td>
</tr>
<tr>
<td>Detector vert. resolution</td>
<td>1944 pixels</td>
</tr>
<tr>
<td>Focal length, f</td>
<td>7.68 mm</td>
</tr>
<tr>
<td>Detector pixel dimensions</td>
<td>2.2 x 2.2 microns</td>
</tr>
<tr>
<td>Camera horiz. FOV</td>
<td>40.7 deg</td>
</tr>
<tr>
<td>Camera vert. FOV</td>
<td>31.1 deg</td>
</tr>
</tbody>
</table>
Performance Characterization

- The illuminated maplet data from these 12 landmarks at 50-m alt.:

(a) B01980  
(b) B02176  
(c) B02246  
(d) B01585  
(e) B01909  
(f) B02235  
(g) B02690  
(h) B02631  
(i) B02642  
(j) B01926  
(k) B01536  
(l) B01595
• Ran Monte Carlo sims (with Latin Hypercube Sampling) of 500 runs per landmark:

<table>
<thead>
<tr>
<th>L-map ID</th>
<th>Sample error mean [pix]</th>
<th>Line error mean [pix]</th>
<th>Sample error std [pix]</th>
<th>Line error std [pix]</th>
<th>Num. not found</th>
<th>Num. below thresh.</th>
<th>Success Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>B01980</td>
<td>-0.136</td>
<td>0.048</td>
<td>0.062</td>
<td>0.096</td>
<td>42</td>
<td>15</td>
<td>0.89</td>
</tr>
<tr>
<td>B02176</td>
<td>-0.163</td>
<td>0.053</td>
<td>0.028</td>
<td>0.066</td>
<td>23</td>
<td>25</td>
<td>0.90</td>
</tr>
<tr>
<td>B02246</td>
<td>-0.111</td>
<td>-0.027</td>
<td>0.041</td>
<td>0.082</td>
<td>31</td>
<td>18</td>
<td>0.90</td>
</tr>
<tr>
<td>B01585</td>
<td>-0.041</td>
<td>0.054</td>
<td>0.033</td>
<td>0.082</td>
<td>36</td>
<td>20</td>
<td>0.89</td>
</tr>
<tr>
<td>B01909</td>
<td>-0.049</td>
<td>0.081</td>
<td>0.043</td>
<td>0.085</td>
<td>36</td>
<td>15</td>
<td>0.90</td>
</tr>
<tr>
<td>B02235</td>
<td>-0.139</td>
<td>0.068</td>
<td>0.025</td>
<td>0.071</td>
<td>39</td>
<td>12</td>
<td>0.90</td>
</tr>
<tr>
<td>B02690</td>
<td>-0.052</td>
<td>-0.056</td>
<td>0.043</td>
<td>0.097</td>
<td>52</td>
<td>16</td>
<td>0.86</td>
</tr>
<tr>
<td>B02631</td>
<td>-0.107</td>
<td>-0.069</td>
<td>0.038</td>
<td>0.076</td>
<td>37</td>
<td>13</td>
<td>0.90</td>
</tr>
<tr>
<td>B02642</td>
<td>-0.117</td>
<td>0.007</td>
<td>0.058</td>
<td>0.113</td>
<td>46</td>
<td>15</td>
<td>0.88</td>
</tr>
<tr>
<td>B01926</td>
<td>-0.193</td>
<td>0.019</td>
<td>0.032</td>
<td>0.078</td>
<td>49</td>
<td>6</td>
<td>0.89</td>
</tr>
<tr>
<td>B01536</td>
<td>-0.208</td>
<td>0.118</td>
<td>0.037</td>
<td>0.083</td>
<td>35</td>
<td>19</td>
<td>0.89</td>
</tr>
<tr>
<td>B01595</td>
<td>-0.114</td>
<td>0.111</td>
<td>0.041</td>
<td>0.080</td>
<td>33</td>
<td>25</td>
<td>0.88</td>
</tr>
</tbody>
</table>
Repeated Monte Carlo runs at 30-sec. time steps during part of descent for 3 landmarks:

(a) L-map B01980
(b) L-map B02176
(c) L-map B02246

Errors do not change significantly over these tests
• The ~90% success rate in these tests is caused by spacecraft position and attitude navigation errors causing the projected maplet data to only partially overlap.
• Also, the onboard rendering methods derived from SPC only approximate the surface shadows.

Retina (Relative Terrain Imaging Navigation) is our onboard version being developed with several modifications:

• Improved shadow predictions for onboard renderer.
• Image-space correlations (vs. maplet-space correlations) for more robust data overlaps.
• Goal is to implement on GSFC SpaceCube

Preliminary Retina results:
• Similar MC simulations resulted in 100% success rate and similar sub-pixel errors.
Summary

• Presented the SPC-derived methods for landmark measurements.

• Showed MC simulation results of perturbing the navigational and model parameters. Resulting errors in line-of-sight landmark measurements were acceptable, but more work needs to be done to improve success rate.

• Introduced Retina algorithms and ongoing work at GSFC for eventual flight SW implementation.