Autonomous Navigation Performance During The Hartley 2 Comet Flyby

EPOXI Mission

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Autonomous Navigation

What?
• The capability to estimate a spacecraft trajectory and calculate maneuvers entirely onboard

Why?
• During high-dynamics events, ground-in-the-loop navigation is not practical due to long transmission and ground processing times

How?
• Optical measurements are recorded by a spacecraft camera

Implementation on EPOXI mission
• AutoNav C-based software package performs image processing, state estimation, and maneuver calculation onboard
• Attitude control uses AutoNav trajectory solution to point instruments

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Comet Flybys

- **AutoNav is critical to small body flybys**
  - Small body ephemerides are not known accurately prior to flyby
  - Time of flight errors cannot be resolved until parallax is observed in observations near closest approach
  - Without AutoNav trajectory updates, the comet nucleus must be captured as a mosaic by scanning the camera across the sky

- **EPOXI Hartley 2 Flyby Requirements**
  - Continuously track comet nucleus in 10-mrad field of view
  - ± 3.5 km trajectory knowledge, ± 0.3 seconds time of flight knowledge

<table>
<thead>
<tr>
<th>Giotto</th>
<th>Deep Space 1</th>
<th>Stardust</th>
<th>Deep Impact</th>
<th>Deep Impact/EPOXI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brightness Tracker</td>
<td>AutoNav 40 m/pixel</td>
<td>AutoNav 14.5 m/pixel</td>
<td>AutoNav 7 m/pixel</td>
<td>AutoNav 7 m/pixel</td>
</tr>
</tbody>
</table>
EPOXI Mission Challenges

• Reuse of Deep Impact Spacecraft with new objectives
  1. Imaging is continuous through 700km closest approach (180° slew)
  2. Hartley 2 is smaller, more active, rotating faster
  3. Relative flyby velocity is faster
  4. Different Sun-Comet-S/C geometry

• Attitude bias errors cannot be estimated using Deep Impact version of AutoNav
• Center of brightness observation is offset from true center of mass
• Goal: Track comet nucleus in camera continuously through closest approach

<table>
<thead>
<tr>
<th></th>
<th>Tempel 1</th>
<th>Hartley 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Objective</td>
<td>Observe impact</td>
<td>Observe nucleus</td>
</tr>
<tr>
<td>Observation Gap</td>
<td>E-50 sec to E+40 min</td>
<td>No Gap</td>
</tr>
<tr>
<td>Comet Size</td>
<td>7.6 km x 4.9 km</td>
<td>2.2 km x 0.5 km</td>
</tr>
<tr>
<td>Comet Period</td>
<td>40.7 hours</td>
<td>18.1 hours</td>
</tr>
<tr>
<td>Relative Velocity</td>
<td>10.2 km/s</td>
<td>12.3 km/s</td>
</tr>
<tr>
<td>Solar Phase Angle</td>
<td>64°</td>
<td>77°</td>
</tr>
<tr>
<td>Max Resolution</td>
<td>7 m/pixel</td>
<td>7 m/pixel</td>
</tr>
</tbody>
</table>

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Optical Measurements

Simulated MRI Field of View

- Cameras
  - Medium Resolution Imager (MRI): 10-mrad FOV
  - High Resolution Imager (HRI): 2-mrad FOV
  - 1024 x 1024 pixel CCD

- Observed-Computed Residuals in MRI Pixels:

\[
\text{Residuals} = \text{Observed} (p,l) - \text{Computed} (p,l)
\]

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Uncertainty Sources

1. Position/Velocity errors in ground-based S/C and comet trajectories
2. Comet pole & phase
3. Attitude knowledge errors
   – Ability of startracker & gyroscope instruments to estimate attitude
   – Modes: Nominal (Startracker $\tau=8000s$), Override1 (gyros only), Override2 (Startracker $\tau=100s$)
   – Startracker error is primarily a bias
   – Gyroscope errors include drift, scale factor, and misalignment effects
Monte Carlo Simulation

- Monte Carlo simulation directly applies user-defined **uncertainty models** to the **simulated image** and **attitude** data processed by the **flight code**.
- Output: 3-\(\sigma\) observed-predicted residuals in camera pixels
Approach Phase

- Approach characterized by transition from ground-based trajectory to AutoNav
- Determination of AutoNav start time is a trade between **signal strength** and the penalty of **stale ephemeris errors**.
  - Imaging commenced at E-50 minutes with a 15 second cadence
  - Orbit determination (OD) updates commenced at E-42 minutes with a 1 minute cadence
Encounter Phase

- Encounter characterized by 180° slew through closest approach
- Pre-flyby and post-flyby measurements do not match a dynamic trajectory model due to center of brightness offset and attitude errors

Filter Adjustments
- Case D: Reduce arc length to 8 min
- Case E: Adjust filter weighting of optical data to 100 pixels from E-7min to E+2min
- Case F: Adjust filter velocity sigma from 0.5 m/s to 2.0 m/s
Departure Phase

- Departure characterized by system recovery after the 180° encounter slew
  - Determine AutoNav end time and transition to ground-based trajectory
  - Correct the gyros-only attitude solution with startracker data
  - Allow sufficient time for AutoNav to react to attitude correction
  - Minimize the pointing impact during the post-flyby IR scans.

- Star trackers reincorporated at E+10min during AutoNav outage

Departure Configuration

- E+10min: Override2 Mode (τ=100s)
- E+18min: Nominal Mode (τ=8000s)
- E+30min: Final OD Update
- E+50min: Transition to ground-based trajectory
Flyby Performance

- AutoNav flyby performance well characterized by Monte Carlo simulations
- First OD update corrects 1 pixel in the pixel axis, 12 pixels in the line axis
- Maximum residual of ~20 pixels observed at E+1 min
- ~10 pixel residual during attitude convergence on departure
Questions?
BACKUP
Attitude Issues

- No capability to estimate attitude knowledge bias errors with the version of AutoNav flying on the Deep Impact spacecraft
- Attitude knowledge errors absorbed into position & velocity estimates
- Position and velocity error estimates combine to create a fixed bias profile in the camera

Position estimation errors

**without attitude errors**
- Orbit Plane X (In Plane)
- Orbit Plane Y (Out of Plane)
- Orbit Plane Z (Along Velocity)

**Position estimation errors with attitude errors**
- Orbit Plane X (In-Plane)
- Orbit Plane Y (Out-of-Plane)
- Orbit Plane Z (Along Velocity)

Velocity estimation errors

**with attitude errors**
- Orbit Plane Velocity Estimation Errors

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Flyby State Errors

AutoNav Position Estimate Relative to Reconstruction in Orbit Frame

Requirements Met In All 3 Axes at E-6 min

AutoNav Position Estimate Relative to Reconstruction - ZOOM

MRO EQV Requirement

Closest Approach

AutoNav Velocity Estimate Relative to Reconstruction in Orbit Frame

Attitude Error Absorption

Post-Flyby Correction

Increasing Parallax

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## Error Models

<table>
<thead>
<tr>
<th>Error Model</th>
<th>3-σ Uncertainty</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position Crosstrack</td>
<td>20 km</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Position Downtrack</td>
<td>300 km</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Velocity Crosstrack</td>
<td>5 cm/s</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Velocity Downtrack</td>
<td>5 cm/s</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Comet Pole RA</td>
<td>360 deg</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Comet Pole DEC</td>
<td>180 deg</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Comet Phase</td>
<td>360 deg</td>
<td>Gaussian</td>
</tr>
</tbody>
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<th>3-σ Uncertainty</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Startracker Bias</td>
<td>300 urad, each axis</td>
<td>Uniform</td>
</tr>
<tr>
<td>Star Changeout</td>
<td>100 urad, each axis</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Startracker</td>
<td>50 urad, each axis</td>
<td>Gaussian</td>
</tr>
<tr>
<td>temporal noise</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gyro Drift</td>
<td>500 urad/hr, each axis</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Gyro Scale Factor</td>
<td>183 ppm, each axis</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Gyro Misalignment</td>
<td>80 urad, each axis</td>
<td>Gaussian</td>
</tr>
</tbody>
</table>