Novel Methods of Spacecraft Navigation using X-ray Pulsars

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Outline

• Introduction
• Background to Navigation with Variable Celestial Sources
• Historical Contributions
• Pulsar Phase Tracking Background
• Pulsar Signal Processing
• Novel 3\textsuperscript{rd} Order Phase Tracking
• Analysis and Simulation Results
• Hybrid Energy Navigation and Horizon Crossing Methods
• Conclusions and Future Work
Introduction: Spacecraft Navigation

- GPS (LEO/HEO, GEO)
- Deep Space Navigation
  - DSN
    - 3 radio communication complexes
  - Optical
    - Star tracker
    - Imaging of target planet
- X-ray Pulsar-based Navigation (XNAV)
  - Standard accuracy throughout solar system
  - Potentially autonomous
  - Reduce load on DSN

NASA/CXC/ASU/J. Hester et al.

Images courtesy of NASA
# Variable Celestial Source Attributes for Navigation

<table>
<thead>
<tr>
<th>Source Types</th>
<th>Unique Attributes</th>
<th>Detection Methods and Techniques</th>
<th>Navigation Applications</th>
</tr>
</thead>
</table>
| Radio Pulsar         | • Periodic  
• Numerous  
• Good geometric distribution | • Large aperture radio antenna or dishes                               | • Timing  
• PT scale  
• Position, velocity             |
| X-ray Pulsar         | • Periodic  
• Generally low flux              | • Gas proportional counters  
• Microchannel Plates  
• Scintillating materials  
• CCD and solid-state semiconductors | • Timing  
• PT scale  
• Position, velocity  
• Relative navigation          |
| Gamma-ray Pulsar     | • Periodic  
• Very low flux                    | • Large volume scintillating materials                                 | • Position, velocity                  |
| Bright X-ray Sources | • Aperiodic  
• Numerous  
• Many emit high flux              | • Scintillating materials  
• CCD and solid-state semiconductors  
• Coded aperture masks  
• X-ray telescopes               | • Relative navigation  
• Attitude                        |
| Gamma-ray Bursts     | • Singular event  
• Omnidirectional  
• Extremely high flux              | • Small volume scintillating materials  
• Semiconductors                  | • Relative navigation            |
Introduction to Pulsars

• Spinning neutron stars
• Discovered in radio band in 1967, Hewish and Bell
• Emit radiation throughout the electromagnetic spectrum
• Formed as result of supernova
  • Spin up to high rates
• Strong magnetic field which accelerates charged particles
  • Misalignment of spin and magnetic field axes
Advantages for Navigation

- Millisecond period pulsars (MSPs)
  - Very stable, reliable signals
- Unique periodic pulse profiles
- Good distribution throughout sky
- Relative position considered fixed
- X-ray band requires smaller detectors
- Large catalog of pulsars
  - Astronomical community
Pulsar-based Navigation

- Celestial “lighthouse”
  - Use each pulsar’s unique profile to provide position and velocity measurements
- Measurements from 3 pulsars for 3D state

\[ \Delta t = \frac{\hat{n} \cdot r}{c} + \text{H.O.T.} \]
# Selected Historical Contributions

<table>
<thead>
<tr>
<th>Name</th>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downs</td>
<td>1974</td>
<td>First to propose radio pulsars for spacecraft navigation</td>
</tr>
<tr>
<td>Chester and Butman</td>
<td>1981</td>
<td>Proposed X-ray pulsars for interplanetary navigation</td>
</tr>
<tr>
<td>Wallace</td>
<td>1988</td>
<td>Radio pulsars for Earth navigation</td>
</tr>
<tr>
<td>Wood</td>
<td>1993</td>
<td>X-ray navigation in near Earth orbit</td>
</tr>
<tr>
<td>Hanson</td>
<td>1996</td>
<td>Doctoral thesis on X-ray pulsars for attitude and time</td>
</tr>
<tr>
<td>Sala</td>
<td>2004</td>
<td>ESA feasibility study</td>
</tr>
<tr>
<td>Sheikh</td>
<td>2005</td>
<td>Doctoral thesis giving extensive XNAV study</td>
</tr>
<tr>
<td>Golshan and Sheikh</td>
<td>2007</td>
<td>Previous attempt at phase tracking X-ray pulsar signals</td>
</tr>
<tr>
<td>Emadzadeh</td>
<td>2009</td>
<td>Doctoral thesis on relative navigation using X-ray pulsars</td>
</tr>
<tr>
<td>Hisamoto and Sheikh</td>
<td>2015</td>
<td>Gamma-ray bursts as aids for spacecraft navigation</td>
</tr>
<tr>
<td>Anderson</td>
<td>2021</td>
<td>Doctoral thesis on phase tracking X-ray pulsar signals for navigation</td>
</tr>
<tr>
<td>Various from China</td>
<td>Recent Years</td>
<td>Range of XNAV investigations including filter design and modeling</td>
</tr>
</tbody>
</table>
Flight Experiments

• USA Experient, ARGOS, NRL, 1999
  • Earth orbit attitude determination

• HASP, University of Minnesota, 2012, 2014, 2016, and 2017
  • High altitude balloon experiments

• XPNAV-1, China, 2016
  • Characterized X-ray pulsar signals

• SEXTANT, NASA, 2017
  • Initial real-time demonstration of XNAV on ISS

XNAV is a work in progress with challenges being addressed in research
<table>
<thead>
<tr>
<th></th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Overview of Deep Spacecraft Navigation Methods</strong></td>
<td></td>
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<tr>
<td><strong>Current State of the Art</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>DSN</strong></td>
<td>• Good range and range rate estimates (1 km/ 1 AU)</td>
<td>• Accuracy decreases far from Earth</td>
</tr>
<tr>
<td></td>
<td>• Uses technology available on spacecraft for communication</td>
<td>• Requires Earth-based processing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Increased load from future missions</td>
</tr>
<tr>
<td><strong>Binning</strong></td>
<td>• Good single pulse TOA measurement (km level accuracy)</td>
<td>• Long observation per estimate (10^4 s)</td>
</tr>
<tr>
<td></td>
<td>• Similar to astronomy approach</td>
<td>• Information lost in binning</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• No Doppler frequency estimate</td>
</tr>
<tr>
<td><strong>2nd Order Phase Tracking</strong></td>
<td>• Frequent estimates</td>
<td>• Constant frequency assumption</td>
</tr>
<tr>
<td></td>
<td>• Estimates phase and Doppler frequency (position and velocity)</td>
<td>• Requires large detectors for MSPs (&gt;25 m^2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>3rd Order Phase Tracking</strong></td>
<td>• Allows for changing observed frequency</td>
<td>• Requires initial frequency and frequency derivative (acceleration) estimates (handoff from DSN)</td>
</tr>
<tr>
<td></td>
<td>• Estimates phase, Doppler frequency, and frequency derivative</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Estimates every 100 to 5000 s</td>
<td></td>
</tr>
</tbody>
</table>
Conceptual Flow for Phase Tracking

Pulsar Scheduling

Photon Events

Phase Tracking (MLE – DPLL)

1D range estimates

Extended Kalman Filter

3D navigation state position & velocity
Analysis of Pulsar Signals

• Source signals are faint
  • Many periods between photon arrivals (cannot just detect signal)
  • Diffuse X-ray background and shot noise from pulsar

• For X-ray detectors that record individual events, Poisson statistics dominate the random noise

• Model photon events as a NHPP

\[ \lambda(t) = R_b + (1 - \rho)R_s + \rho R_s h(\phi_{det}(t)) \quad (ph/s) \]

• Observed signal frequency changes with velocity

\[ \phi_{det}(t) = \phi_0 + f_s(t - t_0) + \phi_d(t) \]
Previous Phase Tracking (Golshan & Sheikh, 2007)

- Partition the observed photon events
  - One second blocks
- MLE for initial phase assuming constant frequency
- Second-Order DPLL
  - Provides Doppler frequency estimate
- Good phase and frequency tracking with Crab Pulsar
- Fails for lower flux pulsars
  - Not enough photons accumulate per block
  - Most of the best pulsars for navigation are orders of magnitude lower in flux than the Crab Pulsar
Proposed Phase Tracking Method

- 2\textsuperscript{nd} order Taylor series for Detector Phase
  - Relax constant observed frequency assumption
  - Longer Block Lengths

\[ \phi_{det}(t) = \phi_0 + f(t - t_0) + \frac{f}{2}(t - t_0)^2 \]

- Estimate of frequency and frequency derivative used to form parabolic model for phase
  - Feedback from a 3\textsuperscript{rd} order DPLL
  - Only unknown is $\phi_0$ for MLE
  - Handoff from DSN or GPS
Phase Tracking Simulations (1D range)

- B1821-24, B1937+21, J0218+4232, J0437-4715
  - 4 and 5 orders of magnitude lower flux than Crab
  - Photon times simulated using XPRESS package from ASTER Labs

- Variety of Dynamic Stress Conditions
  - MSL interplanetary cruise trajectory
  - Cislunar transfer trajectory
  - Earth orbits: DirecTV, GPS, and ISS

- Initial condition errors:
  - 1 km, 1 m/s, 1 mg or 1 cm/s² for cislunar and MSL
  - 10 m, 10 cm/s, 1 mm/s² for Earth orbits

- Detector Area: 1 m²
Empirical MLE Simulations with B1821-24 and Orbit Dynamics

**GPS Orbit**

80 s < T < 500 s

**ISS Orbit**

90 s < T < 170 s
Loop Noise Bandwidth Choice

• $B_L$ is the parameter along with $T$ that can tweak DPLL performance

• Trade-off between steady-state tracking error and sensitivity to dynamic stress
  • Smaller $B_L$ leads to smaller steady-state tracking position error
  • Higher $B_L$ allows the DPLL to stay in-lock for higher dynamic stress
### Pulsar Parameters

<table>
<thead>
<tr>
<th></th>
<th>B0531+21, Crab</th>
<th>B1821-24</th>
<th>B1937+21</th>
<th>J0218+4232</th>
<th>J0437-4715</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Period (s)</strong></td>
<td>0.0334</td>
<td>0.00305</td>
<td>0.0015578</td>
<td>0.00232</td>
<td>0.00575</td>
</tr>
<tr>
<td><strong>Fs (ph/cm(^2)/s)</strong></td>
<td>1.54</td>
<td>1.93e-4</td>
<td>4.99e-5</td>
<td>6.65e-5</td>
<td>6.65e-5</td>
</tr>
<tr>
<td><strong>SNR (α/β)</strong></td>
<td>2.3283</td>
<td>0.18841</td>
<td>0.04262</td>
<td>0.04769</td>
<td>0.01777</td>
</tr>
<tr>
<td><strong>P(_f)</strong></td>
<td>0.7</td>
<td>0.98</td>
<td>0.86</td>
<td>0.73</td>
<td>0.28</td>
</tr>
<tr>
<td><strong>T (s)</strong></td>
<td>10</td>
<td>200</td>
<td>4000</td>
<td>4000</td>
<td>4000</td>
</tr>
</tbody>
</table>

Background Flux \(F_b\) = 0.001 ph/cm\(^2\)/s

Detector Area: 1 m\(^2\)
Phase Tracking Results: B1821-24

MSL Cruise Trajectory

B_L = 0.00025 Hz
T = 200 seconds

• Mean Final Position Error: 1.16 km
• Mean Final Velocity Error: 24 cm/s

DirecTV Orbit

B_L = 0.005 Hz
T = 150 seconds

• Mean Final Position Error: 2.47 km
• Mean Final Velocity Error: 6.25 m/s
## MSL Cruise Trajectory Results

<table>
<thead>
<tr>
<th>Pulsar</th>
<th>End DPLL RMS Range Error (km)</th>
<th>End DPLL RMS Range-Rate Error (cm/s)</th>
<th>MLE Range Error (km)</th>
<th>CRLB (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSR B1821-24</td>
<td>1.16</td>
<td>24</td>
<td>3.38</td>
<td>3.07</td>
</tr>
<tr>
<td>PSR B1937+21</td>
<td>4.12</td>
<td>41</td>
<td>2.53</td>
<td>1.02</td>
</tr>
<tr>
<td>PSR J0218+4232</td>
<td>6.45</td>
<td>63</td>
<td>5.42</td>
<td>4.19</td>
</tr>
<tr>
<td>PSR J0437-4715 (5 m²)</td>
<td>36.19</td>
<td>226</td>
<td>20.30</td>
<td>18.49</td>
</tr>
<tr>
<td>Crab Pulsar</td>
<td>0.61</td>
<td>53</td>
<td>1.46</td>
<td>1.22</td>
</tr>
</tbody>
</table>

## DirecTV Orbit Results

<table>
<thead>
<tr>
<th>Pulsar</th>
<th>End DPLL RMS Range Error (km)</th>
<th>End DPLL RMS Range-Rate Error (cm/s)</th>
<th>MLE Range Error (km)</th>
<th>CRLB (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSR B1821-24</td>
<td>2.47</td>
<td>6.25</td>
<td>3.93</td>
<td>3.55</td>
</tr>
<tr>
<td>Crab Pulsar</td>
<td>0.47</td>
<td>2.08</td>
<td>1.46</td>
<td>1.22</td>
</tr>
</tbody>
</table>

- B1937+21 and J0218+4232 required 8 m²
Detector Areas Needed for Each Pulsar to Phase Track Various Orbits

![Graph showing detector areas needed for various pulsars.](image_url)
EKF Simulations for 3D State

- MSL and Cislunar with 1 m² Detector Area
- Initial Condition Error
  - [2; 2; 2] km and [20; 20; 20] cm/s
- 3 Day Simulation Duration (repeated 10 times)
- Schedule: B1821-24, B1937+21, Crab pulsar, J0218+4232
  - 12000 seconds per pulsar
Cislunar Trajectory EKF Results

Mean Errors: 3.93 km and 5.49 cm/s
HYNAV Concept

- Hybrid-energy Navigation
- Combine radio, x-ray, and gamma-ray observations in single instrument
- Advantages from each type while minimizing negatives
- Single or distributed spacecraft
- Autonomous navigation instrument for multiple spacecraft operation
- 100 – 5000 m MRSE with greater robustness to orbit
- Larger source availability
- Improved operating space where top level position errors are achievable

Combine Hybrid Energy Detectors
Single instrument per Spacecraft

Radio: > 400 MHz
X-ray: 0.1 – 10 KeV
Gamma-ray: > 20 KeV
Navigation using Horizon Crossings

- Position information from timing of X-ray source occultation by planet and atmosphere
- Early work by Kent Wood at NRL
- Similar methods in optical
- Accuracy linked to distance from targeted planet
- Can be non-variable point sources
  - Wider range with high flux
- Recent work at Haverford College
  - NICER horizon crossings
- Simulations to combine XNAV and horizon crossing navigation
Future Work

- Internal MLE phase models for Earth orbits
- Photon level EKF simulations
- CubeSat to test phase tracking methods
- Phase tracking advancements to approach single photon processing
  - Nonlinear or suboptimal filtering
Conclusions

- Fertile area of research for navigation with variable celestial sources
- Many benefits including the potential for more autonomy
- Challenges including that many sources are faint
- Phase tracking and horizon crossing measurement are promising areas for further study
- New phase tracking method shown to track phase and frequency for low flux MSPs with detector area $\approx 1 \text{ m}^2$
- Combined 3D EKF
  - 3 km error for MSL and 4 km for cislunar
Acknowledgments

• Dr. Robert Golshan
  • Formerly, The Aerospace Corporation

• Dr. Keith Gendreau and NICER/SEXTANT
  • NASA Goddard

• Nathaniel Ruhl and Dr. Andrea Lommen
  • Haverford College

• Dr. Kent Wood
  • Formerly, NRL

• Chuck Hisamoto and others at ASTER Labs
Questions?
Backup Slides
Dynamic Stress

- Demonstrates offset from constant acceleration