Precision GNSS-Based Navigation for Miniaturized Distributed Space Systems

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A Vision: Miniaturized Distributed Space Systems

- Space Science
- Planetary Science
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The Enabler: GNSS-Based Navigation (1)
The Enabler: GNSS-Based Navigation (2)

- **Offline** on-ground baseline determination accuracy obtained from GRACE

![Graph showing offline baseline determination accuracy](image1)

- **Real-time** on-board baseline accuracy obtained from PRISMA

![Graph showing real-time baseline accuracy](image2)
Spaceborne GNSS: Technology Aspects (1)

- Hostile environment
  - Thermal-vacuum, vibration, shock loads
  - Radiation long- and short-term effects
- Hard signal tracking
  - Constellation changes rapidly (Doppler shift)
  - Measurement noise and systematic errors
  - Time synchronization
  - Antenna system and multipath
- Regulatory issues
  - Threat of a possible abuse of GNSS
  - Free trade only permitted for locked receivers
Spaceborne GNSS: Technology Aspects (2)

Single event latch-ups on-board PRISMA (Phoenix-S)

South Atlantic Anomaly 2010
Spaceborne GNSS: Receivers and Frequencies (1)

- Annual review of “GPS World”
  - 500 different GNSS receiver models
  - 70 manufacturers world wide
- Spaceborne GNSS receivers
  - Niche market (small and specialized)
  - 500 LEO satellites expected btw. 2007-2016
- Costs
  - Spacegrade units priced from $100k to $1M
  - Commercial-off-the-shelf solutions available
- Single or multiple frequency? Choice driven by
  - Elimination of ionospheric path delays
  - Integer ambiguity resolution

JPL’s Blackjack/TanDEM-X

DLR’s Phoenix/PRISMA
### Spaceborne GNSS: Receivers and Frequencies (2)

Multipe frequency GNSS receivers for space applications

<table>
<thead>
<tr>
<th>Manufacturer (Country)</th>
<th>Receiver</th>
<th>Channels</th>
<th>Ant</th>
<th>Power Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>JPL (US)/BRE (US)</td>
<td>BlackJack/IGOR</td>
<td>$16 \times 3$ C/A, P1/2</td>
<td>4</td>
<td>10 W, 3.2/4.6 kg</td>
</tr>
<tr>
<td>RUAG (A)</td>
<td>POD Receiver</td>
<td>$8 \times 3$ C/A, P1/2</td>
<td>1</td>
<td>10 W, 2.8 kg</td>
</tr>
<tr>
<td>SAAB (S)</td>
<td>GRAS/GPSOS</td>
<td>12 C/A, P1/2</td>
<td>3</td>
<td>30 W, 30 kg</td>
</tr>
<tr>
<td>Thales Alenia Space (IT,FR)</td>
<td>Lagrange</td>
<td>$16 \times 3$ C/A, P1/2</td>
<td>1</td>
<td>30 W, 5.2 kg</td>
</tr>
<tr>
<td>BRE (US)</td>
<td>TopStar 3000 G2</td>
<td>$6 \times 2$ C/A, L2C</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>EADS Astrium (D)</td>
<td>Pyxis POD</td>
<td>16–64 C/A, P1/2, L2C, L5</td>
<td>1–2</td>
<td>20 W, 2 kg</td>
</tr>
<tr>
<td>Javad (US/RUS)</td>
<td>Triumph DG3TH</td>
<td>216; GPS, GAL, GLO</td>
<td>1</td>
<td>2.5 W*, 100 g*</td>
</tr>
<tr>
<td>NovAtel (CA)</td>
<td>OEM4-G2L</td>
<td>12×2 C/A, P2</td>
<td>1</td>
<td>1.5 W*, 50 g*</td>
</tr>
<tr>
<td>Septentrio (B)</td>
<td>PolaR×2</td>
<td>$16 \times 3$ C/A, P1/2</td>
<td>1(3)</td>
<td>5 W*, 120 g*</td>
</tr>
</tbody>
</table>
Observation Types and Measurement Models (1)

> Basic observables

\[ \rho = |\mathbf{r} - \mathbf{r}_{\text{GPS}}| + c \delta t - c \delta t_{\text{GPS}} + I \]

\[ \varphi = \lambda \Phi = |\mathbf{r} - \mathbf{r}_{\text{GPS}}| + c \delta t - c \delta t_{\text{GPS}} - I + \lambda A + \lambda \Psi \]

> Single-difference data types

\[ \Delta \rho_{AB} = \rho_B - \rho_A \]

\[ \Delta \varphi_{AB} = \varphi_B - \varphi_A \]

A, B: receivers

> Double-difference data types

\[ \nabla \Delta \rho_{AB}^{ij} = \Delta |\mathbf{r} - \mathbf{r}_{\text{GPS}}|_{AB}^{ij} \]

\[ \nabla \Delta \varphi_{AB}^{ij} = \Delta |\mathbf{r} - \mathbf{r}_{\text{GPS}}|_{AB}^{ij} + \lambda \nabla \Delta A_{AB}^{ij} \]

i, j: GNSS satellites
Observation Types and Measurement Models (2)

- Residual of L1 single-difference pseudorange measurements from TanDEM-X

- Residuals of L1 single-difference carrier-phase measurements from TanDEM-X
Integer Ambiguity Resolution (1)

- Integer ambiguity resolution translates carrier-phase measurements into pseudoranges with millimeter noise level (our ultimate goal)
- Conceptually, we can compare code and phase measurements and round to the nearest integer

\[
\hat{\Delta} A_{ij}^{AB} = \left[ \frac{1}{\lambda} \left( \hat{\Delta} \varphi_{AB}^{ij} - \hat{\Delta} \rho_{AB}^{ij} \right) \right]_{\text{round}}
\]

- In practice more advanced methods are required, especially for large baselines, high solar activity, and orbit/attitude maneuvers
Integer Ambiguity Resolution (2)

- Offline on-ground “float solution” from GRACE during high solar activity

![Graph showing KBR-RelNav (mm) for 2011/10/22 with values ranging from -12 to 12, with a peak at -0.00 +/- 4.51 mm.]

- “Fixed solution” from GRACE using “on-the-fly” LAMBDA method

![Graph showing KBR-RelNav (mm) for 2011/10/18 with values ranging from -6 to 6, with a peak at 0.00 +/- 1.51 mm.]

70% Success Rate
Reduced Dynamics Orbit Determination (1)

- Numerical models
  - Compliant with high measurement accuracy
  - Individual satellite’s accelerations are modelled, numerically integrated, and subtracted

\[
\begin{pmatrix}
\Delta r_{AB} \\
\Delta v_{AB}
\end{pmatrix} = \begin{pmatrix}
\Delta r_{AB} \\
\Delta v_{AB}
\end{pmatrix}_0 + \int_{t_0}^{t} \left( a_B(t', r_B, v_B) \right) dt' - \int_{t_0}^{t} \left( a_A(t', r_A, v_A) \right) dt'
\]

- Analytical relative dynamics models
  - Solutions of linearized equations (HCW, TH)
  - Cartesian coordinates or relative orbit elements
  - Useful for formation design and control
  - Suitable for precision navigation?
Reduced Dynamics Orbit Determination (2)

- Conservative forces
  - Gravity field models (GGM03S, EIGEN-05C)
  - Third-body perturbations (Sun, Moon)
- Non-conservative forces
  - Atmospheric drag (Harris-Priester, Jacchia)
  - Solar radiation pressure (Conical shadow)
  - Orbit control maneuvers (impulsive or quasi-continuous)
- Un-modelled forces
  - Force model is a trade-off btw. accuracy/complexity
  - Empirical accelerations compensate deficiencies
    - Exponentially correlated random variables (onboard)
    - Piece-wise constant acceleration at 6-15 min intervals (offline)

Offline: $n \sim 70-120$
Onboard: $n \sim 2-30$
Beyond State-of-the-Art: DiGiTaL (Nasa Ames)

- Distributed GNSS Timing and Localization (DiGiTaL) Navigation System
  - Miniaturized system for nanosatellites
  - Targeting 0.5U volume unit
  - Plug-in ready unit (high compatibility)
  - Peer-to-peer, decentralized
  - Improved real-time accuracy (cm-level)
  - Qualification testing to TRL-6
  - Demonstration on BioSentinel nanosatellite

HW/SW Design

DiGiTaL Prototype
Thanks for your attention!

Questions?
Estimation (Filter Concept)

- Batch estimation (e.g., least squares)
  - Thousands of unknowns for 24h data arc
  - Normal matrix can be partitioned to eliminate clocks
  - Float and fixed solution partially de-coupled
- Sequential estimation (e.g., extended Kalman filter)
  - Reduced number of unknowns
  - Float and fixed solution strongly coupled
  - Special care with “implementation” and “tuning”
  - Forward and backwards processing possible
- Alternative filter concepts (e.g., adaptive, unscented)
  - Higher robustness and improved convergence
  - Only in the case of strong non-linearities
Estimation (State Parameters)

- Position and velocity
- Force model parameters
- Receiver clock offset
- Ambiguity parameter
- Ionospheric parameters

PRISMA (single-frequency, short-baseline)

\[
\left( \begin{array}{c} x; p; c\delta t; N \end{array} \right)_M ; \left( \begin{array}{c} x; p; c\delta t; N \end{array} \right)_T ; \delta v
\]

- Absolute or relative formulation possible
- Variety of approaches in literature
  - Typically 12 tracking channels
  - 18 to 80 state parameters
  - Measurement update has the largest computational effort
  - Trade-off necessary on a case-by-case basis
Mission Results: Real-Time Navigation (1)
Mission Results: Real-Time Navigation (2)

<table>
<thead>
<tr>
<th>Operational Scenario</th>
<th>Applied settings</th>
<th>Rel. position-3-D, cm</th>
<th>Rel. velocity-3-D, mm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sparse control/short range (3 April)</td>
<td>Performance</td>
<td>4.74 ± 1.96</td>
<td>0.12 ± 0.13</td>
</tr>
<tr>
<td>Sparse control/far-range rendezvous (5/6 April)</td>
<td>Performance</td>
<td>5.30 ± 2.60</td>
<td>0.20 ± 0.36</td>
</tr>
<tr>
<td>Forced motion control (3 Feb.)</td>
<td>Frequent thrust</td>
<td>14.83 ± 8.01</td>
<td>1.59 ± 1.76</td>
</tr>
<tr>
<td>Large Mango attitude rotations (31 March)</td>
<td>Robust</td>
<td>6.84 ± 2.94</td>
<td>0.08 ± 0.04</td>
</tr>
</tbody>
</table>
Beyond State-of-the-Art: MIDAS (Stanford’s CEAA)