Precise Positioning with Broadcast Ephemerides

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Precise Positioning with Broadcast Ephemerides

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• Broadcast Ephemeris Errors
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• Applications
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GNSS Point Positioning

Single Point Positioning (SPP)
- Code Observations Single/Dual-Frequency
- Broadcast Ephemerides
- Epoch-wise position solution
- Real-time

Precise Point Positioning (PPP)
- Code and Phase Observations Dual Frequency
- Precise Ephemerides
- Sequential position solution
- Offline / Real-time

Meter-level accuracy

Centimeter-level accuracy
**GNSS Signals**

- Common frequencies (L1/E1/B1, L5,E5a,B2a) and inter-operable signals for GPS, Galileo, BeiDou-3
- Dual-frequency GNSS now available for mass market receivers

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PPP with Broadcast Ephemerides?

Precise Point Positioning with Broadcast Ephemerides (PPP-BCE)

- Code and Phase Observations Dual-Frequency (Multi-Constellation)
- Broadcast Ephemerides
- Sequential position solution
- Real-time

(Few) decimeter-level accuracy w/o correction services
Positioning Error

\[ \sigma(|\Delta r|) = \text{DOP} \cdot \sqrt{\text{SISRE}^2 + \text{UEE}^2} \]

- **Signal-in-Space Ranging Error (SISRE)**
  - Contribution of orbit and clock errors to modelled pseudorange
- **User Equipment Error (UEE)**
  - Contribution of measurement errors (and uncompensated atmospheric path delays) to observed-minus-modelled pseudorange
- **Dilution of precision**
  - Ratio of \( \sigma(\text{position error}) \) and \( \sigma(\text{pseudorange error}) \)
  - Depends on number and distribution of tracked satellites
- **Common concept for SPP, partly applicable for (kinematic) PPP**
  - Rule of thumb for assessing impact of ephemeris errors
  - Largely reduced (negligible) UEE when using carrier phase observations
Example: GPS

2 h update

Cesium clock

24 h upload
SISRE of Global Navigation Satellite Systems

SISRE depends on:
- Clock stability
- Upload intervals
- Modulation/Biases

Best results for:
- Galileo
- BeiDou-3

Note: SISRE(PPP) neglects satellite-specific constant clock biases (no impact on carrier phase based positioning)
PPP-BCE Models (Dual Frequency)

• (A) Standard PPP Model

\[ p = |r_r - r_s| + c (dt_r - dt_s) + T + e \]
\[ \varphi = |r_r - r_s| + c (dt_r - dt_s) + T + A + \epsilon \]

• (B) Modified PPP-BCE Model with SISRE estimation

\[ p = |r_r - r_s| + c (dt_r - dt_s) + T + s + e \]
\[ \varphi = |r_r - r_s| + c (dt_r - dt_s) + T + s + A + \epsilon \]

• (C) Simplified PPP-BCE Model, SISRE lumped into ambiguity

\[ p = |r_r - r_s| + c (dt_r - dt_s) + T + e \]
\[ \varphi = |r_r - r_s| + c (dt_r - dt_s) + T + A + \epsilon \]

• Pseudorange \((p)\), carrier phase \((\varphi)\), receiver and satellite position \((r_r, r_s)\), receiver and satellite clock offsets \((dt_r, dt_s)\), tropospheric delay \((T)\), Ambiguity \((A)\), measurement errors \((e, \epsilon)\), SIS range error \((s)\)

• Phase center offsets, patterns, and wind-up ignored for simplicity
Test with IGS Permanent Stations

- 11 globally distributed stations (various rcvs and antennas)
- 31 days (Dec 2019)
- Kinematic processing
- Kalman filter (forward-only)
- 24-h arcs, first hour excluded

- Clear benefit of SISRE handling
- Simplified method gives similar performance at notably reduced complexity
- 0.20-0.40 m 3D rms accuracy with Galileo or GPS+Galileo

(DOI 10.1007/s10291-021-01111-4; CC-BY)
Boat Test

- 1 h boat ride on Lake Ammer (11 Sep. 2019)
- AsteRx3 rcv, Zephyr 3 antenna
- RTK reference solution
- 0.1 RMS horizontal, 0.3 m up for GPS+Galileo
- 15 min convergence
Flying High: Real-Time Orbit Determination

- Dynamical Model
  - Predict satellite motion (and uncertainty) under known external forces
- Observations
  - Pseudorange and carrier phase
  - One or multiple GNSSs
- Kalman filter
  - Time update (state and covariance prediction)
  - Measurement update (correct state with observations)
- Applications
  - Constellation/formation control
  - Onboard science data processing (radio occultation, images, SAR)
Playback Real-time Navigation Filter

- Extended Kalman filter in forward-only mode
  - Position & velocity
  - Drag, SRP, empirical accelerations
  - 1 clock offset per constellation
  - 1 float ambiguity per tracked satellite
- Earth gravity, luni-solar perturbations, empirical accelerations
- Multi-constellation, dual-frequency code and phase observations
- GNSS orbit, clock & EOP data from broadcast ephemerides (RINEX)
- Line-of-sight SISRE errors lumped into float ambiguity

Study:
- True GPS observations for Swarm-C satellite
- Simulated GPS, Galileo, BeiDou observations
Results (Multi-GNSS, simulated)

![Bar chart showing 3D RMS Orbit Error in cm for different GNSS systems.

- **G (GPS):** 28.7 cm
- **G(L2C):** 26.0 cm
- **E (Galileo):** 10.2 cm
- **C (BeiDou):** 11.2 cm
- **GE:** 9.9 cm
- **EC:** 8.5 cm
- **GEC:** 8.3 cm

DOI: 10.1002/navi.416; CC-BY]
Summary and Conclusions

- Carrier-phase positioning with broadcast ephemeris ("PPP-BCE") works!
- (Few) decimeter accuracy achievable
- Applicable to terrestrial and low-Earth orbit navigation
- Best prospects for new GNSSs (Galileo, BeiDou-3)
- Particularly attractive for dual- (or even triple-)constellation L1/L5 use

Further Reading
