Precise Positioning with Broadcast Ephemerides

Oliver Montenbruck, Luca Carlin, André Hauschild

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Precise Positioning with Broadcast Ephemerides

- Motivation
- Broadcast Ephemeris Errors
- Models
- Applications
    - Terrestrial
    - Space
- Summary and Conclusions

GNSS Point Positioning

Single Point Positioning (SPP)

- Code Observations Single/Dual-Frequency
- Broadcast Ephemerides
- Epoch-wise position solution
- Real-time

Meter-level accuracy

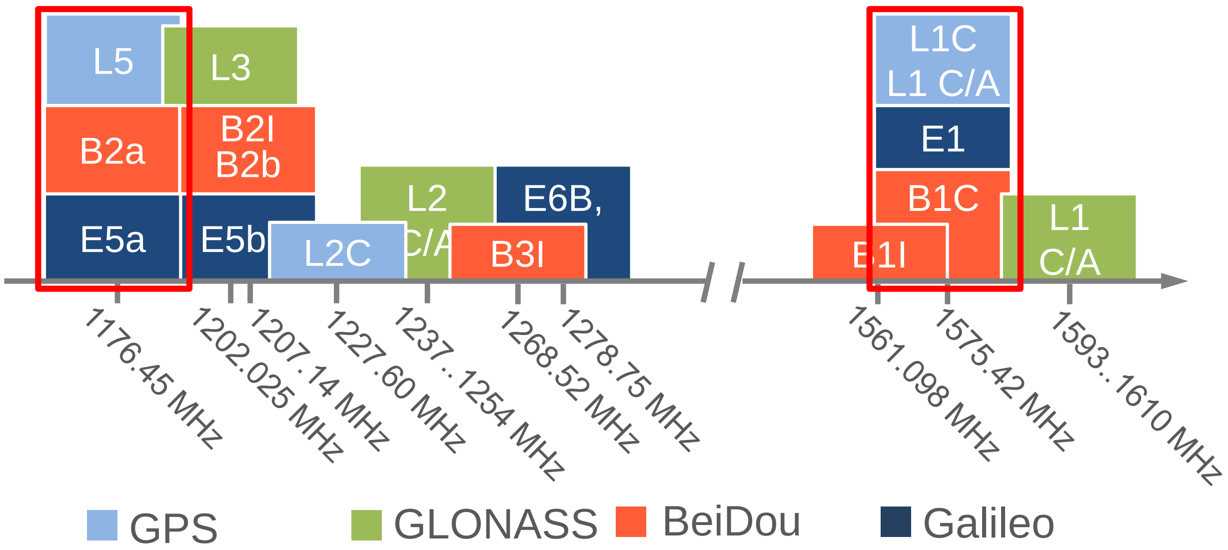
?

Precise Point Positioning (PPP)

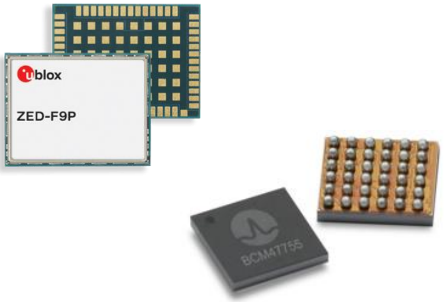
- Code and Phase Observations Dual Frequency
- Precise Ephemerides
- Sequential position solution
- Offline / Real-time

Centimeter-level accuracy

GNSS Signals



Adapted from DOI 10.1109/PLANS46316.2020.9110208



- 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

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

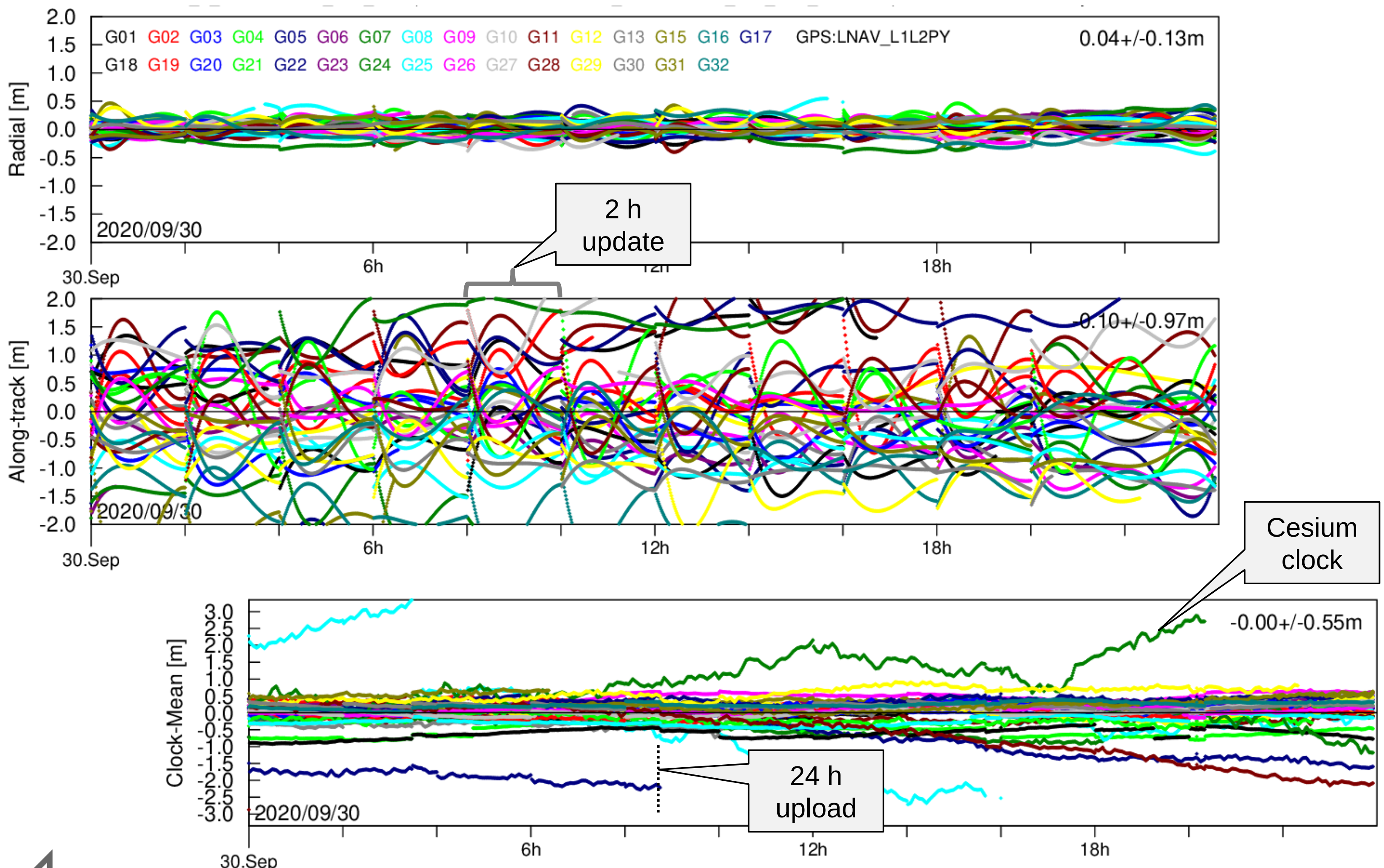
(Few) decimeter-level accuracy w/o correction services

Positioning Error

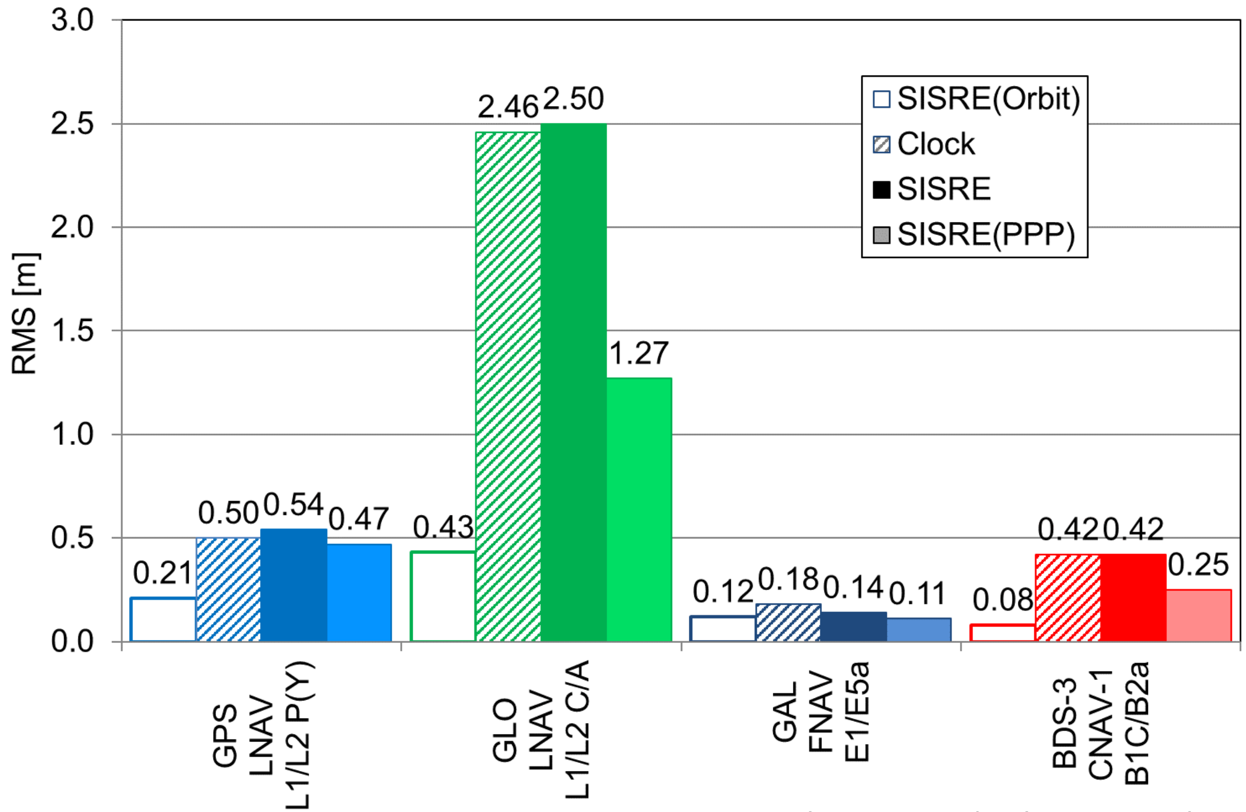
$$\sigma(|\Delta \boldsymbol{r}|) = \mathrm{DOP} \cdot \sqrt{\mathrm{SISRE}^2 + \mathrm{UEE}^2}$$

- 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 σ(position error) and σ(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


G01 G02 G03 G04 G05 G06 G07 G08 G09 G10 G11 G12 G13 G15 G16 G17 GPS:LNAV_L1L2PY
G18 G19 G20 G21 G22 G23 G24 G25 G26 G27 G28 G29 G30 G31 G32
0.04+/-0.13m
Radial [m]
2020/09/30
30.Sep
6h
18h
2 h
update
-0.10+/-0.97m
Along-track [m]
2020/09/30
30.Sep
6h
12h
18h
Cesium
clock
-0.00+/-0.55m
Clock-Mean [m]
24 h
upload
2020/09/30
30.Sep
6h
12h
18h

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

$$p = |\boldsymbol{r}_r - \boldsymbol{r}^s| + c\,(dt_r - dt^s) + T + e$$
$$\varphi = |\boldsymbol{r}_r - \boldsymbol{r}^s| + c\,(dt_r - dt^s) + T + A + \epsilon$$

modelled
estimated
estimated, process noise

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

$$p = |\boldsymbol{r}_r - \boldsymbol{r}^s| + c\,(dt_r - dt^s) + T + s + e$$
$$\varphi = |\boldsymbol{r}_r - \boldsymbol{r}^s| + c\,(dt_r - dt^s) + T + s + A + \epsilon$$

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

$$p = |\boldsymbol{r}_r - \boldsymbol{r}^s| + c\,(dt_r - dt^s) + T + e$$
$$\varphi = |\boldsymbol{r}_r - \boldsymbol{r}^s| + c\,(dt_r - dt^s) + T + A + \epsilon$$

- Pseudorange (p), carrier phase (φ), receiver and satellite position ($\boldsymbol{r}_r$, $\boldsymbol{r}^s$), receiver and satellite clock offsets (dt_r, dt^s), tropospheric delay (T), Ambiguity (A), measurement errors (e, ϵ), SIS range error (s)
- Phase center offsets, patterns, and wind-up ignored for simplicity

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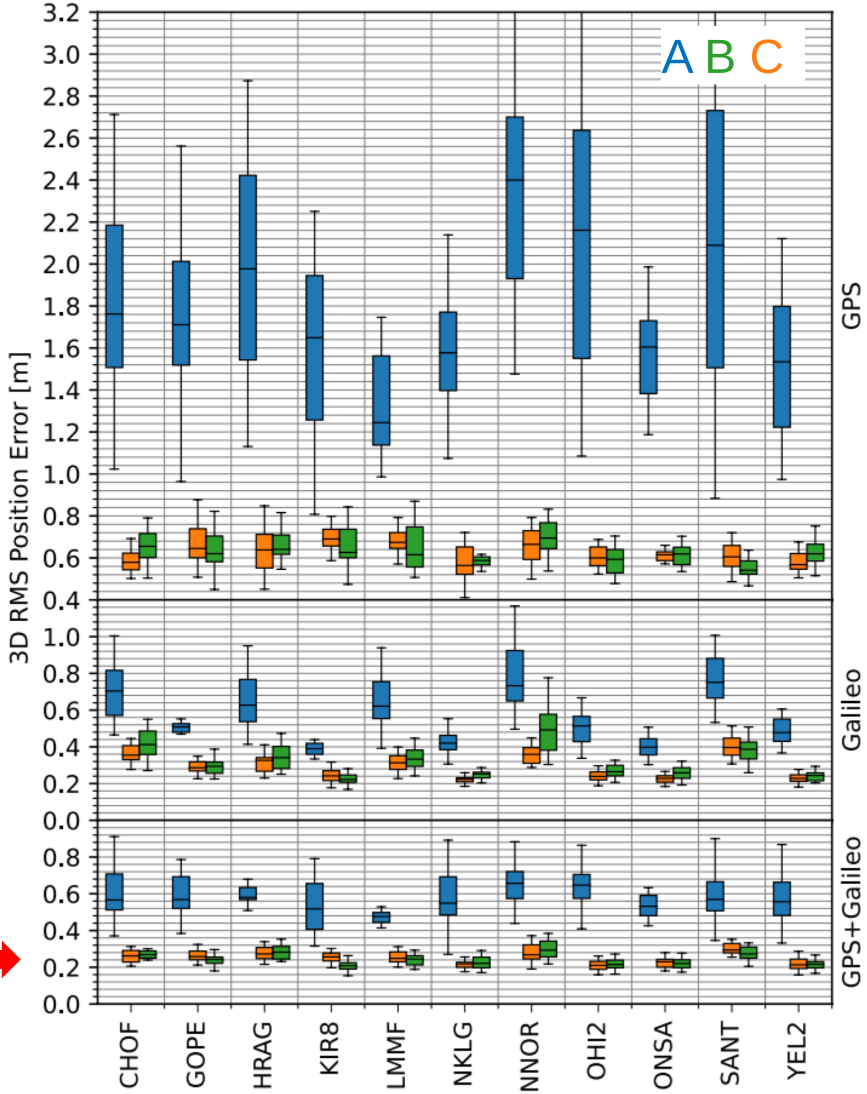
Test with IGS Permanent Stations



- 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)

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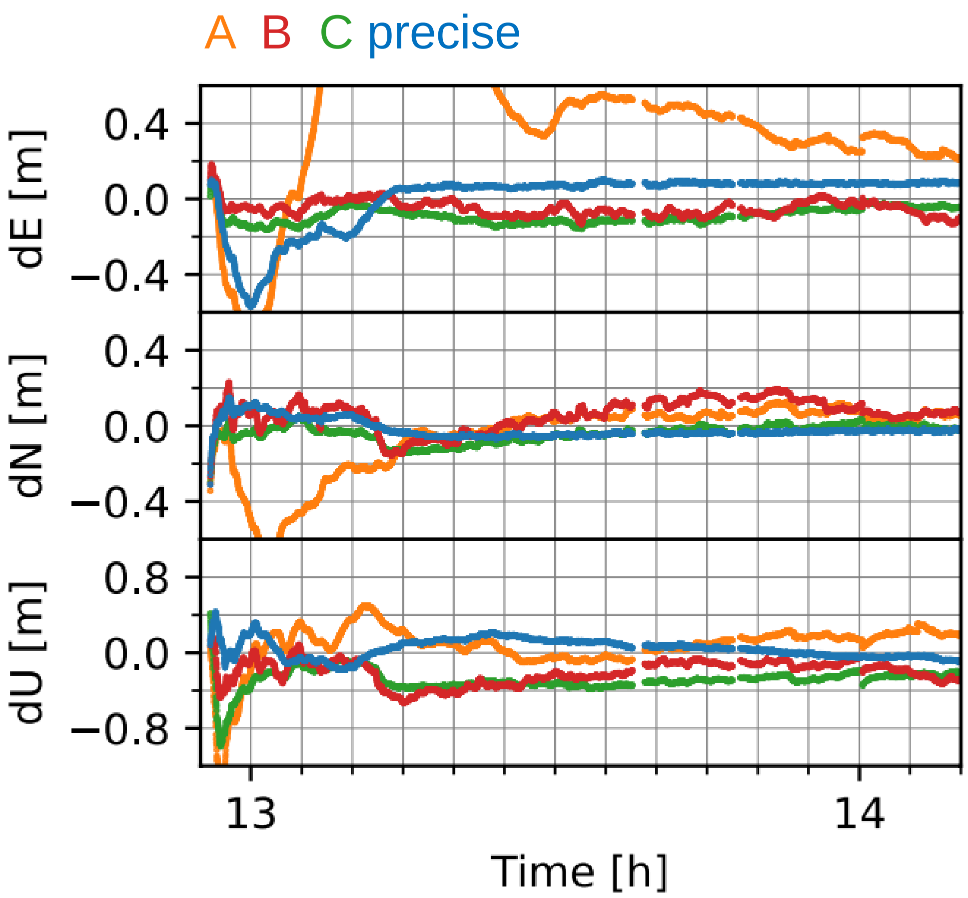
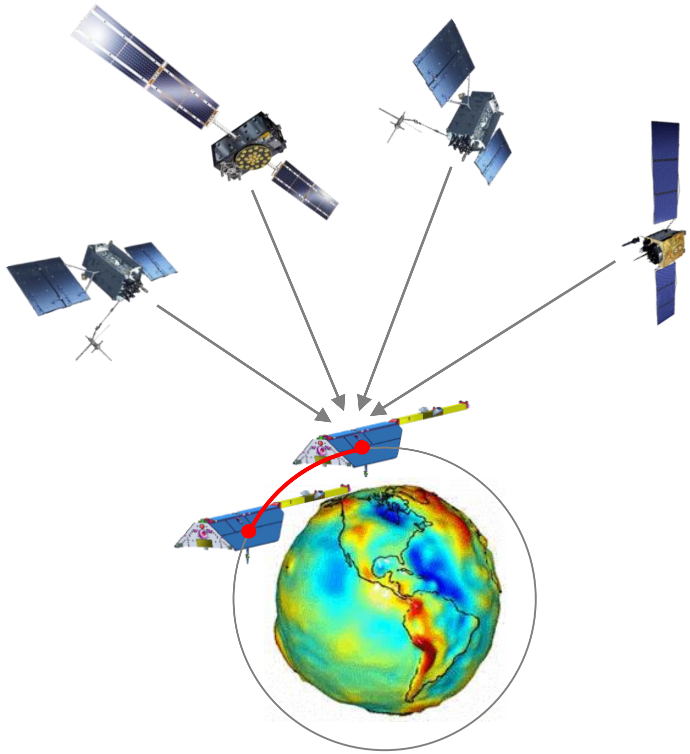
Boat Test



- 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)

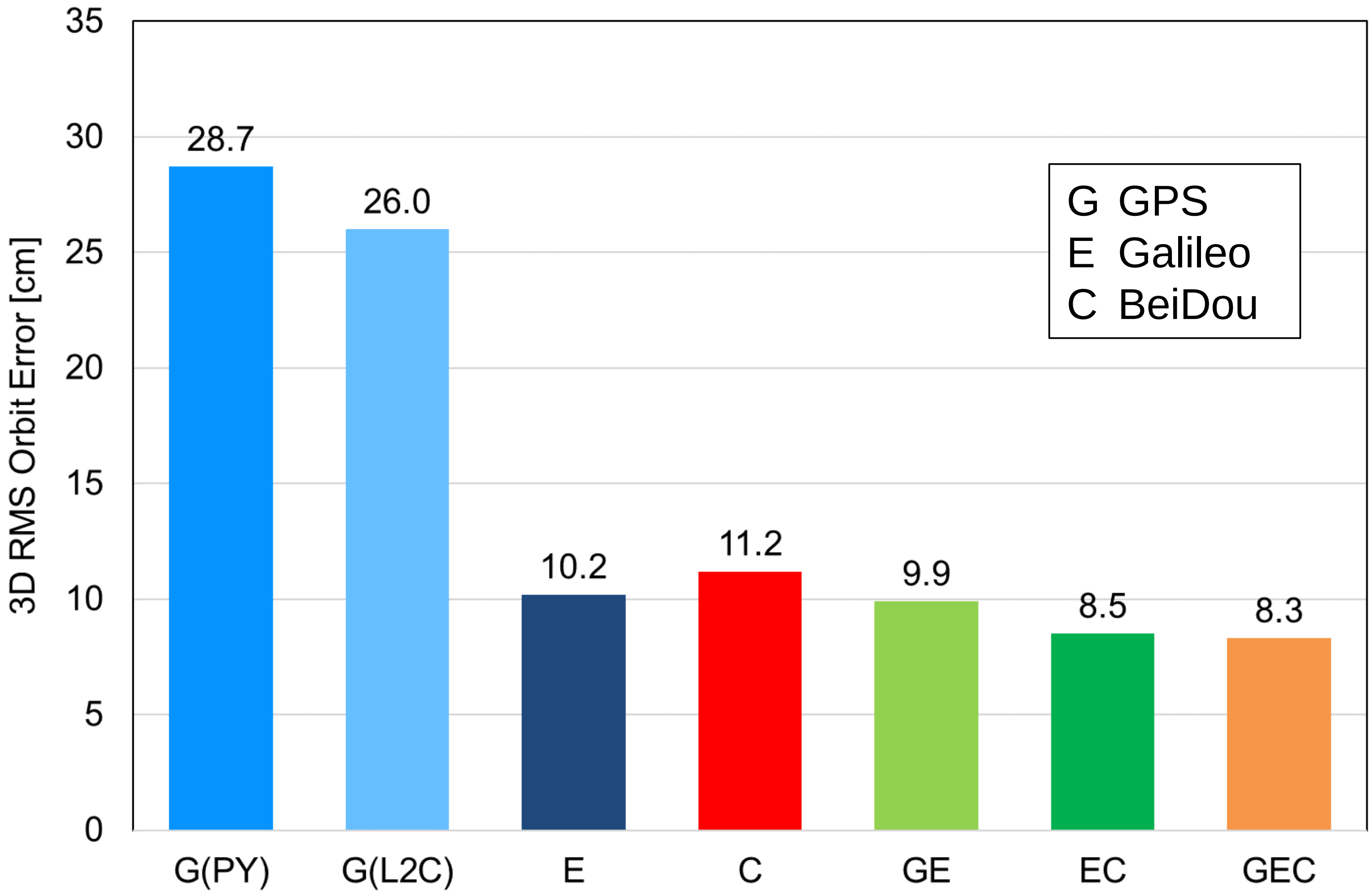


Playback Real-time Navigation Filter

- 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)



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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

Carlin L., Hauschild A., Montenbruck O., Precise Point Positioning with GPS and Galileo Broadcast Ephemerides; GPS Sol 25(2):77 (2021) DOI 10.1007/s10291-021-01111-4

Hauschild A., Montenbruck O.; Precise On-Board Navigation of LEO Satellites with GNSS Broadcast Ephemerides; Navigation 68(29):419-432 (2021) DOI 10.1002/navi.416

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