LEO augmentation in wide-area PPP-RTK positioning & time transfer

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01

Wide-area PPP-RTK Positioning & LEO

Static & kinematic mode

Ambiguity-fixed and -float modes

Single- & dual-GNSS

Wide-area

PPP-RTK

Multiple systems

Undifferenced and uncombined

S-basis Theory

- **Parameter recombination eliminates rank deficiency**
- **Hardware delays & ambiguities linked in time**

Network Part

$$\mathrm{E}\left(\Delta\varphi_{r,j}^{s}\right) = g_r^s\Delta\tau_r + d\tilde{t}_{r,g} - d\tilde{t}^s - \mu_j\tilde{\iota}_r^s + \tilde{\delta}_{r,j,g} - \tilde{\delta}_{,j}^{s} + \lambda_j\tilde{N}_{r,j}^{s}$$

$$\mathrm{E}\left(\Delta p_{r,j}^{s}\right) = g_r^s\Delta\tau_r + d\tilde{t}_{r,g} - d\tilde{t}^s + \mu_j\tilde{\iota}_{r,g}^s + \tilde{d}_{r,j,g} - \tilde{d}_{,j}^{s}$$

Satellite clock

Satellite phase bias

Satellite code bias (*j*>2)

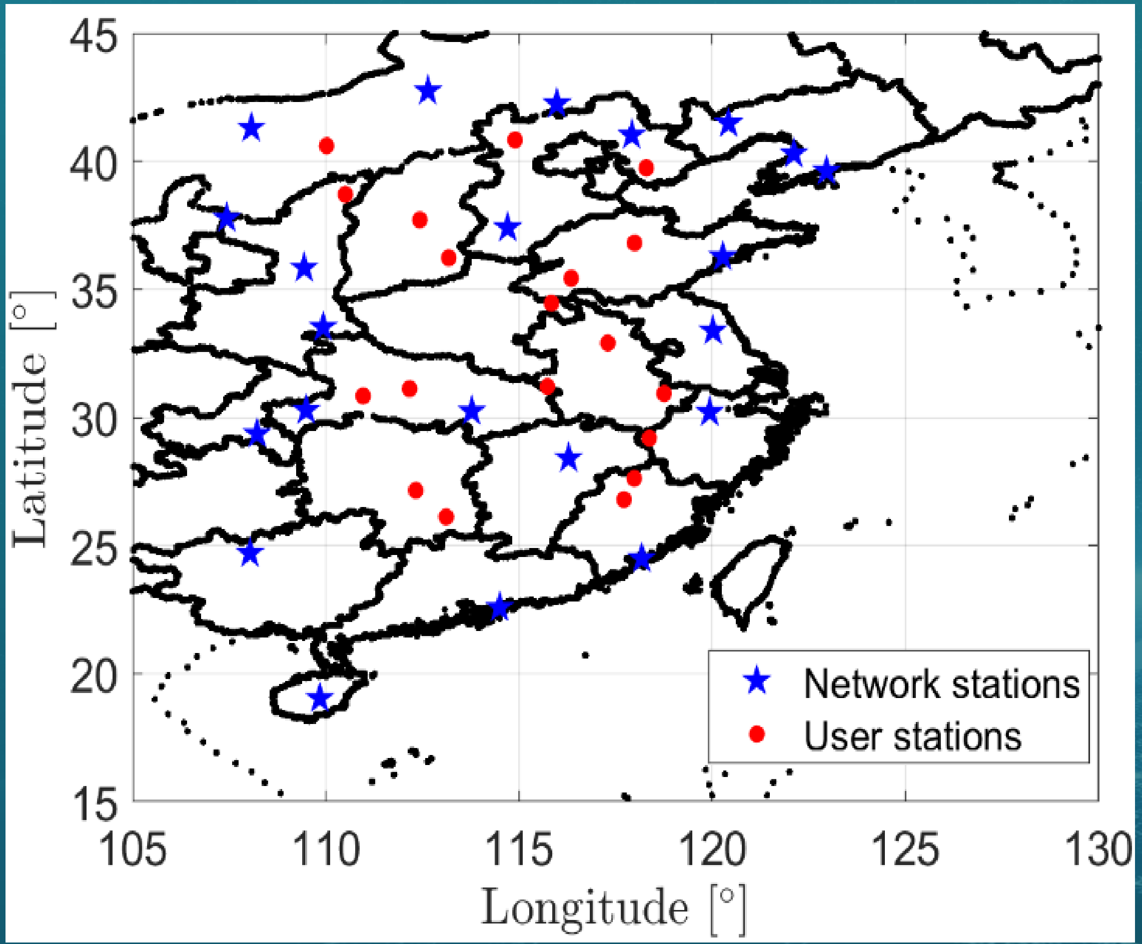
Estimable parameter	Formulation
$d\tilde{t}_{r,g}(t_i)$	$dt_{1r}(t_i) + d_{1r,\mathrm{IF},g}(t_1)$
$d\tilde{t}^s(t_i)$	$dt^s(t_i) + d_{,\mathrm{IF}}^s(t_1) - dt_1(t_i) - d_{1,\mathrm{IF},g}(t_1)$
$\tilde{\iota}_r^s(t_i)$	$\iota_r^s(t_i) + d_{r,\mathrm{GF},g}(t_1) - d_{,\mathrm{GF}}^s(t_1)$
$\tilde{\delta}_{r,j,g}(t_i)$	$\delta_{r,j,g}(t_i) - \delta_{1,j,g}(t_1) + \mu_j d_{1r,\mathrm{GF},g}(t_1) - d_{1r,\mathrm{IF},g}(t_1) + \lambda_j N_{1r,j,g}^1(t_i)$
$\tilde{\delta}_{,j}^s(t_i)$	$\delta_{,j}^s(t_i) + \mu_j\left(d_{,\mathrm{GF}}^s(t_1) - d_{1,\mathrm{GF},g}(t_1)\right) - d_{,\mathrm{IF}}^s(t_1) + d_{1,\mathrm{IF},g}(t_1) - \delta_{1,j,g}(t_1) - \lambda_j N_{1,j}^s(t_i)$
$\tilde{d}_{r,j,g}(t_i)$	$d_{r,j,g}(t_i) - d_{1,j,g}(t_1) - d_{1r,\mathrm{IF},g}(t_1) - \mu_j d_{1r,\mathrm{GF},g}(t_1)$
$\tilde{d}_{,j}^s(t_i)$	$d_{,j}^s(t_i) - d_{,\mathrm{IF}}^s(t_1) - \mu_j d_{,\mathrm{GF}}^s(t_1) - d_{1,j,g}(t_1) + d_{1,\mathrm{IF},g}(t_1) + \mu_j d_{1,\mathrm{GF},g}(t_1)$
$\tilde{N}_{r,j}^s(t_i)$	$N_{1r,j}^s(t_i) - N_{1r,j,g}^1(t_i)$

User Part

$$\mathrm{E}\left(\Delta\varphi_{u,j}^{s} + d\tilde{t}^s + \tilde{\delta}_{,j}^{s}\right) = (G_u^s)^{\mathrm{T}}\Delta x_u + g_u^s\Delta\tau_u + d\tilde{t}_{u,g} - \mu_j\tilde{\iota}_u^s + \tilde{\delta}_{u,j,g} + \lambda_j\tilde{N}_{u,j}^{s}$$

$$\mathrm{E}\left(\Delta p_{u,j}^{s} + d\tilde{t}^s + \tilde{d}_{,j>2}^{s}\right) = (G_u^s)^{\mathrm{T}}\Delta x_u + g_u^s\Delta\tau_u + d\tilde{t}_{u,g} + \mu_j\tilde{\iota}_u^s + \tilde{d}_{u,j,g}$$

- **Ground stations sparsely distributed**
- **No ionospheric interpolation/correction**
- **Long convergence time**
- **Sensitive to observation model**



Gound network in China

- 2550 km (Nroth & South) × 1300 km (East & West)
- GPS (L1 & L2) + BDS (B1I & B3I)

Network Part

Static

22 stations

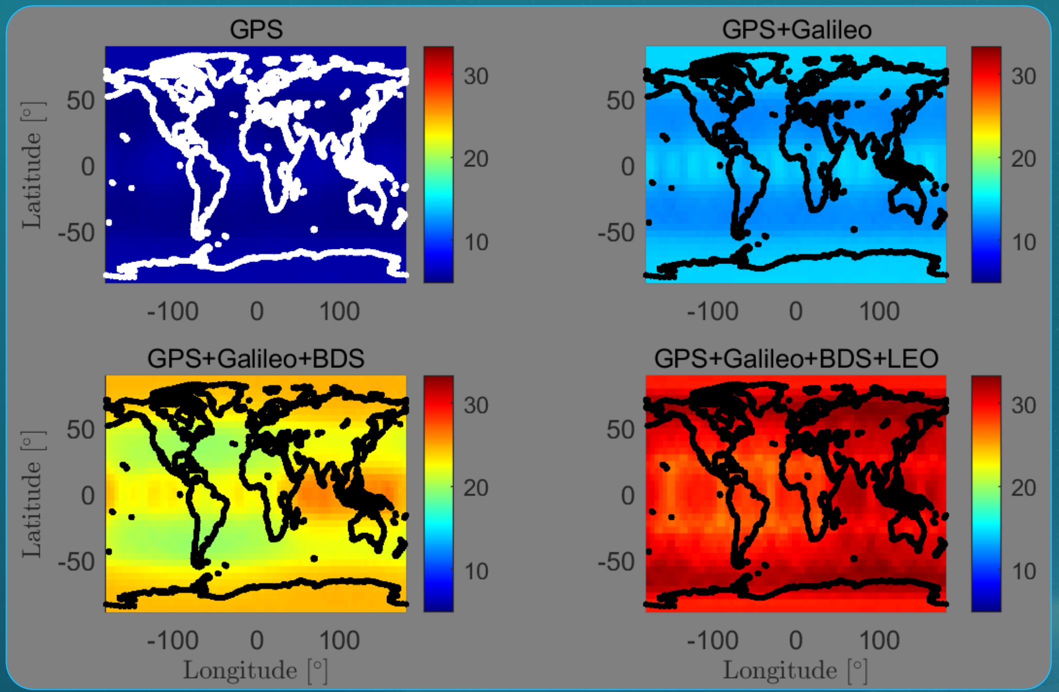
User Part

Static & kinematic mode

Ambiguity-fixed and -float modes

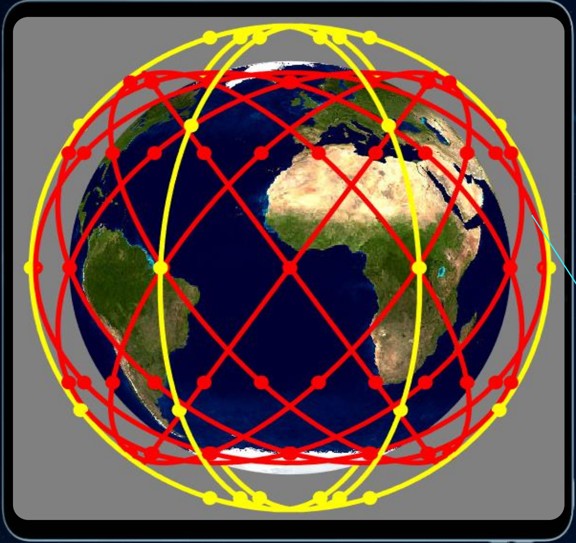
19 stations

LEO Constellation Configuration



L1/L5, E1/E5a, B1C/B2a

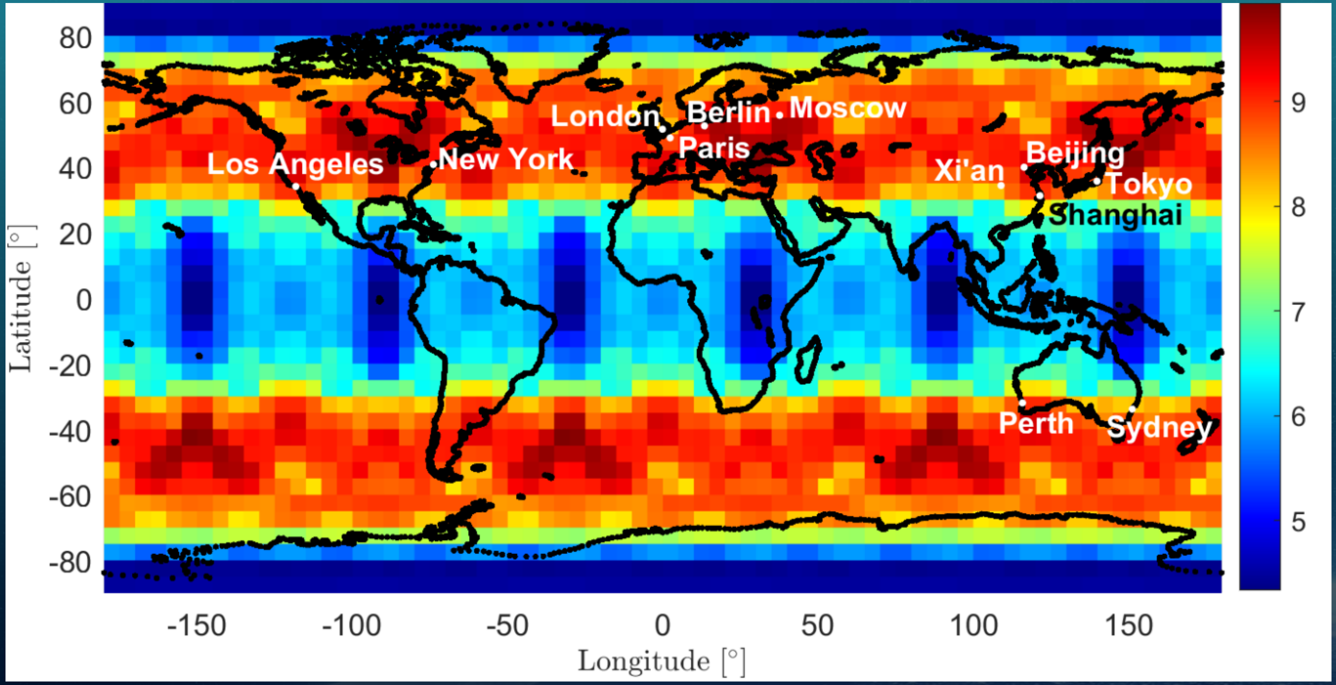
- **Average daily number of visible satellites**
- **Elevation mask: 5 degrees**

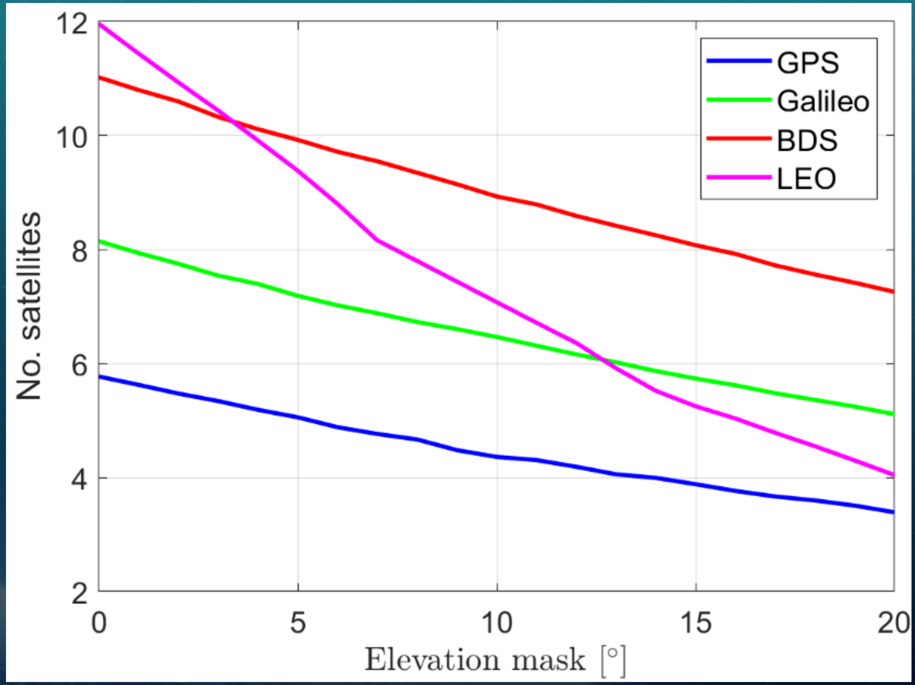


CentiSpace Configuration

	Layer A	Layer B
Satellites	**120**	**30**
Orbital planes	**12**	**3**
Orbital height	**975 KM**	**1100 KM**
Inclination	**55 degrees**	**87.4 degrees**

Numbers & Elevation





Mid-latitude friendly

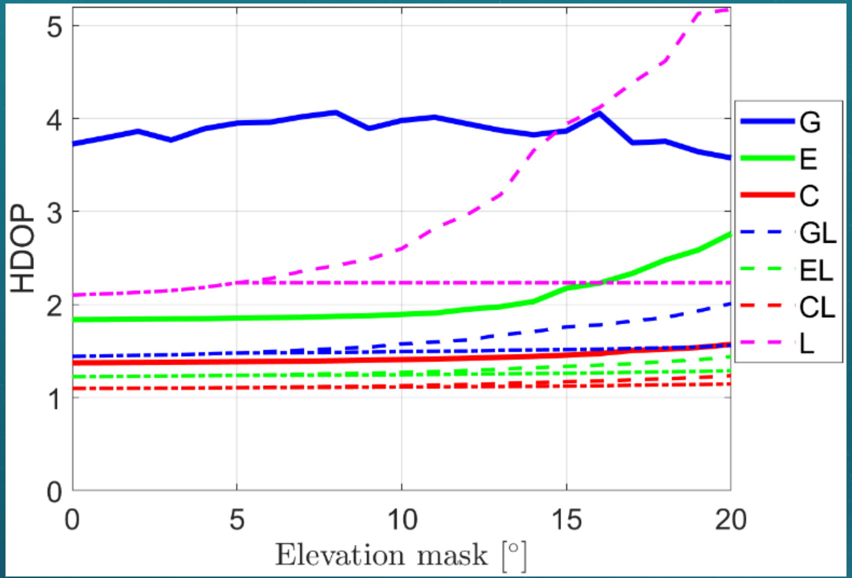
- Big cities with strong visibilities
- Visible satellites ~ 9

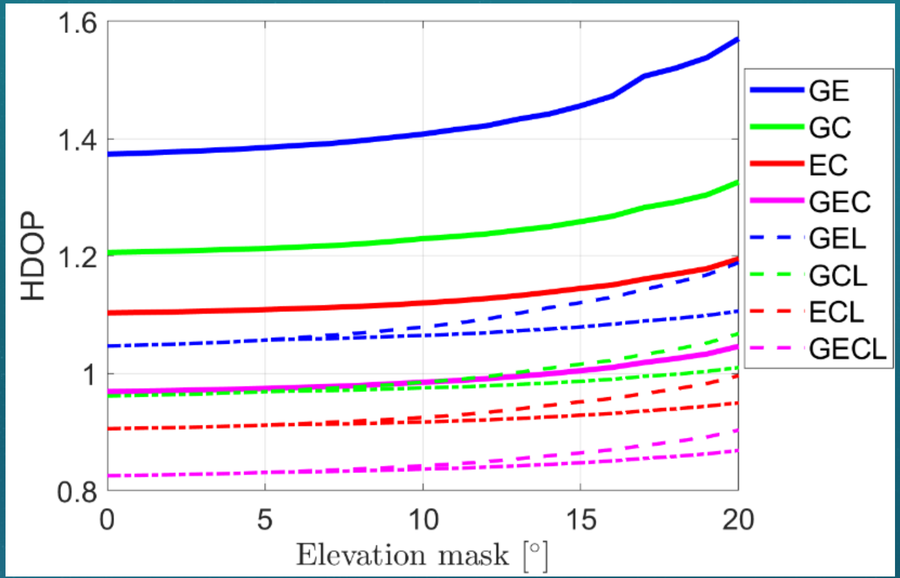
LEO satellites

- Low elevation angles
- Sharp decrease of the visible satellites with elevation angles

Measurement geometry

HDOP（L1/L5）





Improvements in single-GNSS scenario

Elevation mask: 10°/20°

Galileo	Galileo	BDS-3	BDS-3
33%	48%	20%	21%

Improvements in multi-GNSS scenarios

Elevation mask: 20°

G&E	G&C	E&C	G&E&C
30%	24%	21%	17%

Characteristics & differences

LEO ~ GNSS

L — Large quantity

Improve visibility
Improve measurement geometry
Reduce PDOP, TDOP

W — Wide coverage

Coverage in remote areas
Coverage in oceans
Coverage in polar areas

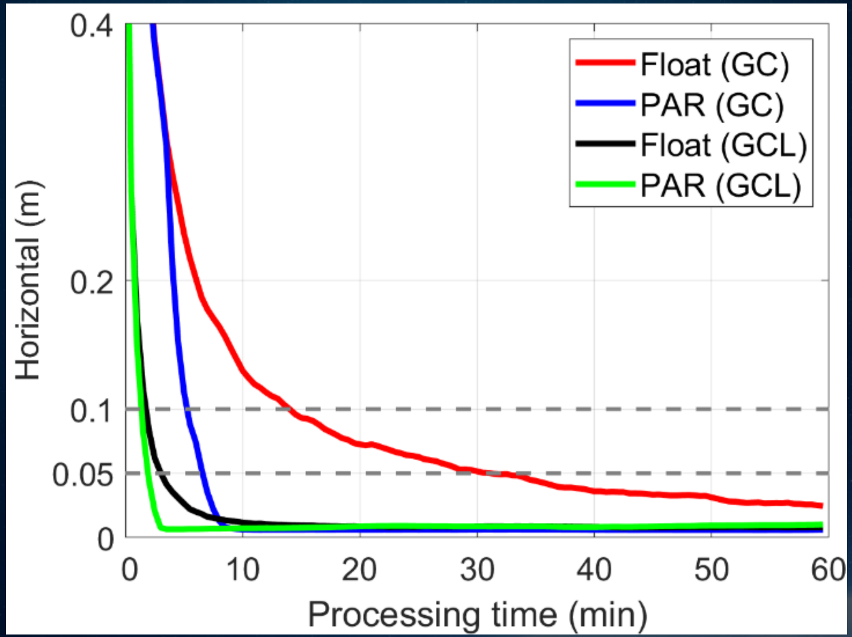
F — Fast speed

Accelerate geometric changes
Shorten PPP & PPP-RTK convergence time
Whiten multipath effects

O — Low orbital height

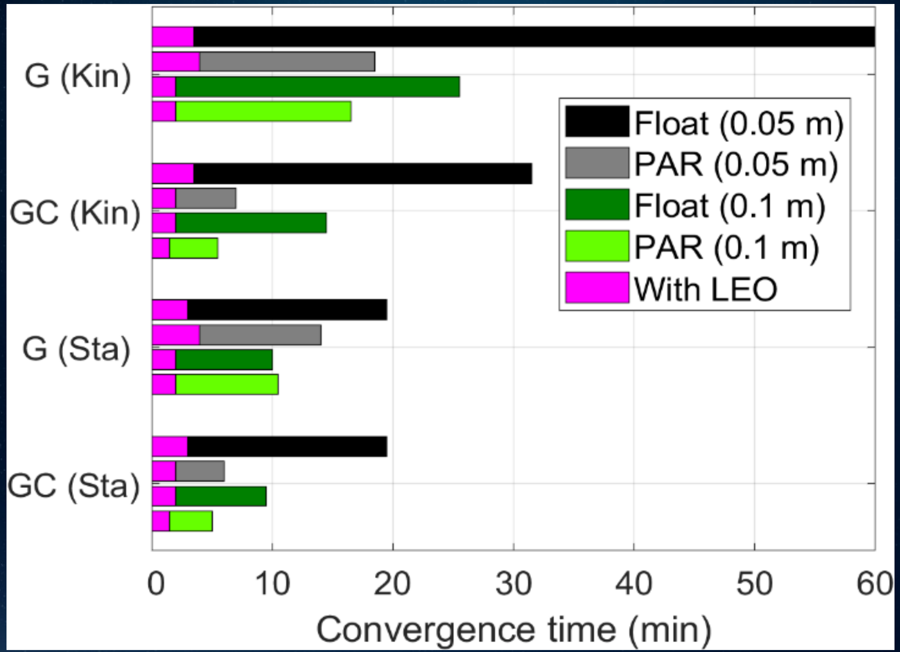
Strong signal strength
Anti-jamming

LEO enhanced wide-area PPP-RTK positioning



1σ **Percentile line of horizontal errors**

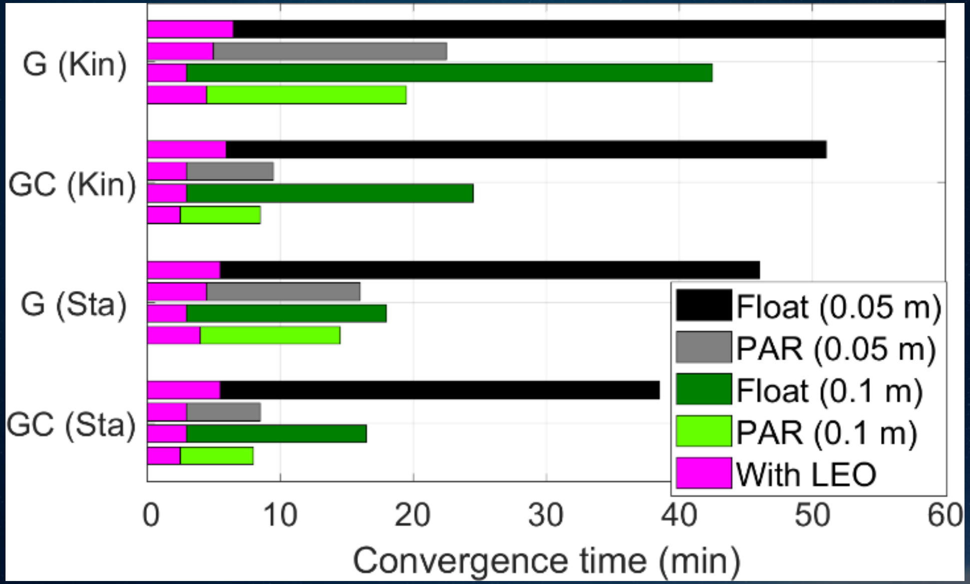
- Static mode
- Ambiguity-fixed and -float modes
- GPS + BDS

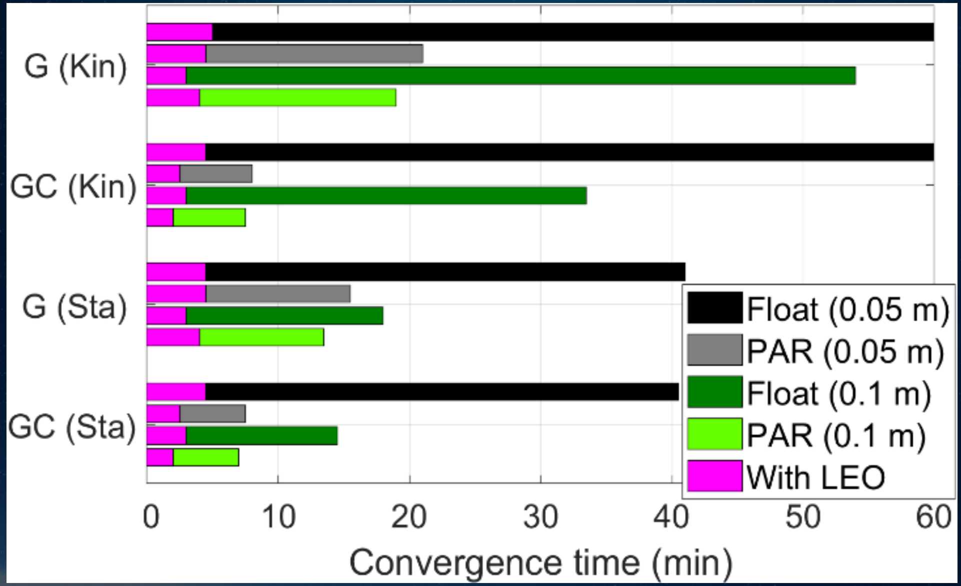


Fast convergence
Insensitive to the observation model

- Static & kinematic modes
- Ambiguity-fixed and -float modes
- Single- & dual-GNSS

LEO enhanced wide-area PPP-RTK positioning





90% Percentile line of vertical errors

- Static & kinematic mode
- Ambiguity-fixed and -float modes
- Single- & dual-GNSS

90% Percentile line of horizontal errors

- Improved integrity

02

Long-baseline time transfer based on UDUC wide-area PPP-RTK & LEO

Method

Stability

Convergence

Wide-area

PPP-RTK

Multiple systems + UDUC

Step 1:

The user solves the receiver clock

$$d\tilde{t}_{u,g}(t_i) = dt_{1u}(t_i) + d_{1u,\mathrm{IF},g}(t_1)$$

- **Difference between receiver clock and network reference clock**
- **Difference between the first-epoch receiver IF code delay and first-epoch reference station IF code delay**
- **Processing for each GNSS**
- **Separation between the clocks and hardware delays**

Step 2:

Between-station difference of the receiver clocks

$$d\tilde{t}_{uv,g}(t_i) = dt_{uv}(t_i) + d_{uv,\mathrm{IF},g}(t_1)$$

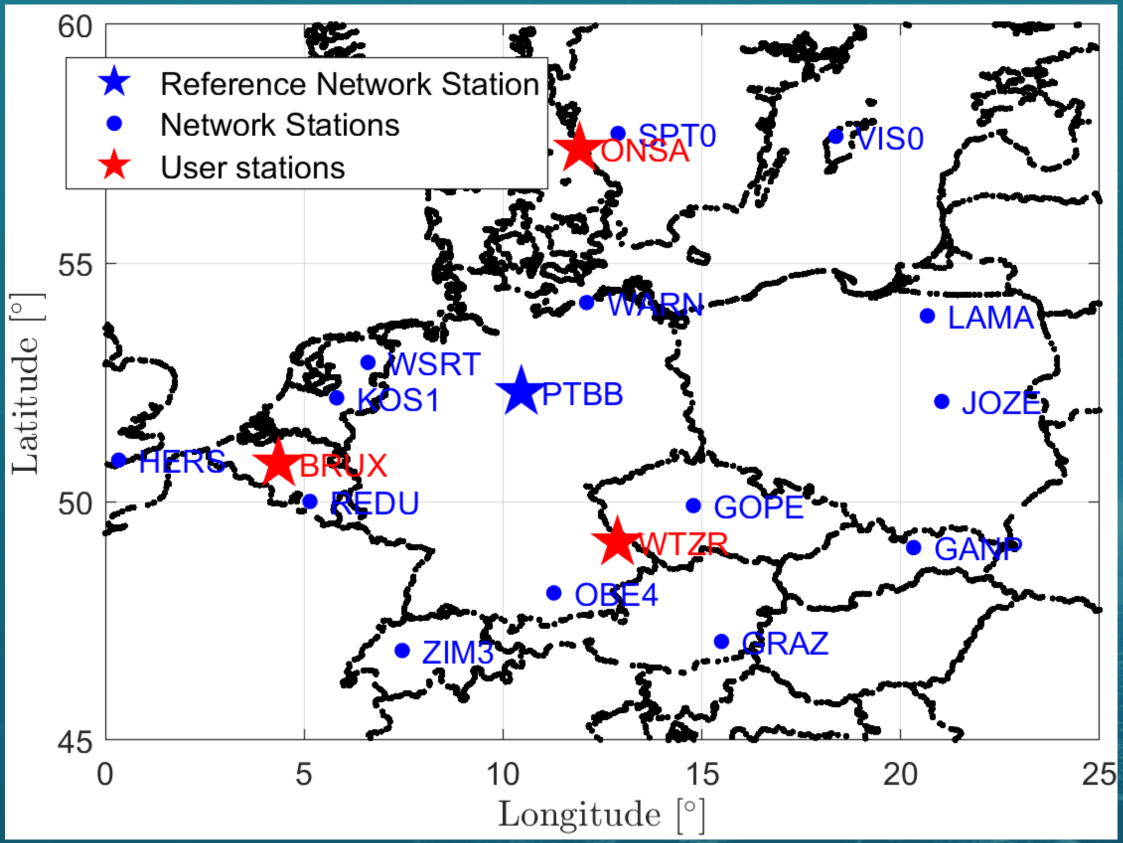
- **Reduce systemic effects**
- **The second user station can be a time lab**

Step 3:

Weighted average of solutions for each GNSS

$$d\tilde{t}_{uv}(t_i) = dt_{uv}(t_i) + \sum_{g=1}^{n}\left(\alpha_g d_{uv,\mathrm{IF},g}(t_1)\right)$$

Ground Network



Ground network in Europe

- ~1440 km
- GPS (L1 & L2) & Galileo (E1 & E5a)

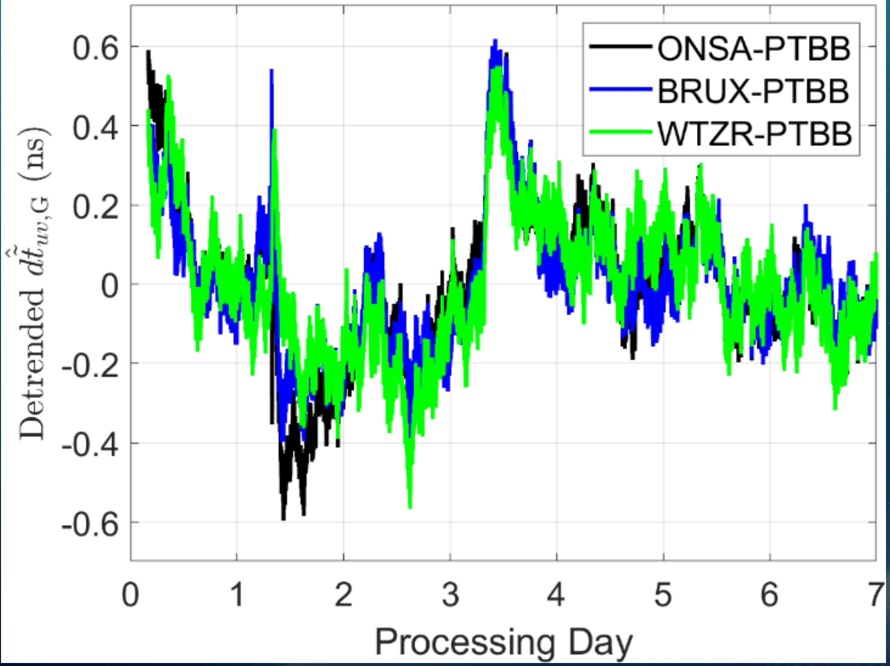
Network Part

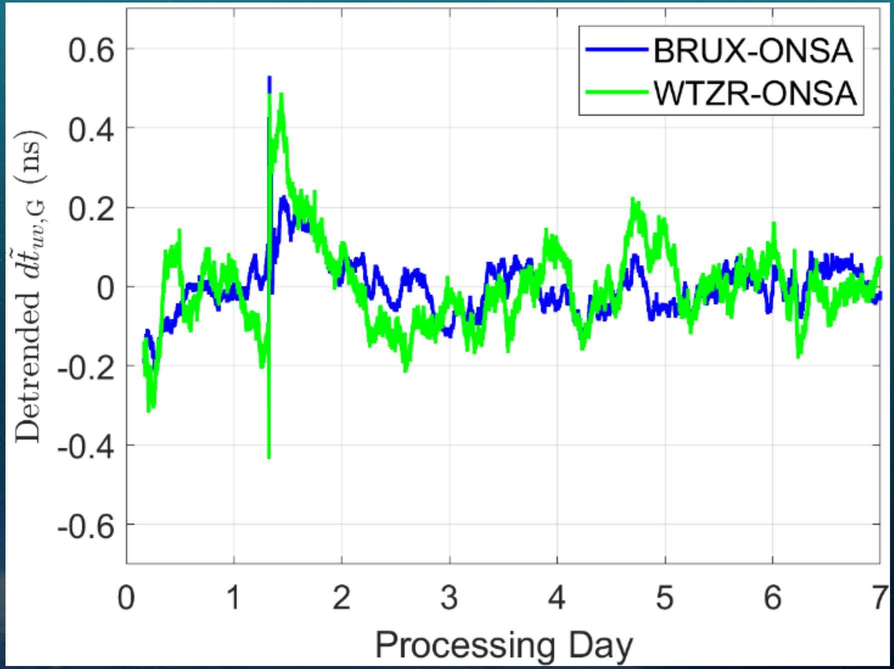
- Static, Ambiguity-fixed and -float modes
- Reference Station PTBB ~ H-Maser

User Part

- Fixed & Static & kinematic modes
- Ambiguity-fixed and -float modes
- H-Masers

Between-station clocks
Step 1 & 2





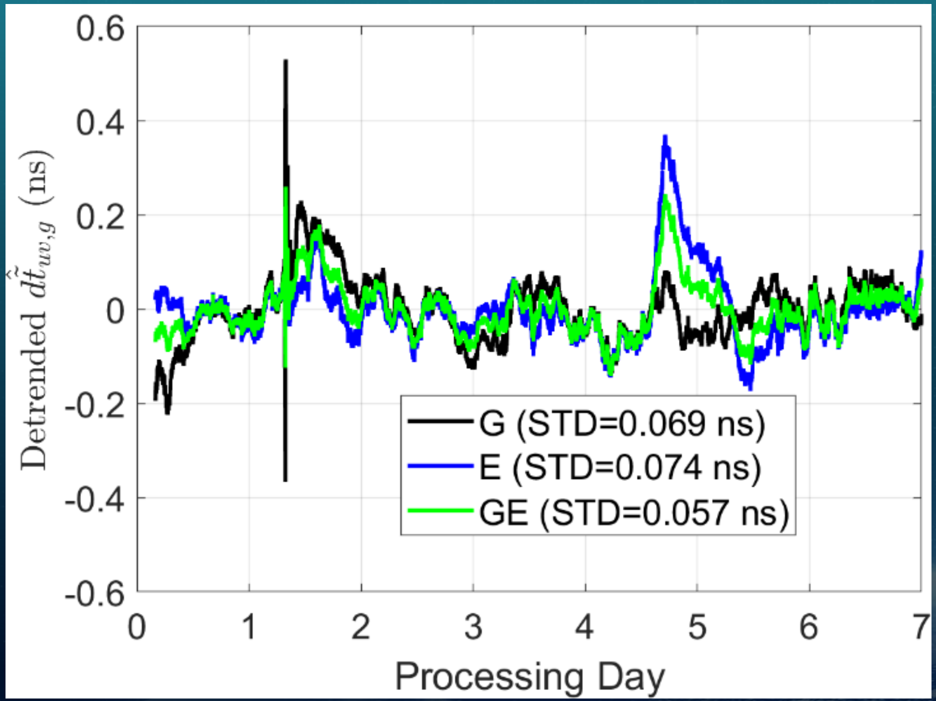
Step 1

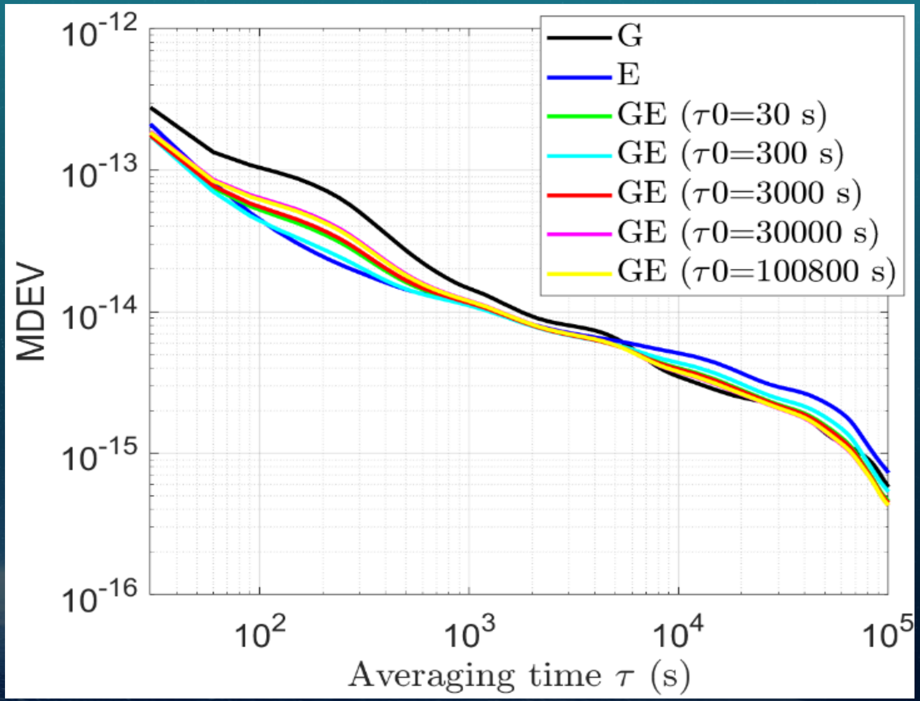
- Directly estimated receiver clock in Step 1
- 7-day STD about 0.15-0.2 ns

Step 2

- Systematic effects largely reduced
- 7-day STD 0.07~0.11 ns, 1-day STD 0.03~0.07 ns

Multi-system weighting
Step 3





Step 3

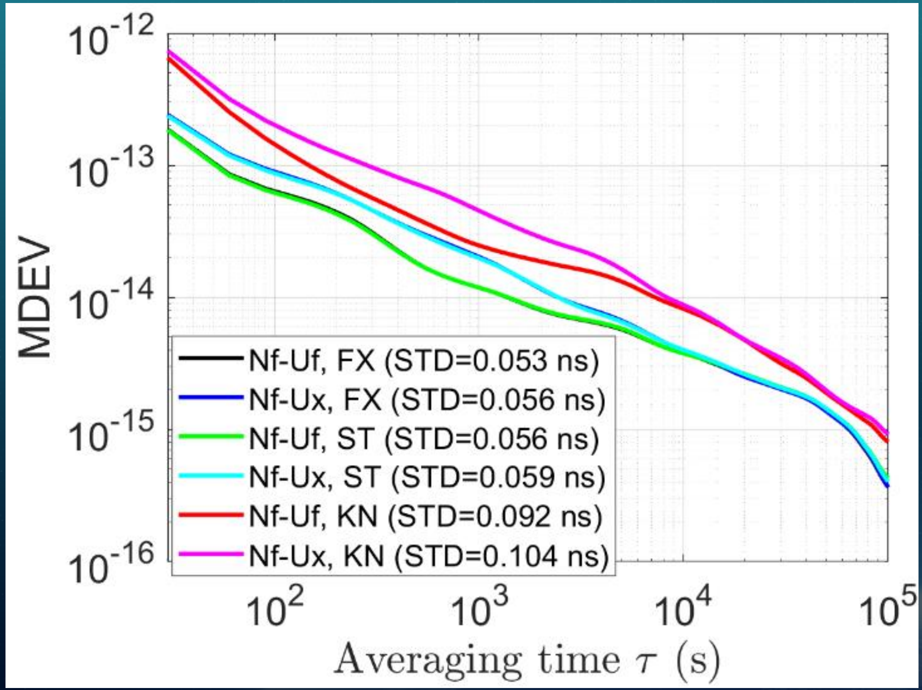
- **Multi-system weighted averaged improves the stability**
- **7-day STD ~ 0.06 ns**

Weighting factor selection

- **Different weighting factors can be selected for different averaging times**

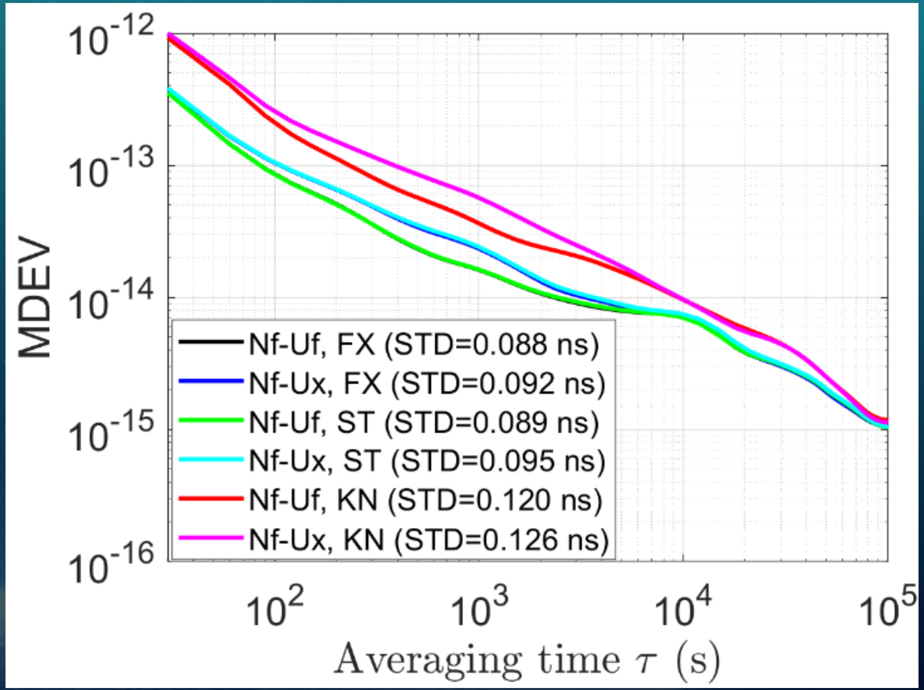
MDEV (G+E)

Different modes
different stages



BRUX-ONSA (884 km)

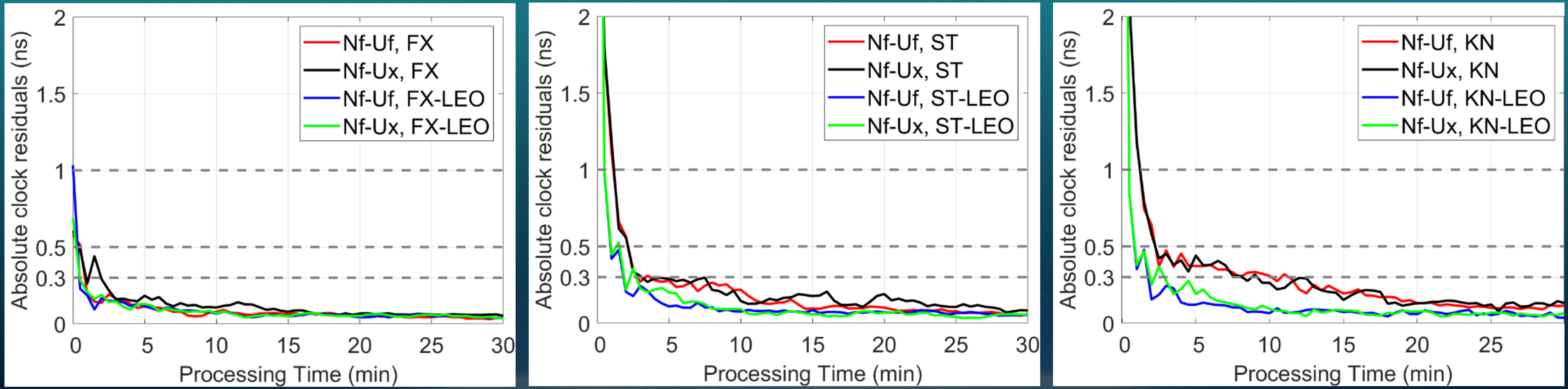
- **Fixed- & Static-mode stability better than kinematic mode**
- **Ambiguity fixing not beneficial for short-term stability**



WTZR-ONSA (920 km)

- **No significant difference between Fixed and static modes**
- **Averaging time at 86400: 10^{-15}**

GNSS→GNSS+LEO Convergence



Fixed

No significant improvement

Static

Convergence speed increased by 2 to 3 times

Kinematic

Convergence speed increased by 3 to 5 times

03

Simulation & Reality

LEO Navigation Signals

Biases of downlink antennas

Real-time LEO satellite orbits/clocks

04

Summary & Outlook

Summary & Outlook

01
Wide-area PPP-RTK Positioning & LEO

Fast convergence

Insensitive to the observation model

No need of ionospheric corrections and interpolations

02
Long-baseline time transfer based on UDUC wide-area PPP-RTK & LEO

Convergence speed increased by

2-3 times in static mode

3-5 times in kinematic mode

03
Challenges

Challenges from simulation to engineering practice

04
Outlook

Future trend in satellite-based PNT services for next 10 years

THANKS

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