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A Cost-Effective Crowdsourced Q4DIM Method for Rapid PPP Implementation in Wide Areas

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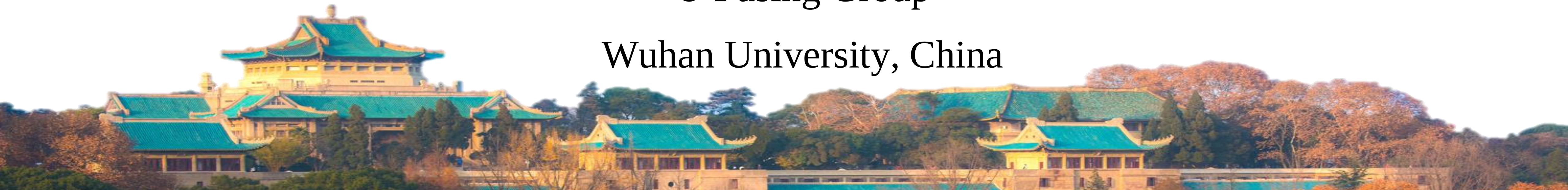
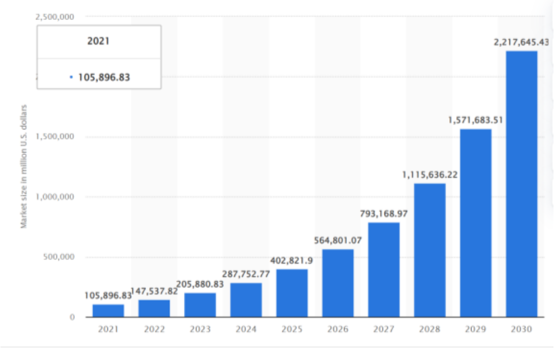


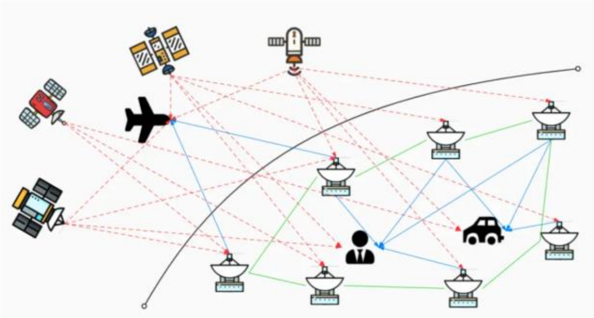
Background

- Statista forecasts that, during the period from 2019 to 2030, a total of 58 million autonomous vehicles will be sold by 2030 (Statista, 2023) . These GNSS-enable devices can benefit from the services provided by Precise Point Positioning (PPP), and have the potential to function as reference stations. This support enables the generation of wider-coverage and higher-resolution ionospheric products, ultimately achieving rapid PPP that relies on user collaboration.



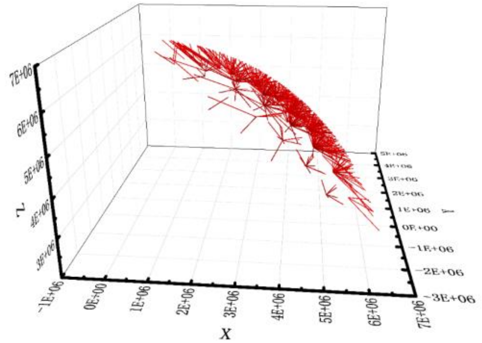
(Statista, 2023)

- Rapid PPP still faces two main challenges:
  - ✓ Generation of ionospheric corrections remains dependent on the sparsely distributed reference stations. Research on low-cost extraction of ionospheric information from massive public receivers is still limited.
  - ✓ Effectively receiving and processing the substantial corrections may present challenges to the data communication link and user computing unit.

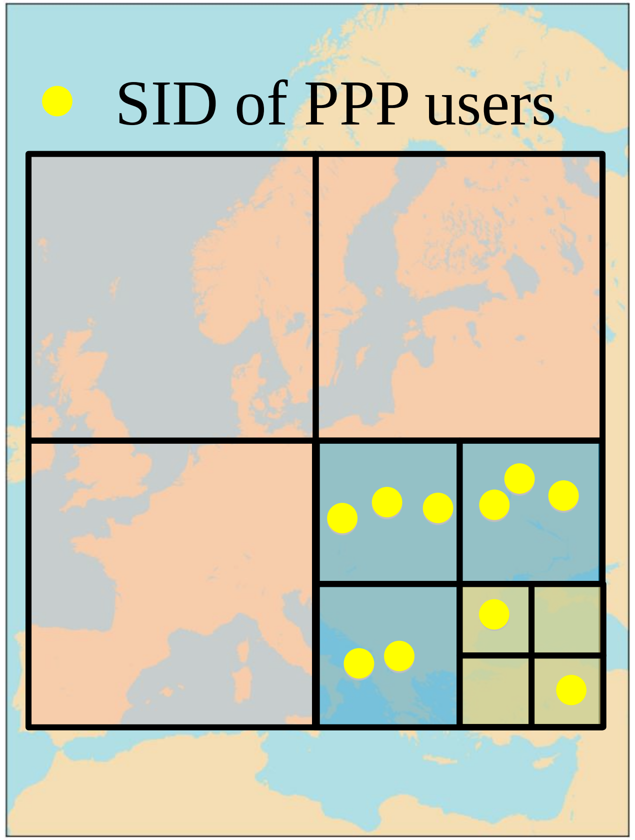


(Sohu, 2023)

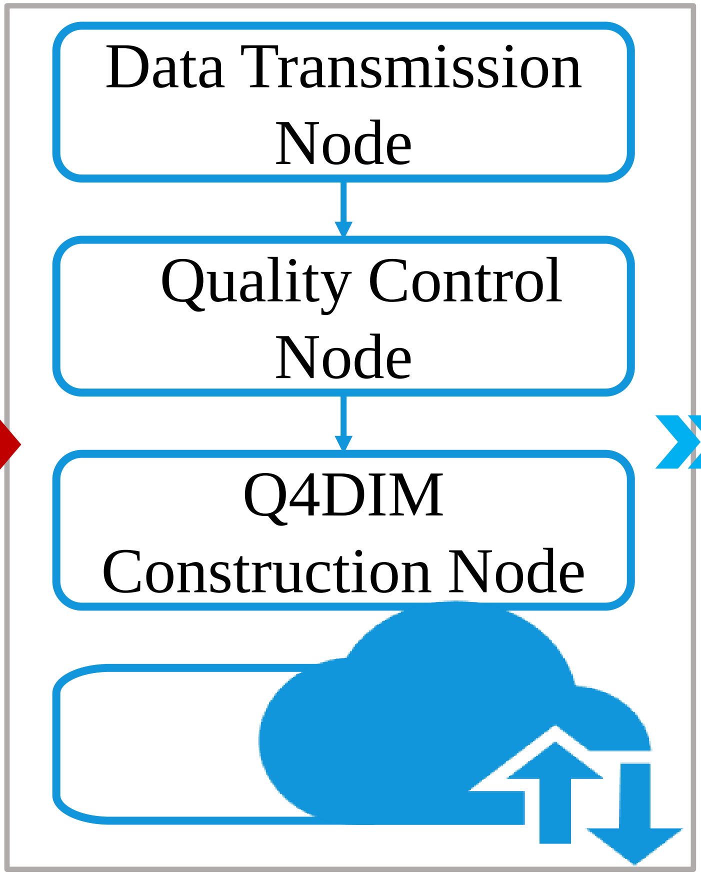
- Quasi-4-Dimensional Ionospheric Modeling (Q4DIM) introduced by Gu et al. (2022) greatly reduces the data volume of ionospheric corrections, alleviating communication burdens and computational memory consumption, especially for users coupled with dense reference stations.



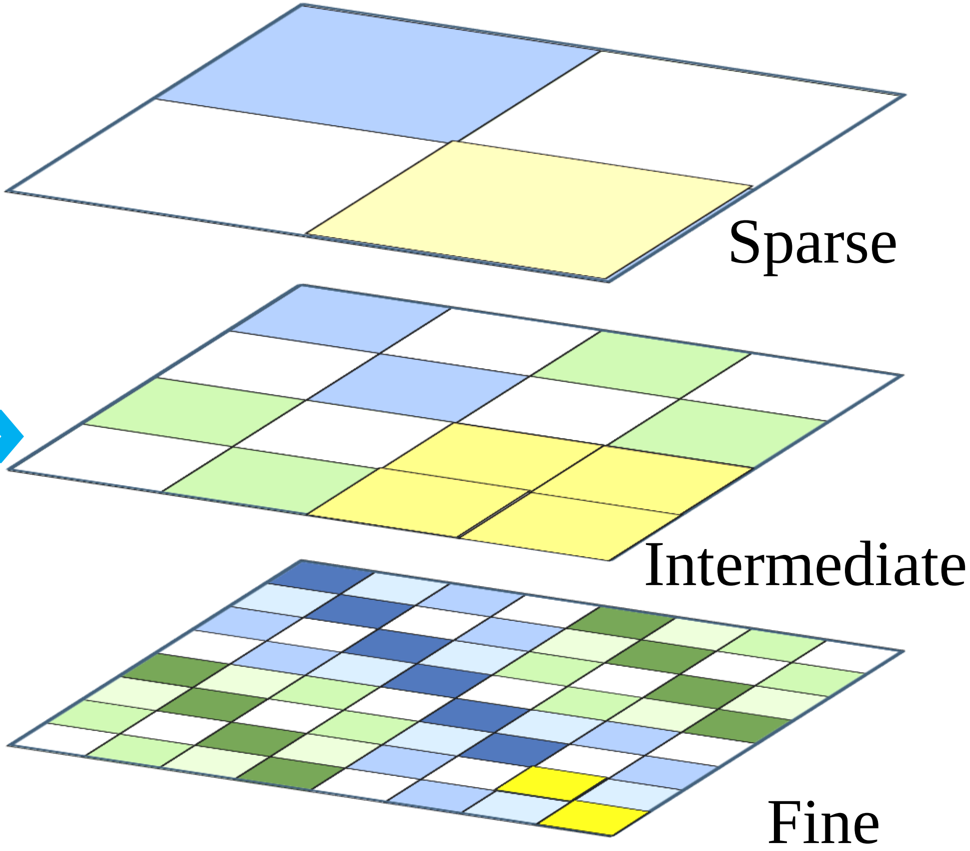
Crowdsourced Q4DIM System



SIDs Extraction from Massive Crowdsourced PPP Users



Q4DIM Construction on Cloud Server



Sparse-to-Fine Resolution Q4DIM Broadcasting

SIDs Extraction with PPP Model plus DESIGN

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- The UDUC PPP is conducted at each station to extract the SIDs, which is mathematically expressed as (Li et al., 2022):

$$\begin{cases} \Delta P_{r,i}^{s} = \boldsymbol{\mu}_r^s \cdot \mathbf{x} + t_r - t^s + m_{r,d}^s \cdot T_d + m_{r,w}^s \cdot T_w + \eta_i \cdot I_r^s + d_{r,i} - d_i^s + \varepsilon_P \\ \Delta \Phi_{r,i}^{s} = \boldsymbol{\mu}_r^s \cdot \mathbf{x} + t_r - t^s + m_{r,d}^s \cdot T_d + m_{r,w}^s \cdot T_w - \eta_i \cdot I_r^s + \lambda_i \cdot \left(N_{r,i}^s + B_{r,i} - B_i^s \right) + \varepsilon_\Phi \end{cases}$$

- Simplified UDUC PPP models treat ionospheric parameters as white noise or random walk for estimation, in which the receiver code hardware delay is hard to distinguish (Xiang et al., 2019). Therefore, the DESIGN method is introduced to mitigate the receiver-specific DCB, which estimates receiver-specific DCB as a constant, and ionospheric delay is constrained by the following equation (Zhao et al., 2019) :

$$\begin{cases} I_r^s = C_0 + C_1 \cdot \mathrm{d}l + C_2 \cdot \mathrm{d}l^2 + C_3 \cdot \mathrm{d}b + C_4 \cdot \mathrm{d}b^2 + r_r^s \\ C_i(t) = \alpha_0 + \sum_{j=1}^{3} \left(\beta_j \cdot \sin\left(2\pi t f_j\right) + \gamma_j \cdot \cos\left(2\pi t f_j\right) \right), i = 0,1,2,3,4 \end{cases}$$

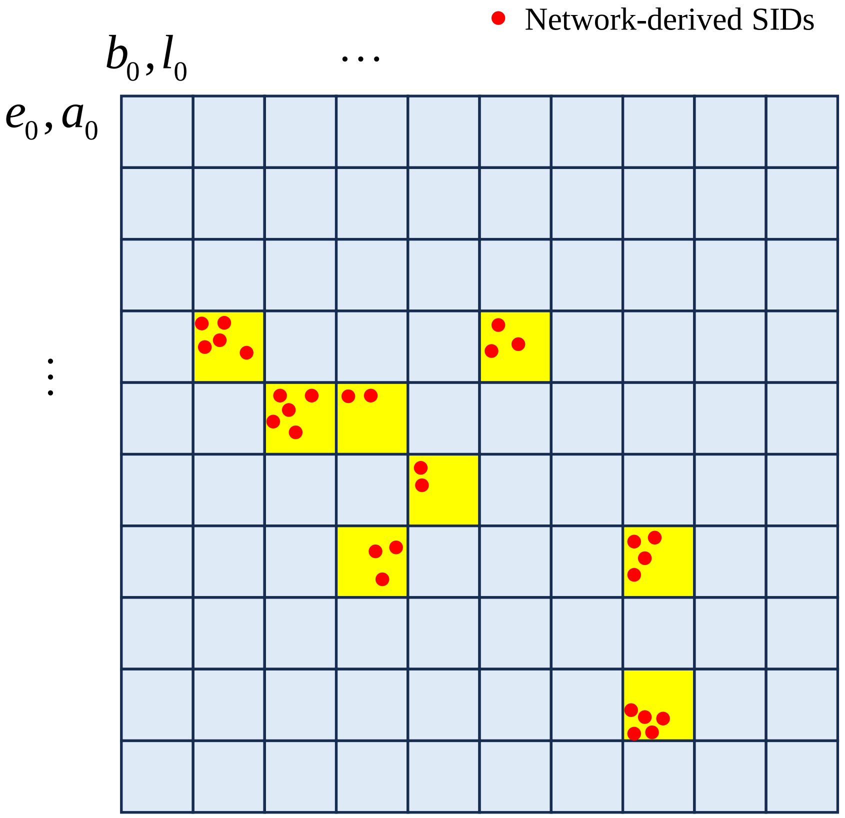
Q4DIM Generation and Update

- The Quasi-4-Dimension Ionospheric Modeling (Q4DIM) is a flexible atmospheric model that enables enhanced PPP positioning from wide-area to regional applications. It divides the slant ionospheric delays (SIDs) from a station network into various clusters based on the latitude and longitude of the Ionosphere Piercing Point (IPP), satellite elevation, and satellite azimuth (Gu et al., 2022).

- The network-derived SIDs are classified into their nearest grid points (denoted as target grid points) based on the minimum Euclidean distance criterion, which can be expressed as:

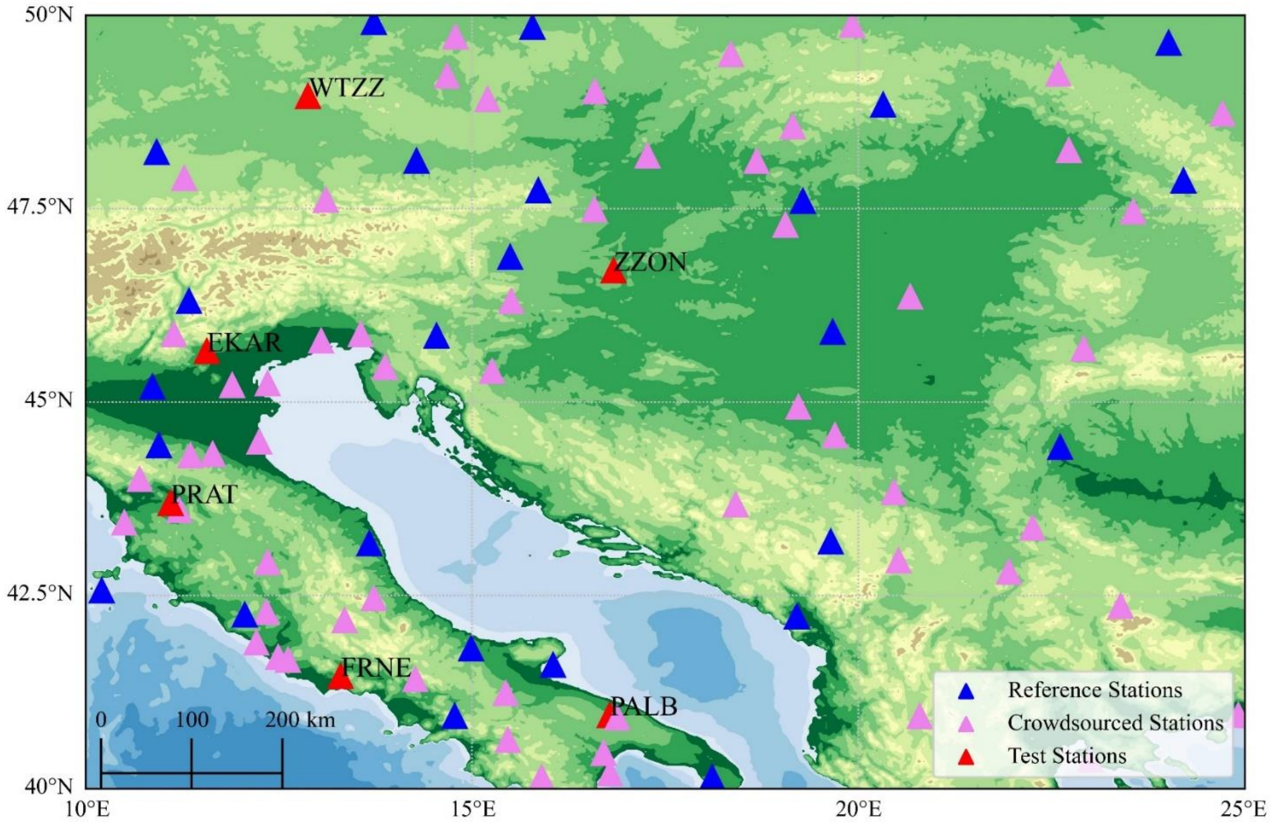
$$\mathbf{G}_{mnop} = \arg\min_{\boldsymbol{\Gamma}^{grid}} \left\| \boldsymbol{\Gamma}_{k}^{los} - \boldsymbol{\Gamma}_{ijmn}^{grid} \right\|_2$$

- Finally, the new classified SIDs will be involved in the generation of Q4DIM.



Schematic of the Q4DIM grid (simplified 2D projection) and some of network-derived SIDs (red points) assigned to the target grid points.

Experiments on European CORS



Grids Information：

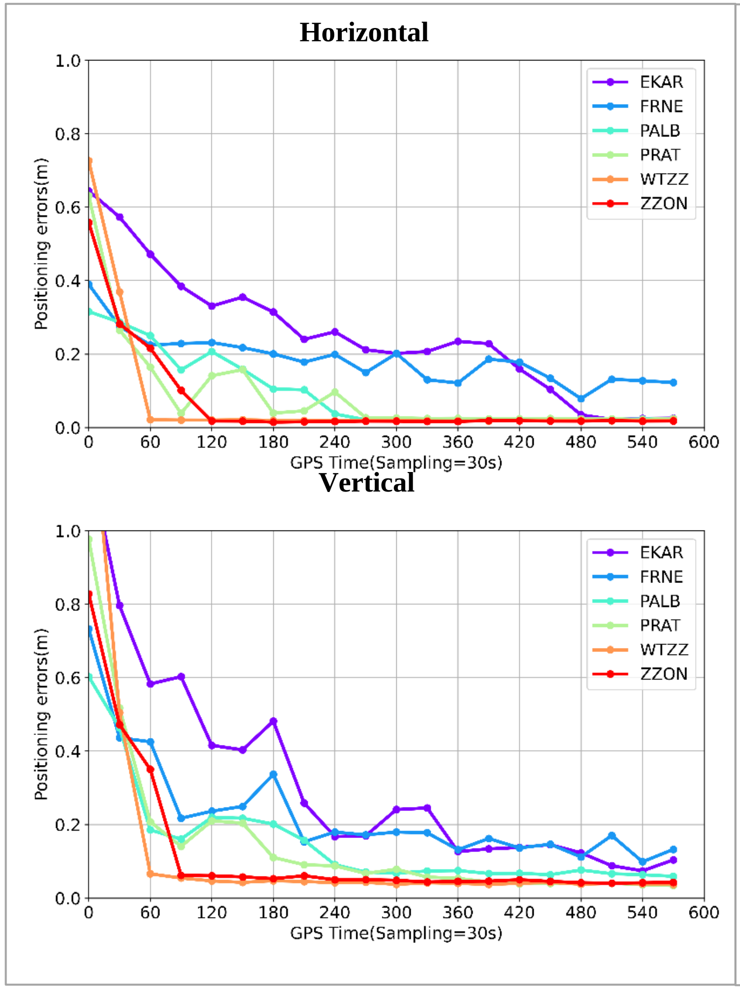
- Latitude: (40°N, 42.5° N, 45°N, 47.5°N, 50°N)
- Longitude: (10°E, 15°E, 20°E, 25°E)
- Elevation: (0°, 3°, …, 90°)
- Azimuth: (0°, 4°, …, 360°)

Experiments Information：

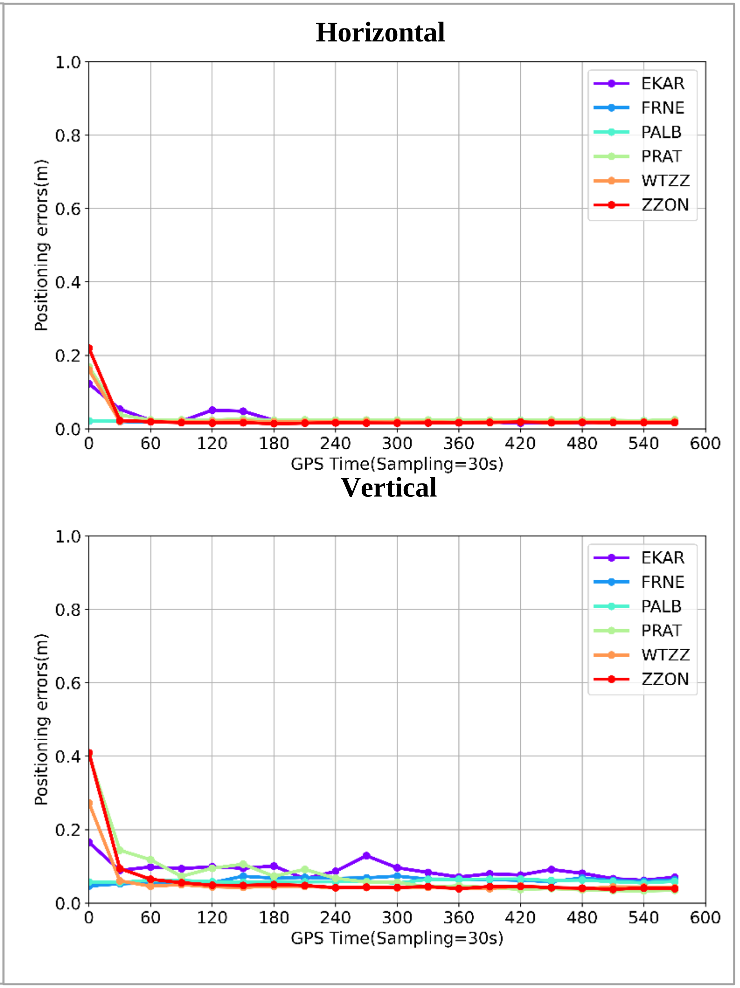
- Time: February 1, 2024
- Observation System: GPS + Galileo + BDS
- Observation Sampling: 30 s
- Stations Setting:
  - ✓ Stations marked by blue triangles are designated as the reference station, which is used for extracting the original Q4DIM map. The average inter-station distance within each latitude and longitude grid is approximately 200 km.
  - ✓ Stations marked by pink triangles are designated as crowdsourced stations, which are used for extracting the crowdsourced Q4DIM map.
  - ✓ Stations marked by red triangles are used for evaluating the performance of the two maps.
- Divide the 24-hour data into 144 segments at 600-second intervals, and conduct independent repeated experiments for evaluation in each segment.

Results

95% confidence level



PPP Enhanced by the Original Map



PPP Enhanced by the Crowdsourced Map

Results shows:

- Position errors enhanced by the crowdsourced Q4DIM map are significantly better than those of the original Q4DIM map.
- Besides station EKAR and station FRNE, the positioning error series of the original solution converges within **5 epochs** to within 10 cm in the horizontal direction and 20 cm in the vertical direction (reliable state); EKAR takes 9 epochs to reach a reliable state, while FRNE has never reached a reliable state.
- Compared to the original solution, the positioning error series of the crowdsourced solution reaches a reliable state in **2 epochs**; the positioning accuracy improves by **48.2%** in the **horizontal** direction and **41.2%** in the **vertical** direction.

Thanks for Your Attention!

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