GNSS-based Precise Troposphere Zenith Path Delay Determination with high Temporal Resolution

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Abstract: The Global Navigation Satellite System (GNSS)-based precise troposphere Zenith Pass Delay (ZPD) determination with high temporal resolution needs precise positioning for ground stations, which can be done with Precise Point Positioning (PPP). There are two main approaches to estimate the ZPD parameters using PPP: first one is modeled the zenith path delay parameter as random walk for each observation epoch with process noise; second one is modeled the parameter as piecewise linear or piecewise constant for a certain time interval. Currently for estimating troposphere ZPD parameters, batch estimation is used for the piecewise linear or constant parameters; sequential estimation is used for the random walk parameters, which can compensate the stochastic model errors by adding process noise. But when the interval is same for both approaches, the results should be close. However, the estimated some troposphere ZPD parameters are not stable and have jump problems between the parameters for piecewise constant parameterization. To solve for such problems, adding process noise for ZPD parameters in batch estimation is proposed. The main goal of this study is to obtain a stable and smooth solution under no significant loss of signals for ZPD. The result shows such a solution for ZPD parameters can be obtained with the proposed approach.

Background and Motivations

- GNSS-based tropospheric Zenith Path Delay (ZPD) determination requires a **precise positioning** (DGNSS or PPP).
- DGNSS for ZPD is based on a **sufficient large distance** (> 500 km), or to estimate the ZPD differences for a small distance (< 500 km).
- PPP is **flexible.** And it can be used for estimating the **absolute** ZPD.
- ZDP solutions are sometimes not stable (jump problem), when the temporal resolution is higher.
- How can we get **a stable** solution for ZPD with as **high temporal resolution** as possible?
- Adding process noise for ZPD batch estimation is proposed to use to get a stable solution.

Objectives

- Review the **current approaches** for ZPD determination.
- Describe the proposed **approach (adding process noise for ZPD in batch estimation)**, which we used for our study.
- Study the **impact of different process noises (mapping factors)** on ZPD estimates.
- Assess the results through **internally** relative comparisons and **externally** absolute comparisons.

Approaches for ZPD Determination

Institute	CSR (This study)	IGS	JPL
Method	PPP	PPP	PPP
Software	MSODP	Bernese	GIPSY
Temporal resolution (Min)	5.0	5.0	5.0
Data arc (hour)	24 - 30	27	24
Ele. cutoff (Deg)	7	7	7
Parametrization	Piecewise constant	Piecewise linear	Random walk
A priori for ZPD	No / 0.4 m	1 mm	0.1 m
Process noise	2 mm	no	3 cm/h

Parametrizations for ZPD

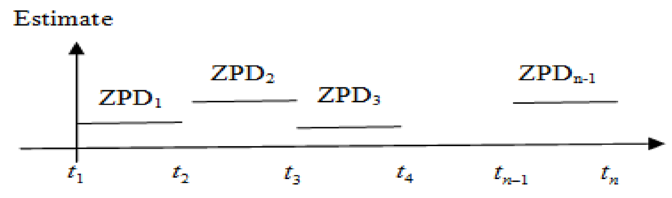

Figure 1 Piecewise constant ZPD parametrization

Piecewise Constant

$$t_{i-1} \le t < t_i$$

$$ZPD(t) = ZPD_{i-1}$$

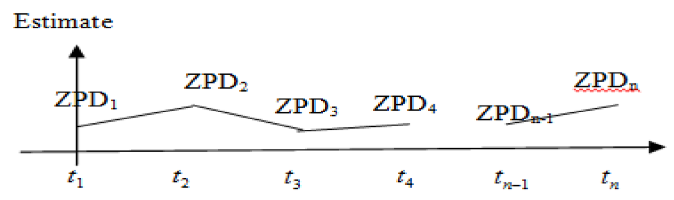

Figure 2 Piecewise linear ZPD parametrization

Piecewise Linear

$$ZPD(t) = \frac{t - t_{i-1}}{\Delta t} ZPD_i + \frac{t_i - t}{\Delta t} ZPD_{i-1}$$

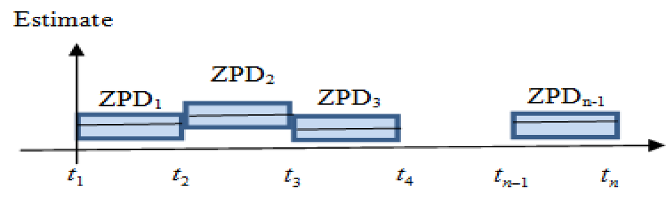

Figure 3 Random walk ZPD parametrization

Random Walk

$$ZPD(t) = ZPD_{i-1}$$

$$ZPD_i = ZPD_{i-1} + w(t)\Delta t$$

Process Noise in Batch Estimation

General linearized equations:

$$\vec{y} = A\vec{x} + B\vec{z} + \vec{\varepsilon} \qquad \text{Observation equation}$$

$$\vec{0} = C\vec{z} + \vec{v}_p \qquad \text{Process noise equation}$$

Solution:

$$\begin{bmatrix} \hat{\vec{x}} \\ \hat{\vec{z}} \end{bmatrix} = \left\{ \begin{bmatrix} A^TWB & A^TWB \\ B^TWA & B^TWB \end{bmatrix} + \begin{bmatrix} O & O \\ O & C^TP^{-1}C \end{bmatrix} \right\}^{-1} \left\{ \begin{bmatrix} A^TW\vec{y} \\ B^TW\vec{y} \end{bmatrix} \right\}$$

Sample Process Noise in Batch Estimation

When the first-order Gauss-Markov process is used to generate process noise, the process satisfies following equation:

$$z_{i+1} = mz_i + w_i \quad i = 1, 2 \ldots n$$

$$E(w_i^2) = \sigma^2(1 - m^2) \qquad m_i = e^{-(t_{i+1} - t_i)/\tau}$$

where *m* is mapping factor.

When the entire arc is divided into four intervals of equal duration , the matrices can be express as following:

$$C = \begin{bmatrix} m & -1 & 0 & 0 \\ 0 & m & -1 & 0 \\ 0 & 0 & m & -1 \end{bmatrix} \qquad P^{-1} = \begin{bmatrix} \frac{1}{(1-m^2)\sigma^2} & & \\ & \frac{1}{(1-m^2)\sigma^2} & \\ & & \frac{1}{(1-m^2)\sigma^2} \end{bmatrix}$$

$$C^TP^{-1}C = \frac{1}{(1-m^2)\sigma^2} \begin{bmatrix} m^2 & -m & 0 & 0 \\ -m & 1+m^2 & -m & 0 \\ 0 & -m & 1+m^2 & -m \\ 0 & 0 & -m & 1 \end{bmatrix}$$

Test Data and Test Cases

The PPP for station **BJFS** was carried out for determining ZPD using the IGS data from January 1 to 31, 2015.

Case name	5MN	5MPN1	5MPN2	5MPN3
Data arc length [hours]	24	24	24	30
Mapping factor	N/A	0.99499	0.99995	0.99995

Fig. 1. Case 5MN, 5MPN1 vs 5MPN2

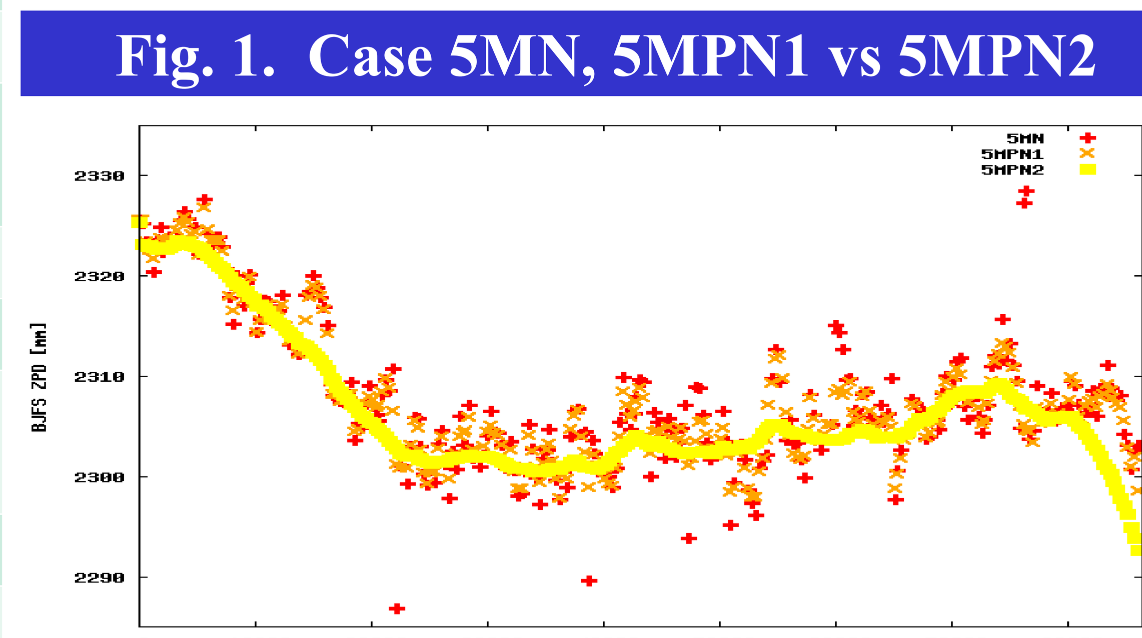

Fig. 2. Case 5MPN2 vs 5MPN3

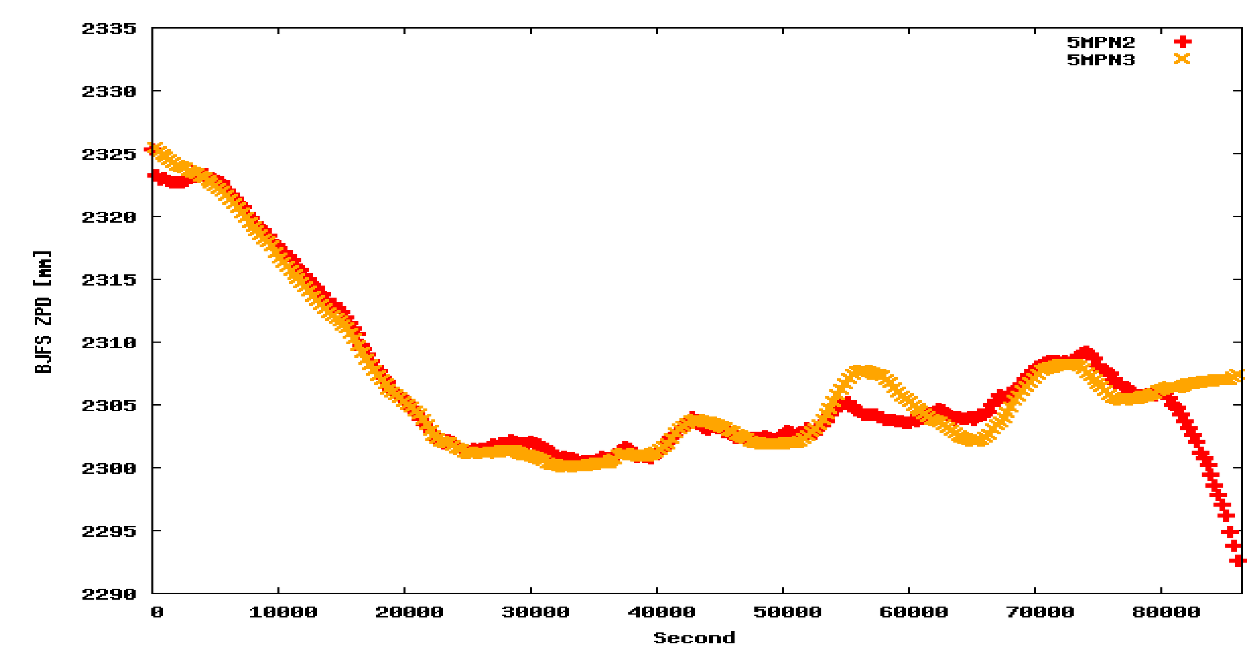

Fig. 3. Case 5MN vs 5MPN1

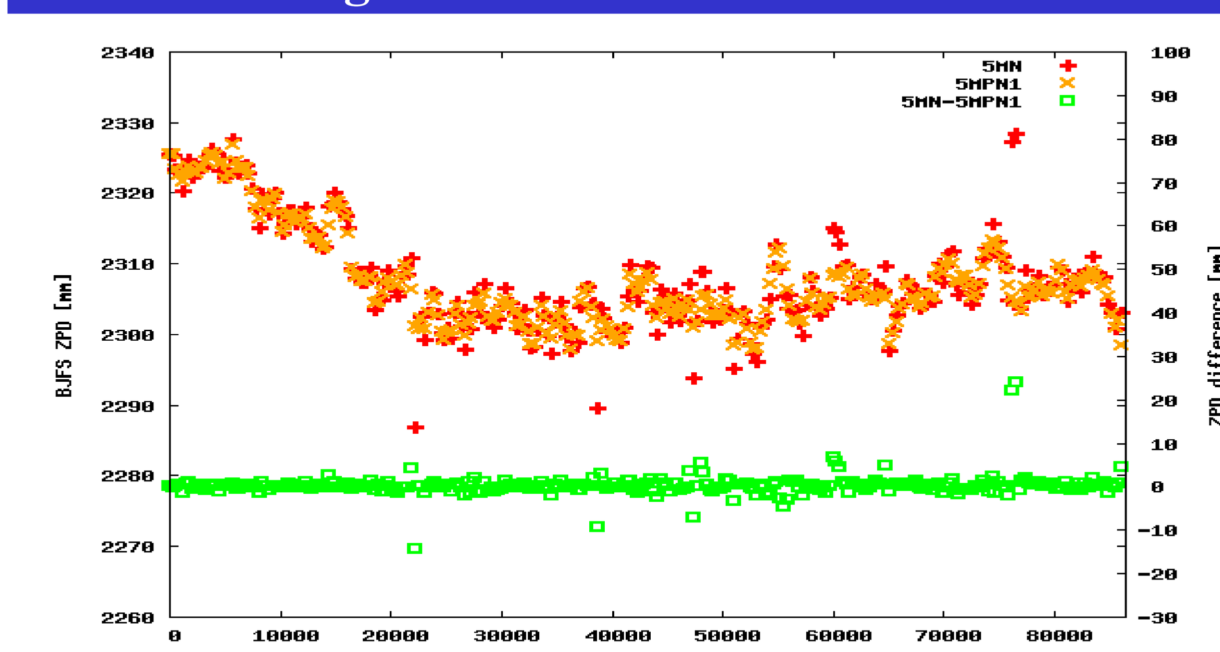

Fig. 4. ZPD External Comparisons

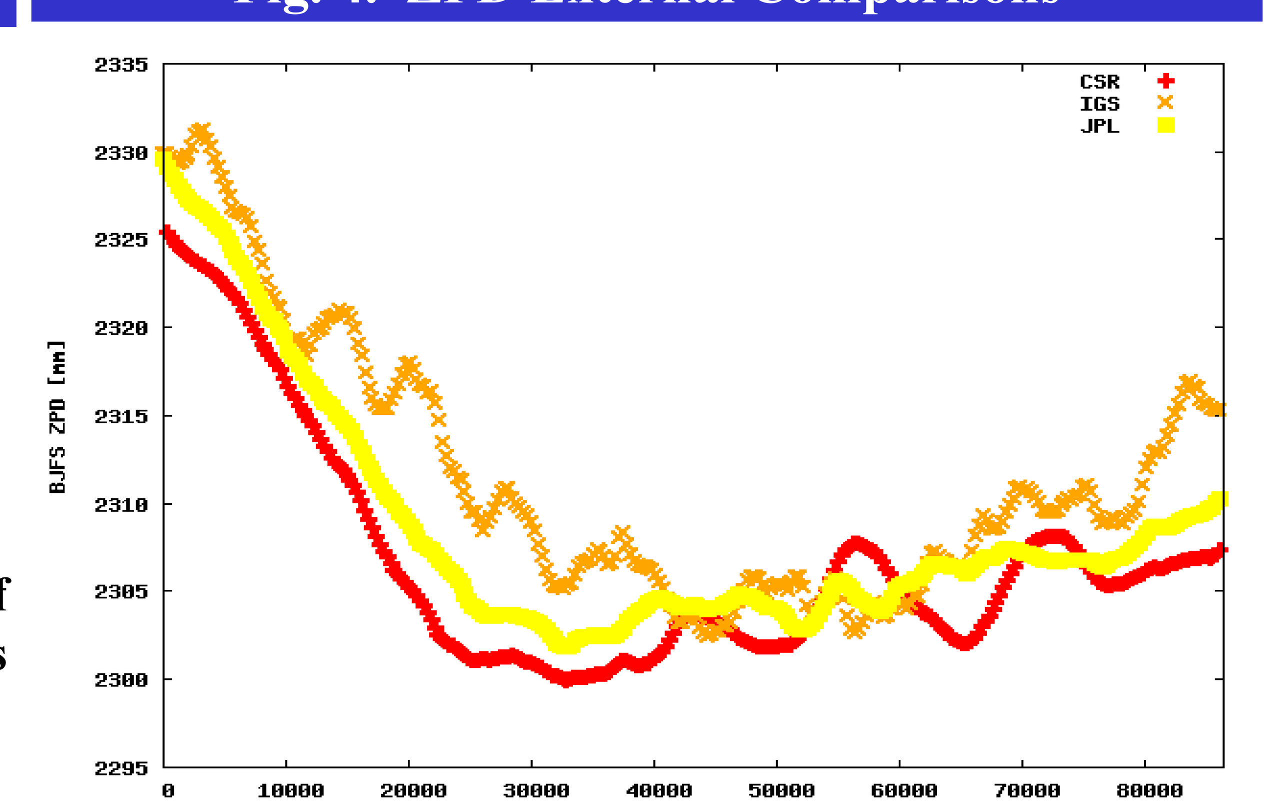

Table 1. ZPD Differences [mm]

	Case	5MN	5MPN1	5MPN2	5MPN3
IGS	Mean	-1.0	-1.3	-2.7	-3.5
	Std.	4.9	4.6	4.0	3.2
	RMS	5.1	5.0	4.9	4.8
JPL	Mean	0.2	-0.1	-0.9	-1.5
	Std.	4.2	3.7	2.5	1.6
	RMS	4.4	3.8	2.8	2.2

Summary and Conclusions

- The GNSS-based stable and smooth solution for ZPD with a temporal resolution of 5 minutes can be achieved using **piecewise constant parametrization by adding process noise in batch estimation.**
- A stable and smooth solution for ZPD parameters is obtained by selecting a **proper process noise, mapping factor and data arc length**.
- Based on the external comparisons with IGS and JPL ZPD products, the accuracy of the CSR ZPD estimates is about 5 mm.