Qiao WANG, Xiao-jun JIN, Wei ZHANG, Shi-ming MO, Zhao-bin XU, Zhong-he JIN, 2019. An online error calibration method for spaceflight TT&C systems based on LEO-ground DDGPS. *Frontiers of Information Technology & Electronic Engineering*, 20(6):829-841. https://doi.org/10.1631/FITEE.1800308

# An online error calibration method for spaceflight TT&C systems based on LEO-ground DDGPS

**Key words:** Spaceflight; low Earth orbit (LEO); Filter; Optimization; Calibration

Corresponding author: Xiao-jun JIN
E-mail: axemaster@zju.edu.cn
ORCID: Xiao-jun JIN, http://orcid.org/0000-0002-8804-9890;
Qiao WANG, http://orcid.org/0000-0002-0678-047X

# Motivation

1. To ensure the measurement accuracy of spaceflight telemetry, tracking and command (TT&C) systems, the measurement errors of spaceflight TT&C systems need to be calibrated.

2. The disadvantages of traditional calibration methods can be summarized into the following three issues:

   (1) When calibrated with pre-calibration methods, the residual measurement error is still large;

   (2) The precalibration methods cannot reflect the real error characteristics of on-orbit space missions;

   (3) The precalibration methods cannot cope with the time-varying characteristics of measurement errors during the on-orbit operation phase.

# Main idea

A new online error calibration method based on low Earth orbit satellite-to-ground double-differential GPS (LEO-ground DDGPS) is proposed in this study. Using the precise baseline solution of double-differential GPS (DDGPS) as a reference, the measurement error of spacecraft TT&C systems can be precisely calibrated.

# Method

1. LEO-ground baseline determination:

   (1) LEO-ground double-differential GPS (DDGPS) was formed;

   (2) An adaptive robust Kalman filter (ARKF) was using to determinate the baseline;

   (3) The fixed-interval smoother was used to smooth the baseline solution of the forward and backward ARKFs;

   (4) The cascading integer resolution method based on the ACO algorithm was adopted to fix integer ambiguity.

2. Solving the range error model of TT&C systems using a batch LSQ algorithm.

3. Carrying out three groups of experiments based on the proposed method.

# Results of baseline determination

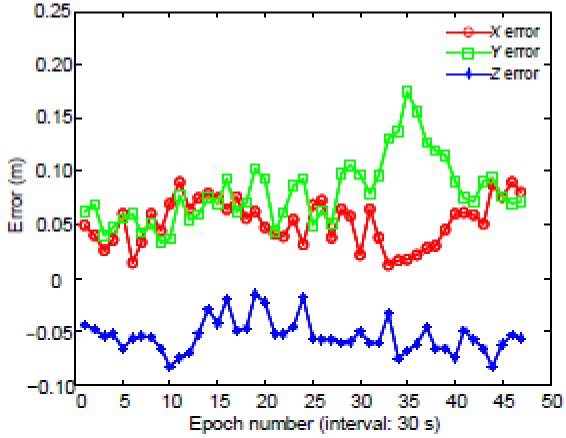


Fig. 4 Solution error of baseline B1

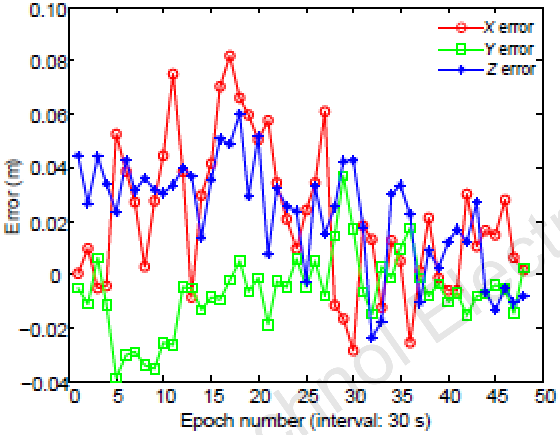


Fig. 5 Solution error of baseline B2

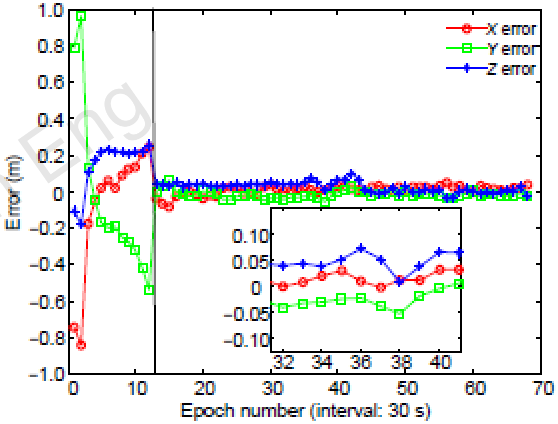


Fig. 6 Solution error of baseline B3

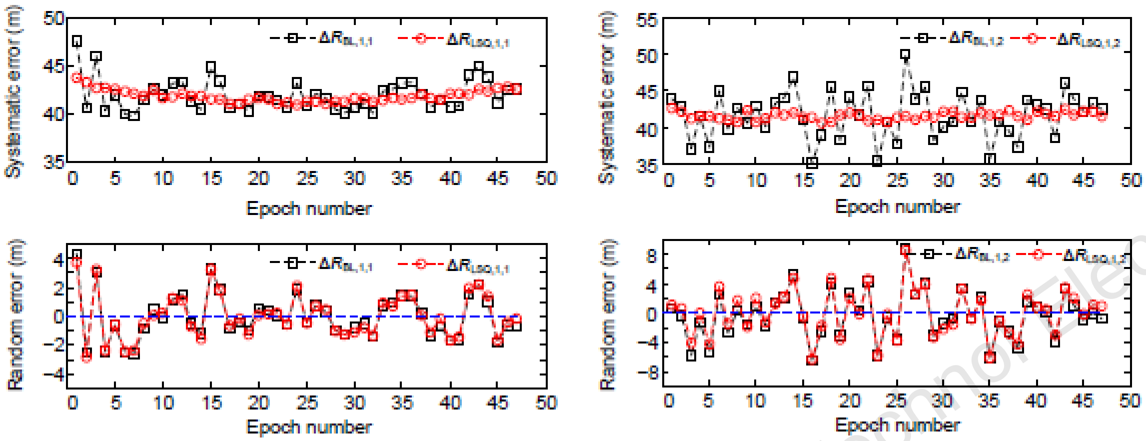
**Table 5 The smoothed baseline accuracy and the fixing probability of carrier phase ambiguity**

| Item | Value | | |
|---|---|---|---|
| | B1 | B2 | B3 |
| *x*-axis (RMS, m) | 0.057 | 0.033 | 0.025 |
| *y*-axis (RMS, m) | 0.094 | 0.015 | 0.024 |
| *z*-axis (RMS, m) | 0.054 | 0.030 | 0.036 |
| \|baseline\| (RMS, m) | 0.120 | 0.047 | 0.050 |
| NW | 57% | 55% | 48% |
| $N_1$ | 30% | 32% | 36% |

With the fixed-interval smoother, a baseline accuracy (RMS, single axis) of better than 10 cm is achieved.

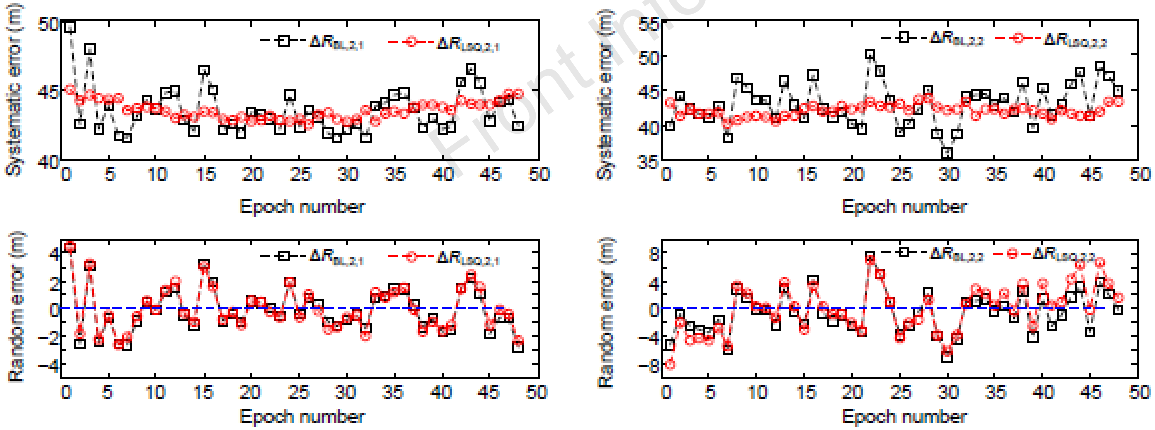
The convergence of the baseline solution is affected by the geometric configuration of the observed GPS satellites and the observation noise of the GPS receivers.

# Results of range error calibration (1)



(a) (b)

Fig. 7 Error calibration of B1: (a) $\varepsilon_{BL,1,1}$=1.5; (b) $\varepsilon_{BL,1,2}$=3



(a) (b)

Fig. 8 Error calibration of B2: (a) $\varepsilon_{BL,2,1}$=1.5; (b) $\varepsilon_{BL,2,2}$=3

The range error expressed as $\Delta R_{\mathrm{LSQ},i,j}$ calibrated by the batch LSQ algorithm precisely fits the variation of the range error $\Delta R_{\mathrm{BL},i,j}$.

The bias $\varepsilon_{\mathrm{LSQ},i,j}$ is quite consistent with the random error $\varepsilon_{\mathrm{BL},i,j}$.

# Results of range error calibration (2)

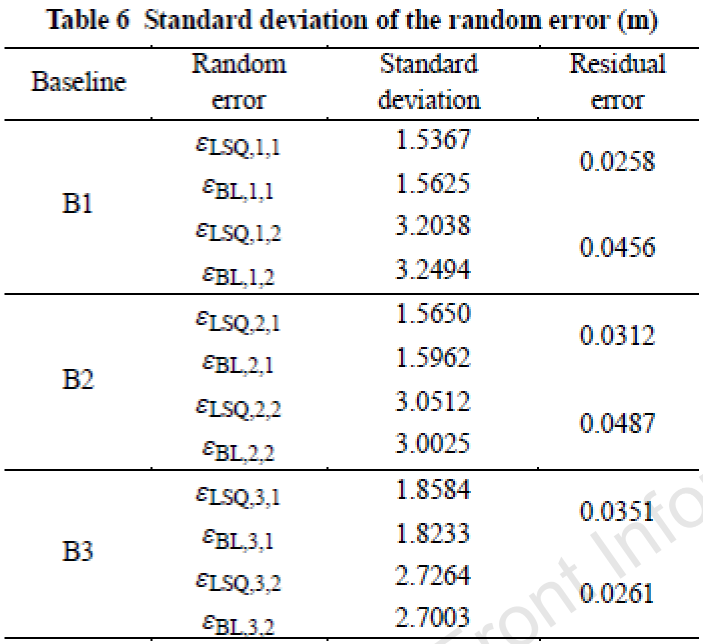


Table 6 Standard deviation of the random error (m)

| Baseline | Random error | Standard deviation | Residual error |
|---|---|---|---|
| B1 | $\varepsilon_{LSQ,1,1}$ | 1.5367 | 0.0258 |
| | $\varepsilon_{BL,1,1}$ | 1.5625 | |
| | $\varepsilon_{LSQ,1,2}$ | 3.2038 | 0.0456 |
| | $\varepsilon_{BL,1,2}$ | 3.2494 | |
| B2 | $\varepsilon_{LSQ,2,1}$ | 1.5650 | 0.0312 |
| | $\varepsilon_{BL,2,1}$ | 1.5962 | |
| | $\varepsilon_{LSQ,2,2}$ | 3.0512 | 0.0487 |
| | $\varepsilon_{BL,2,2}$ | 3.0025 | |
| B3 | $\varepsilon_{LSQ,3,1}$ | 1.8584 | 0.0351 |
| | $\varepsilon_{BL,3,1}$ | 1.8233 | |
| | $\varepsilon_{LSQ,3,2}$ | 2.7264 | 0.0261 |
| | $\varepsilon_{BL,3,2}$ | 2.7003 | |

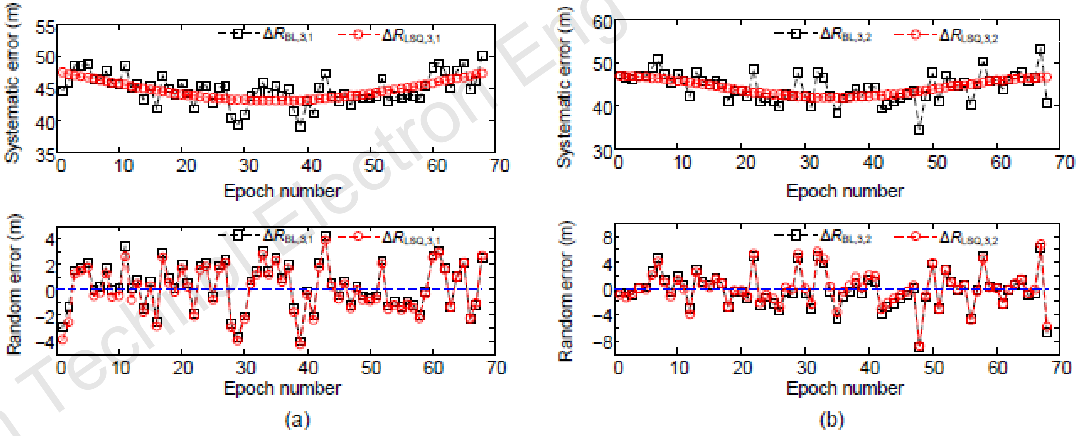


Fig. 9 Error calibration of B3: (a) $\varepsilon_{BL,3,1}$=1.5; (b) $\varepsilon_{BL,3,2}$=3

After calibration, the residual systematic error of the range data is less than 5 cm.

The online error calibration results showed that the online error calibration method can accurately separate the systematic error of the range data, and thus the accuracy of the range data is affected only by the random error.

# Conclusions

1. With the proposed method, an LEO-ground baseline solution with an accuracy of better than 10 cm can be obtained, and the systematic error of range measurement can be accurately separated, which results in a residual systematic error of less than 5 cm.

2. The measurement error of TT&C systems is almost fully calibrated and thus affected only by the random error.

3. The proposed method showed its superiority over the traditional error calibration method.