Flight Test Data Validation of GPS Ranging Error Characteristics

Haochen Tang

Todd Walter, Juan Blanch and Per Enge

Stanford University

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Introduction and Motivation

• Dual-frequency GPS signals exclude the ionosphere delays

• However, the measurement combination increases signal noises

• Carrier smoothing is developed to alleviate the ranging signal noise

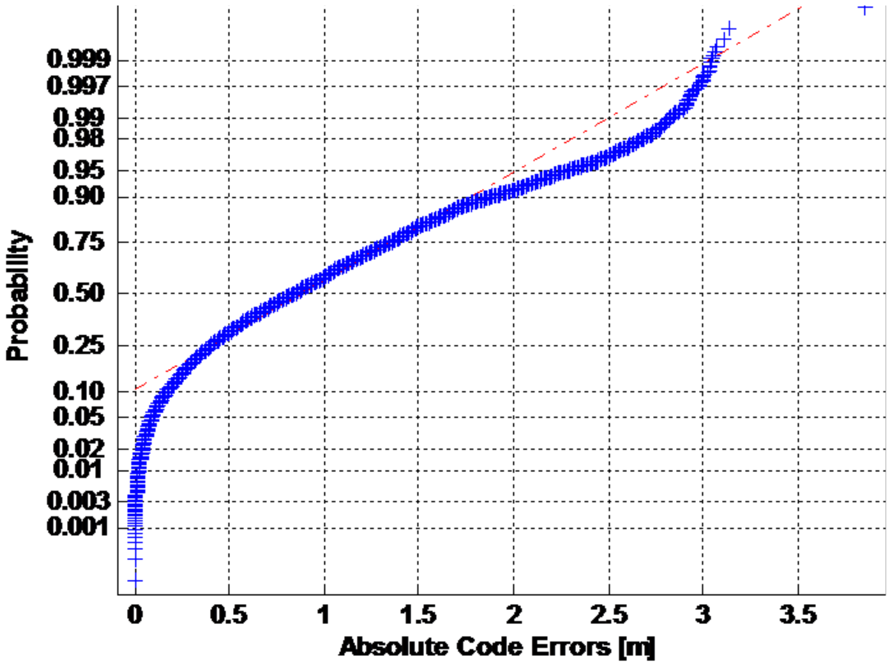
• Unexpected results occur when processing the flight test GPS measurement data with algorithms developed for static receiver data processing

→ Shown in the followed flight test data error statistics

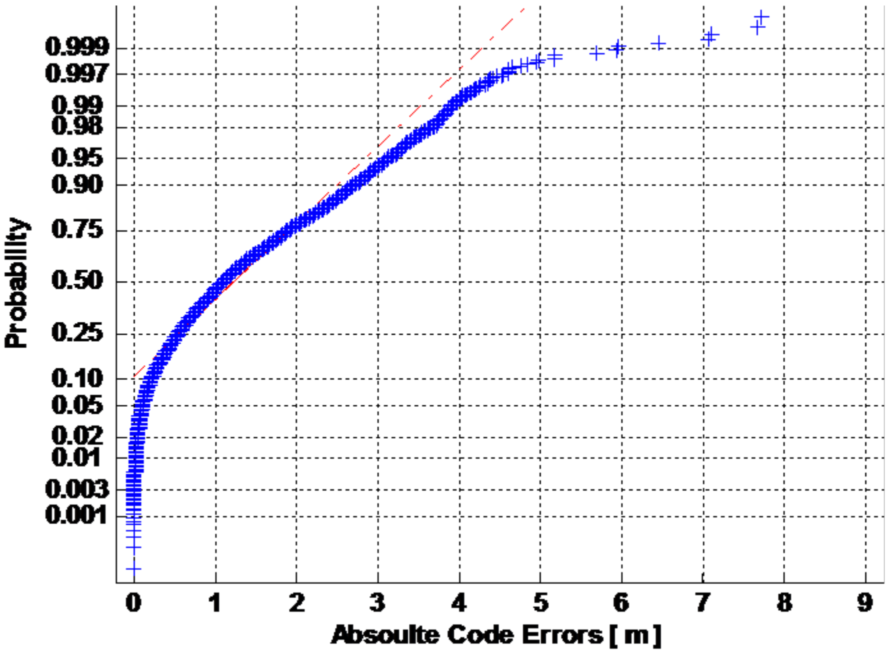
Code Measurement Error Statistics

WAAS corrected ranging errors in the flight test

Non-smoothed L1 code error distribution



Non-smoothed dual-freq code error distribution



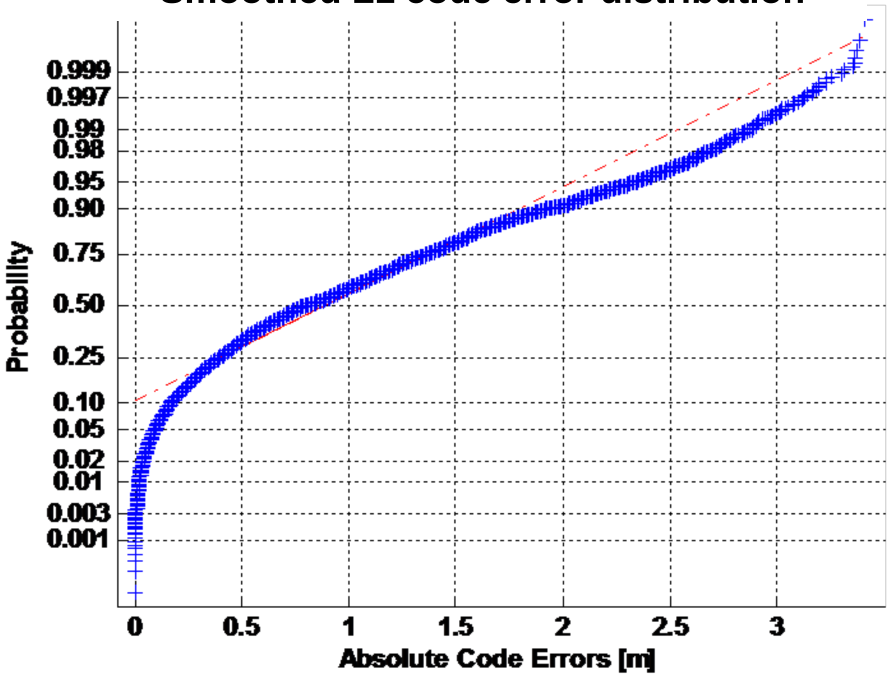
95% of Non-smoothed L1-only errors are within ±2.4m
95% of Non-smoothed dual-freq errors are within ±3.1m

Only a small increase in the noise going from L1-only to Dual-freq signal

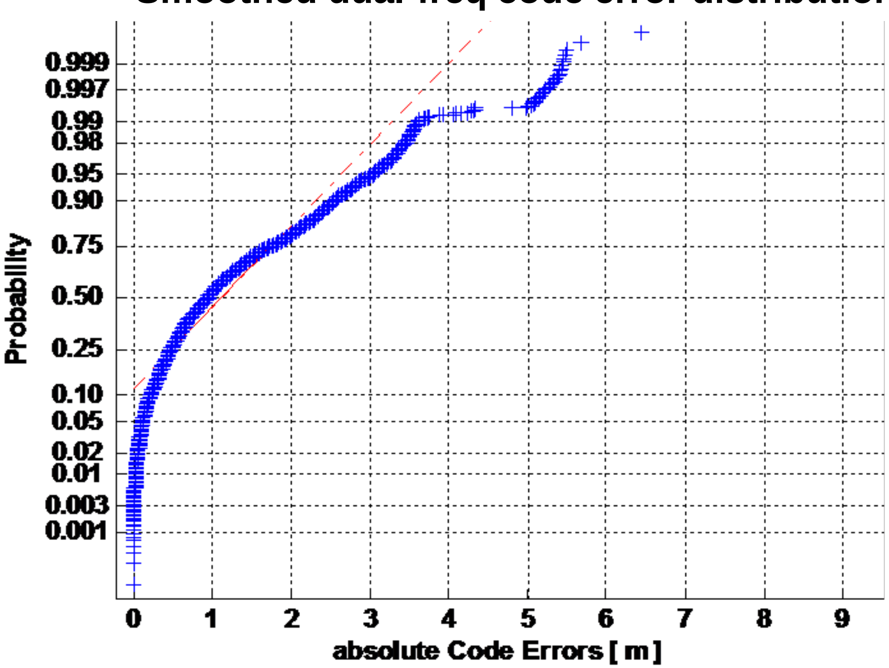
Code Measurement Error Statistics

WAAS corrected and Carrier smoothed ranging errors

Smoothed L1 code error distribution



Smoothed dual-freq code error distribution



95% of Smoothed L1-only errors are within ±2.3m (±2.4m)
95% of Smoothed dual-freq errors are within ±3m (±3.1m)

Carrier smoothing did NOT effectively reduce the apparent meas. noises

Introduction and Motivation

Error statistics do NOT agree with well-established concepts:

- **<u>Dual-freq signals should be much noisier than L1-only signals</u>**
- **<u>Carrier smoothing should effectively reduce code meas. Noises</u>**

Are there any unidentified errors with the flight test data?

Before get into details of the data, take a brief look at the data processing background.

Flight test Data Collection and Record

<u>Date</u>: Sep 19th, 2006

<u>Site</u>: Memphis Int'l Airport, TN

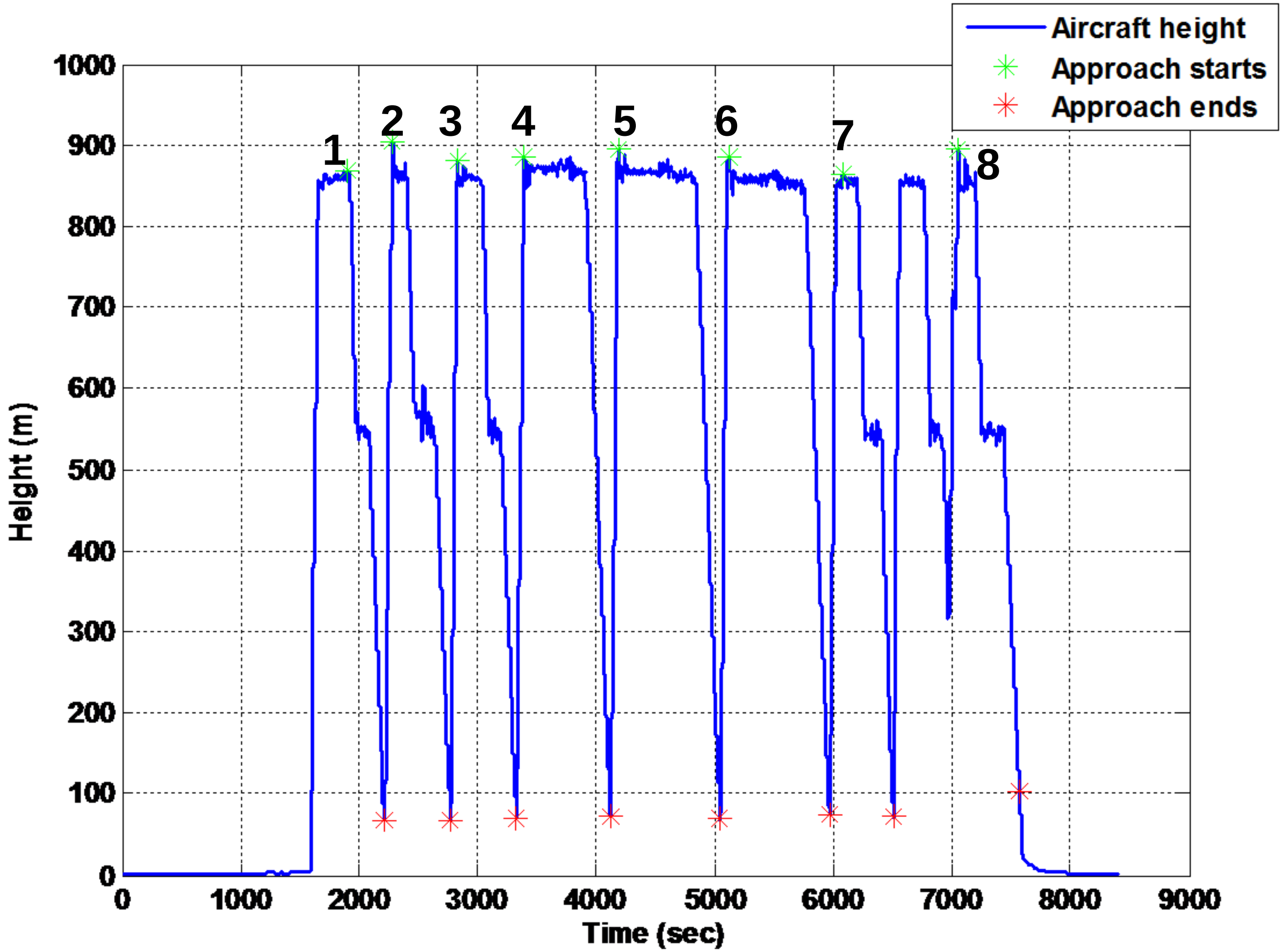
<u>Data</u>: 2 sets of dual-freq 1Hz GPS data;
Aircraft position data file (TSPI);
WAAS broadcast messages.

On-board Receiver

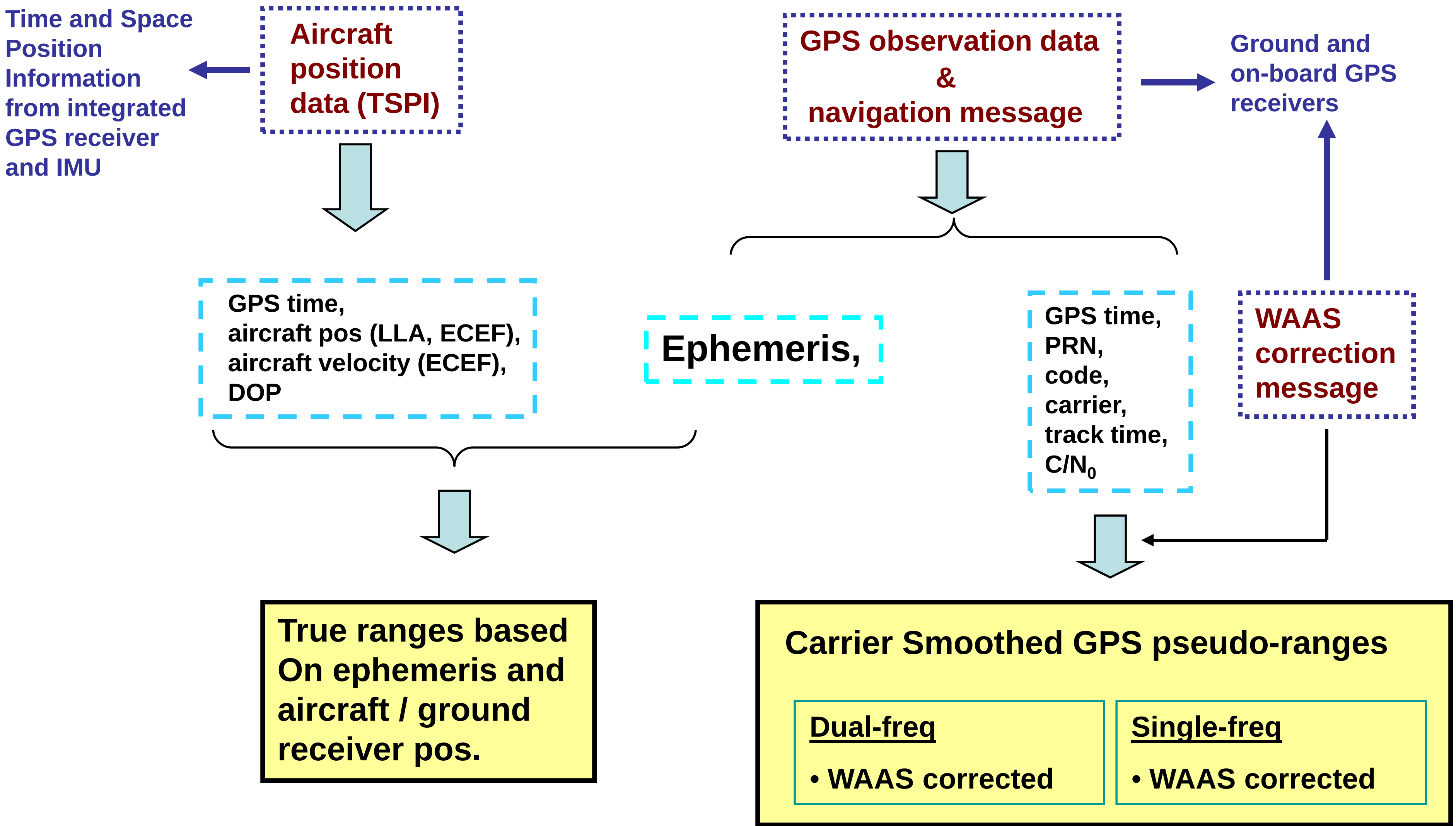
Ground Receiver

Flight test Data Collection and Record

- Total 8 flight approaches: climb-keep-dive



Data Process Steps



Code Measurement Error Findings

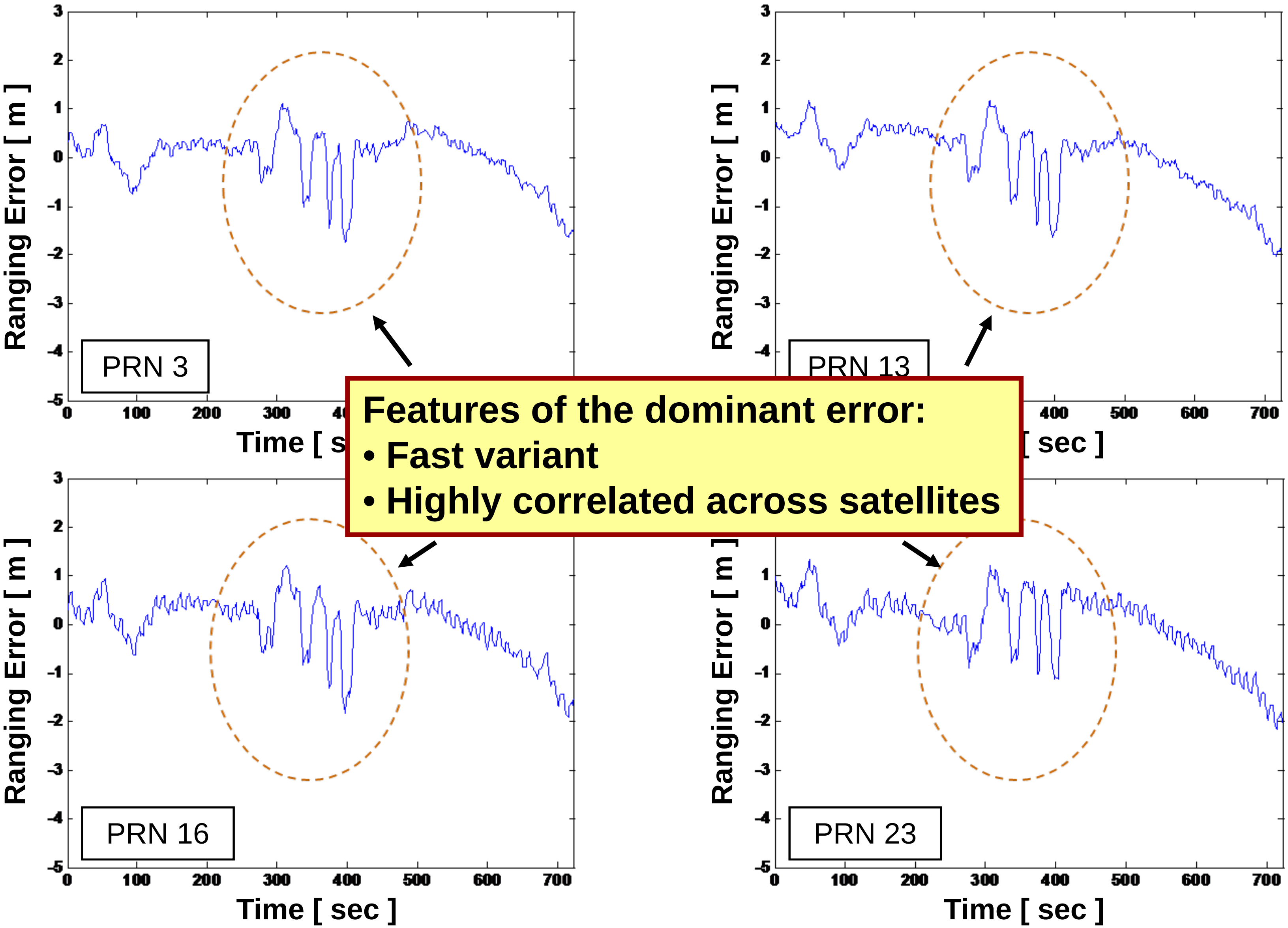
Shown in the error statistics:

Only a small noise increase for the dual-frequency signal comparing with the single-frequency signal

The carrier smoothing does not effectively reduce the error, either for the L1-only signal or the dual-frequency one

To identify the problem we investigated the ranging errors of several satellites

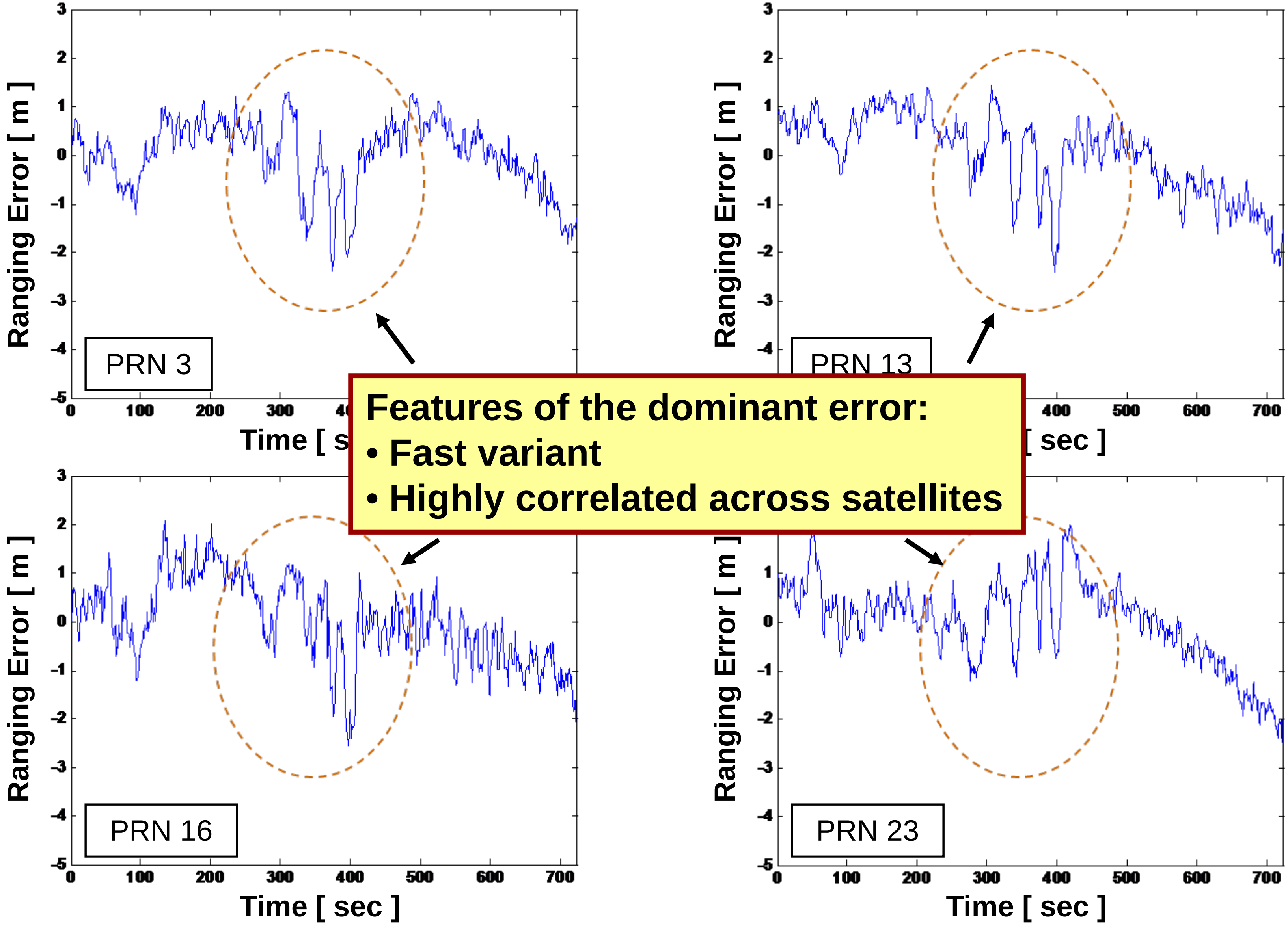
Non-smoothed L1-only signal



Features of the dominant error:

- **Fast variant**
- **Highly correlated across satellites**

Non-smoothed Dual-freq signal



Features of the dominant error:

- **Fast variant**
- **Highly correlated across satellites**

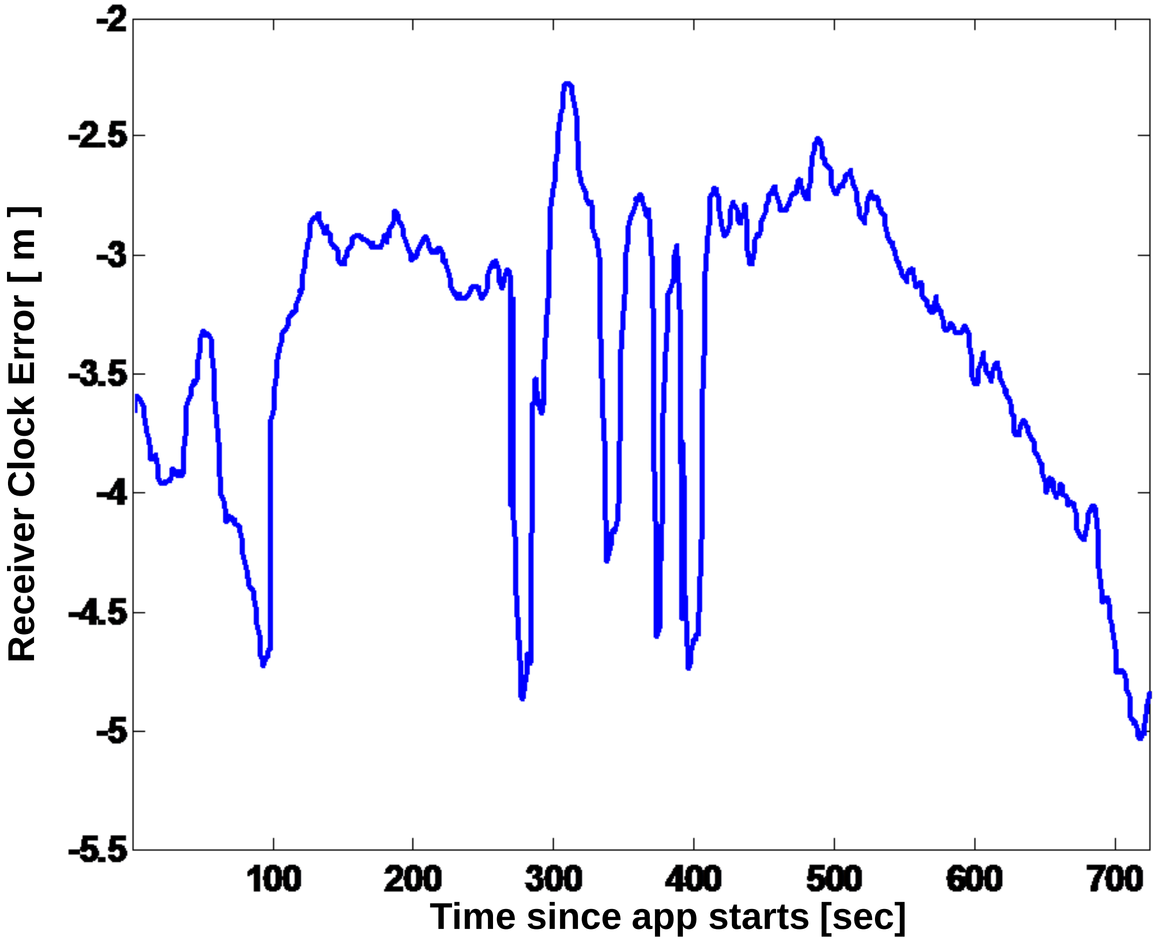
Receiver Clock Error

- The fast-changing receiver clock error is the dominant error term
- The receiver clock error variations are identical across all satellites
- To clearly identify the desired error characteristics, the receiver clock errors need to be better estimated
- The airborne receiver clock error is estimated by averaging the measurement errors at each epoch
  - previously assumed smoothly varying clock over several hundred seconds

Airborne Receiver Clock error → **Remove the airborne carrier measurement ϕ_{air} cycle slips** → **Averaging the carrier measurement errors across all the SV at each time epoch** → b_{air}

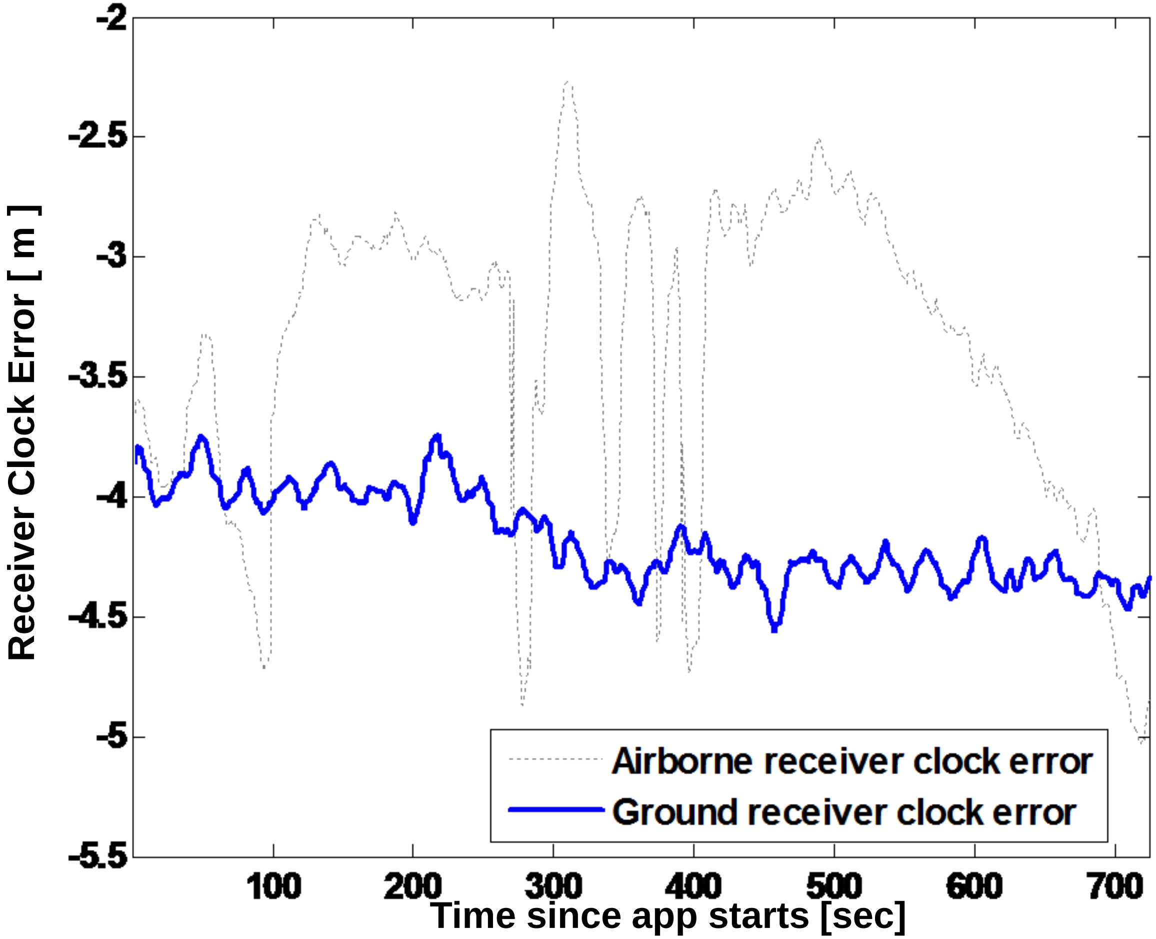
Receiver Clock Error Estimate Result

On board receiver clock error



Receiver Clock Error Estimate Result

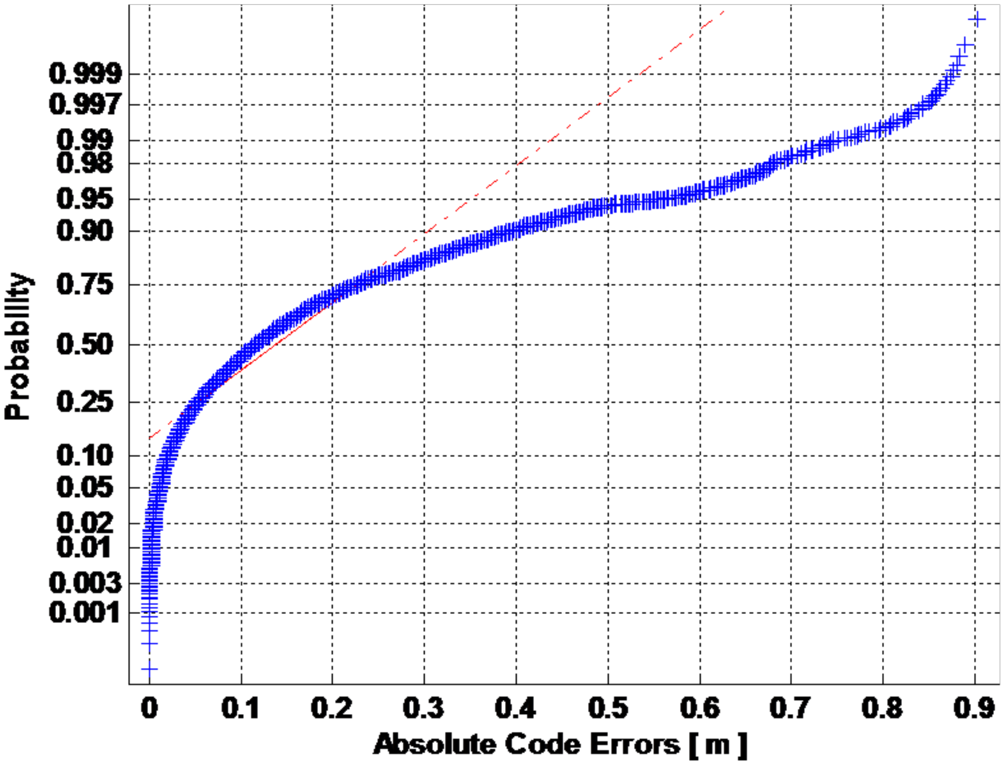
Ground receiver clock error



Error Results Validation

WAAS-corrected ground receiver ranging error: 95% are within ±0.55m.
WAAS PAN Report, Sep 2006: 95% error at Atlanta GA are within ±1.4m.

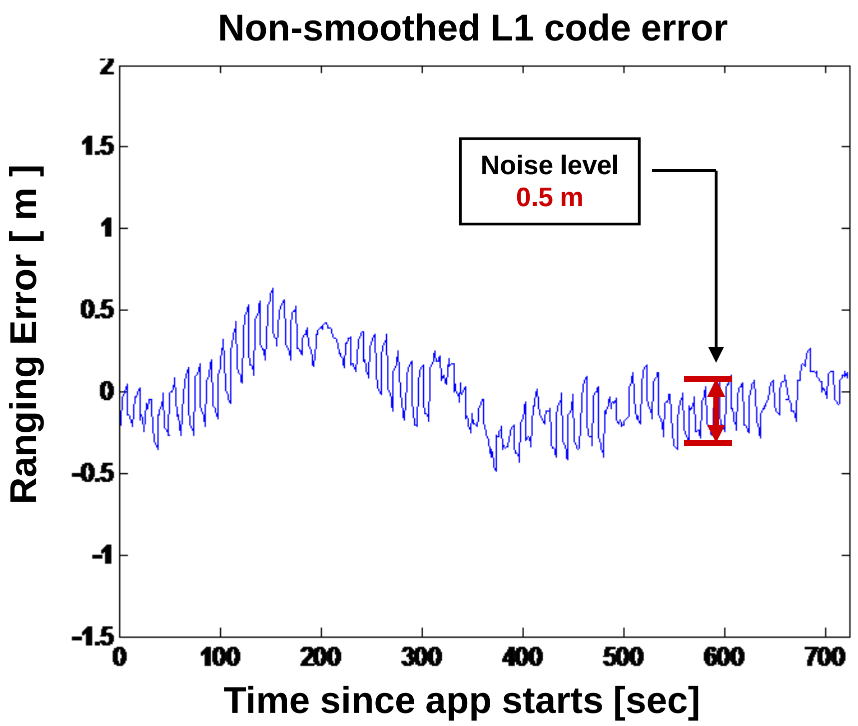
WAAS-corrected ground receiver measurement error

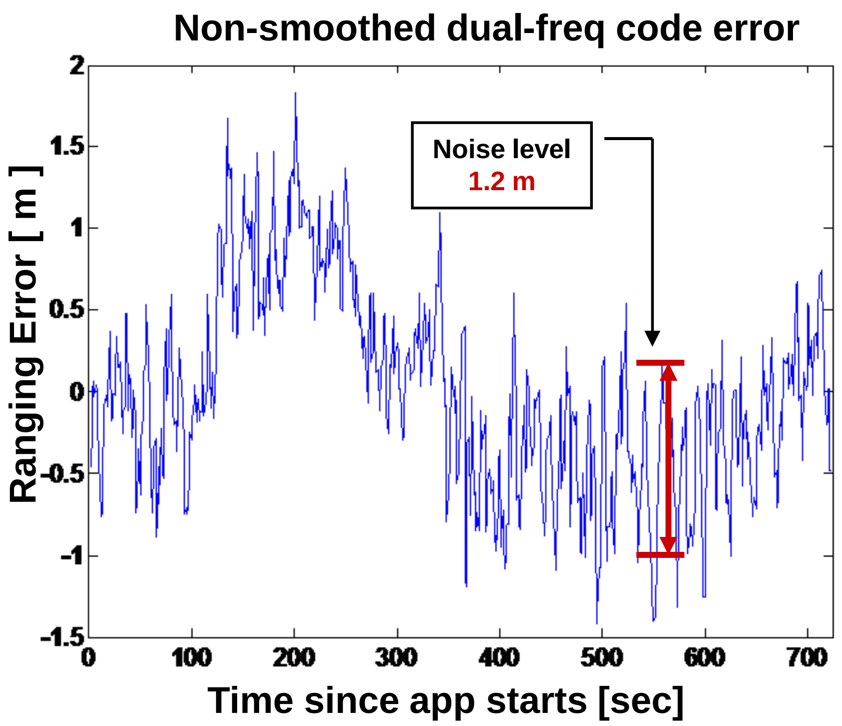


Data Duration: 6 minutes
All Satellites

Airborne Code Measurement Error

PRN 16 WAAS-corrected code meas.

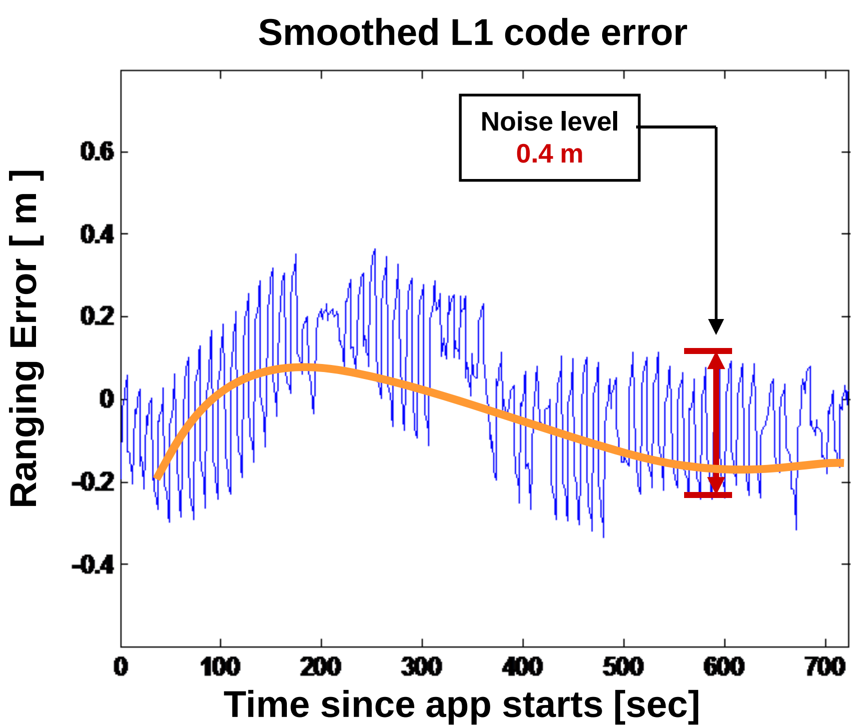


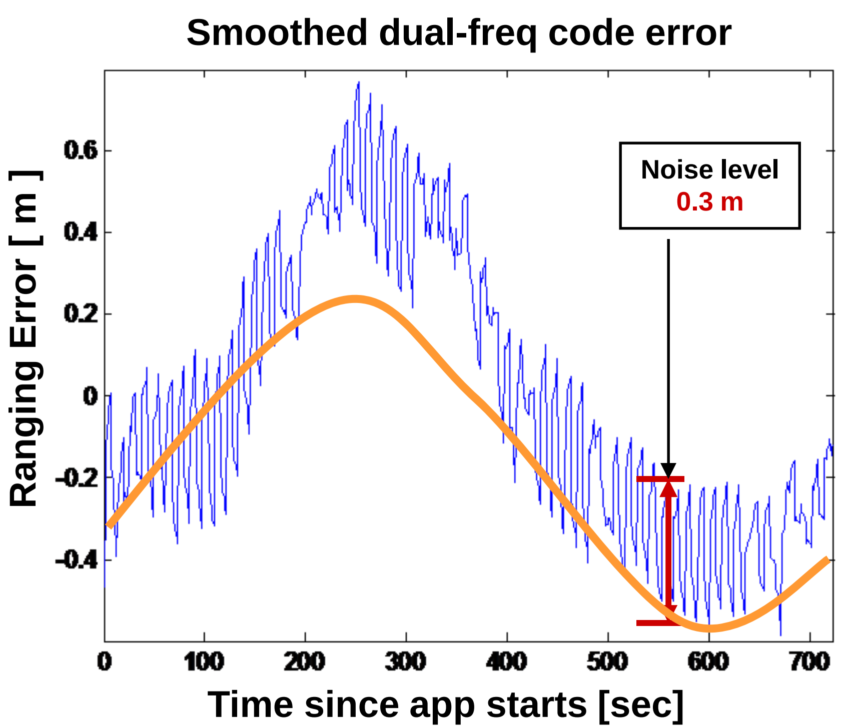


Dual-freq signal noise is more than twice of the L1-only noise before smoothing

Airborne Code Measurement Error

PRN 16 WAAS-corrected code meas.





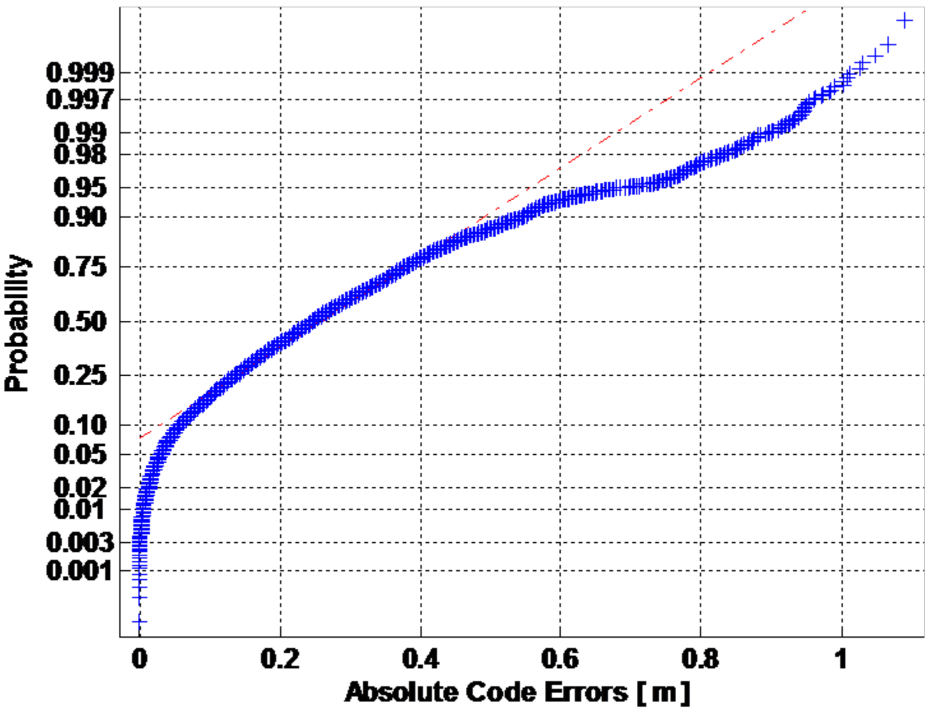
Carrier smoothing works effectively and the two signal noises are comparable

- **High-frequency oscillation caused by WAAS corrections**
- **Still noticeable low-frequency error remains**

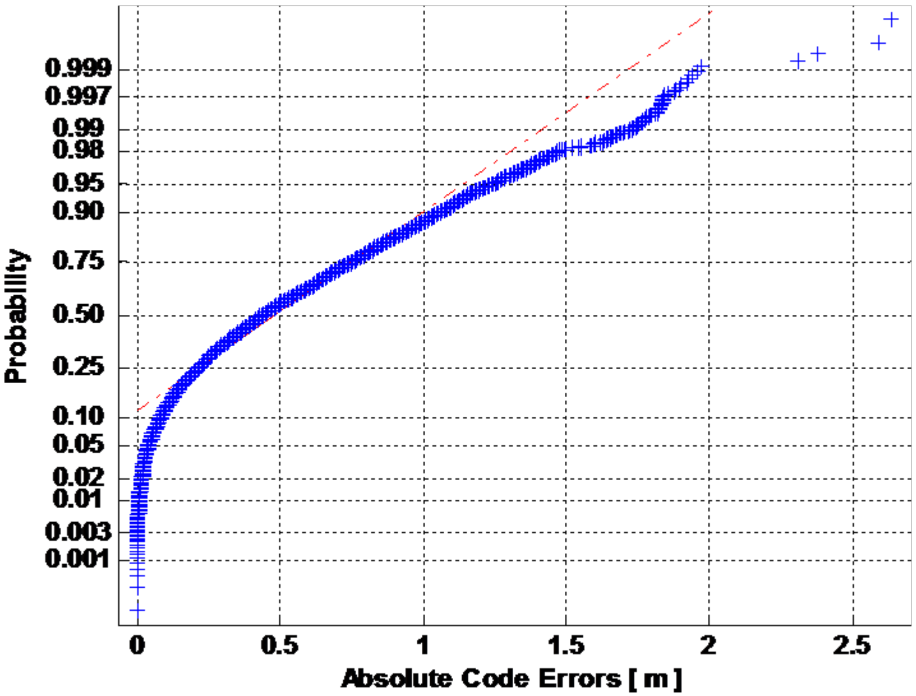
Airborne Error Results

WAAS corrected ranging errors in approach 4

Non-smoothed L1 code error distribution



Non-smoothed dual-freq code error distribution



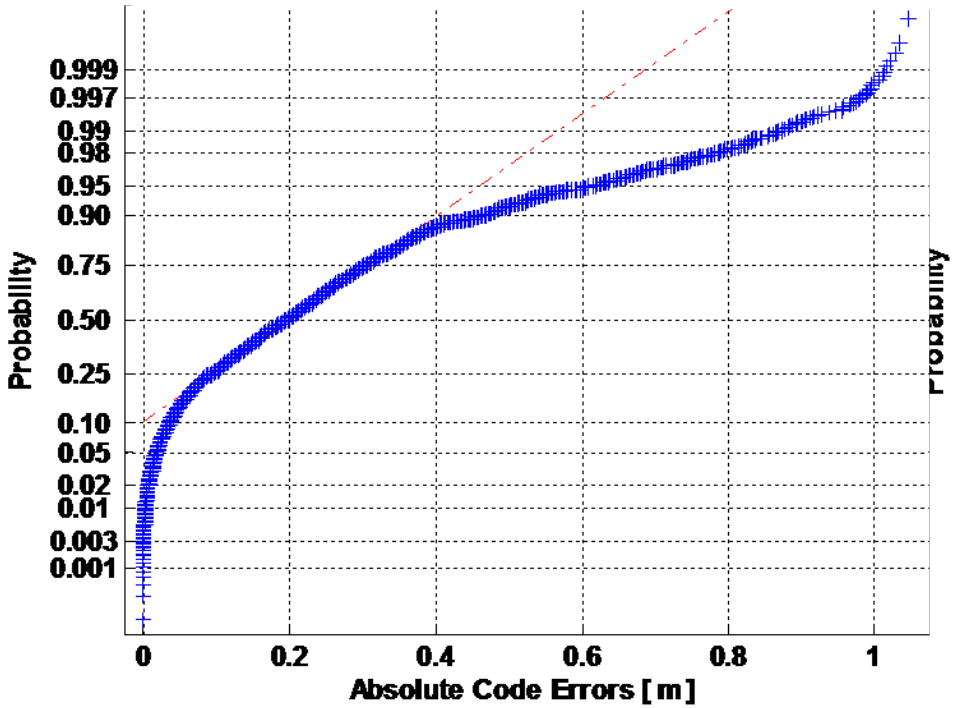
95% of Non-smoothed L1-only errors are within ±0.7m
95% of Non-smoothed dual-freq errors are within ±1.3m

Significant noise increase by dual-freq combination, but still less than expected

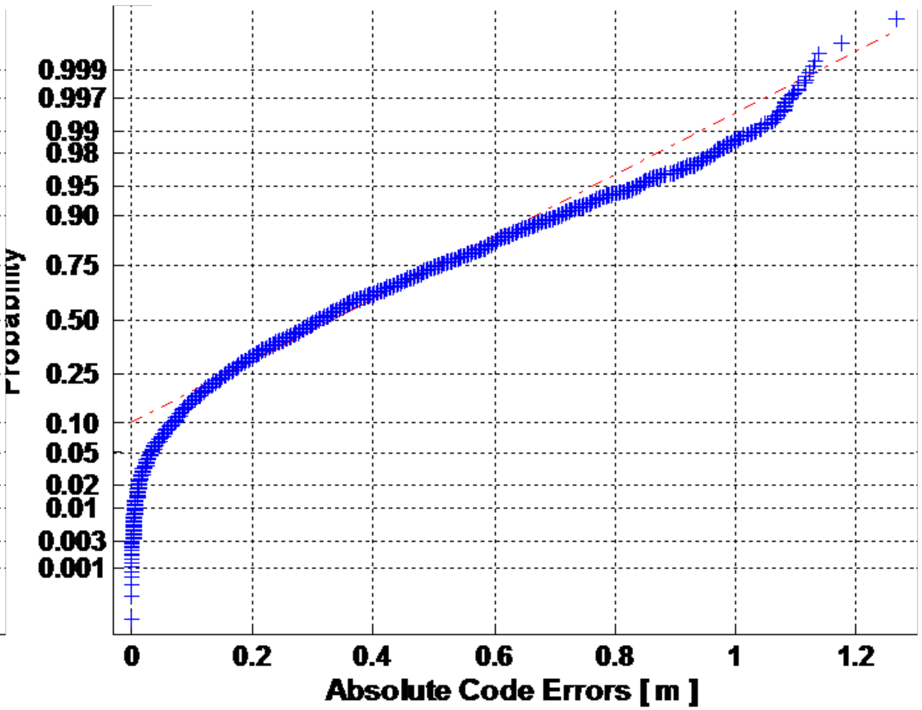
Airborne Error Results

WAAS corrected ranging errors in approach 4

Smoothed L1 code error distribution



Smoothed dual-freq code error distribution



95% of Smoothed L1-only errors are within ±0.6m (±0.7m)
95% of Smoothed dual-freq errors are within ±0.8m (±1.3m)

Carrier smoothing works effectively, especially for dual-freq signals
Comparable noise level after carrier smoothing

Findings

After exclude the receiver clock error:

Dual-freq meas. combination greatly increases the signal noise before the smoothing

The errors of both the L1 and dual-frequency signals are effectively mitigated by the carrier smoothing

The noise levels of the L1 and dual-frequency signals are comparable after smoothing

Conclusions and Future Works

- **The high rate of on-board receiver clock variation makes identification of measurement errors more difficult on flight test data**

- **A GPS receiver clock error estimation method is developed and its effectiveness is validated**

- **The ranging error noises of the two signals are similar after the carrier smoothing**

  - May still be other error terms present obscuring desired error terms

- **The future work will include clearly understand and identify all the error sources**

- **The future work will include the protection level calculations with better understanding of the error characteristics**

Q & A
Thank you