Position Yourself Ahead of the Crowd

Department of Geomatics Engineering

Schulich School of Engineering
University of Calgary

PPP Research Progress at U of C

Yang Gao
Department of Geomatics Engineering
The University of Calgary
ygao@ucalgary.ca www.ucalgary.ca/~ygao

GEOIDE PPP WORKSHOP
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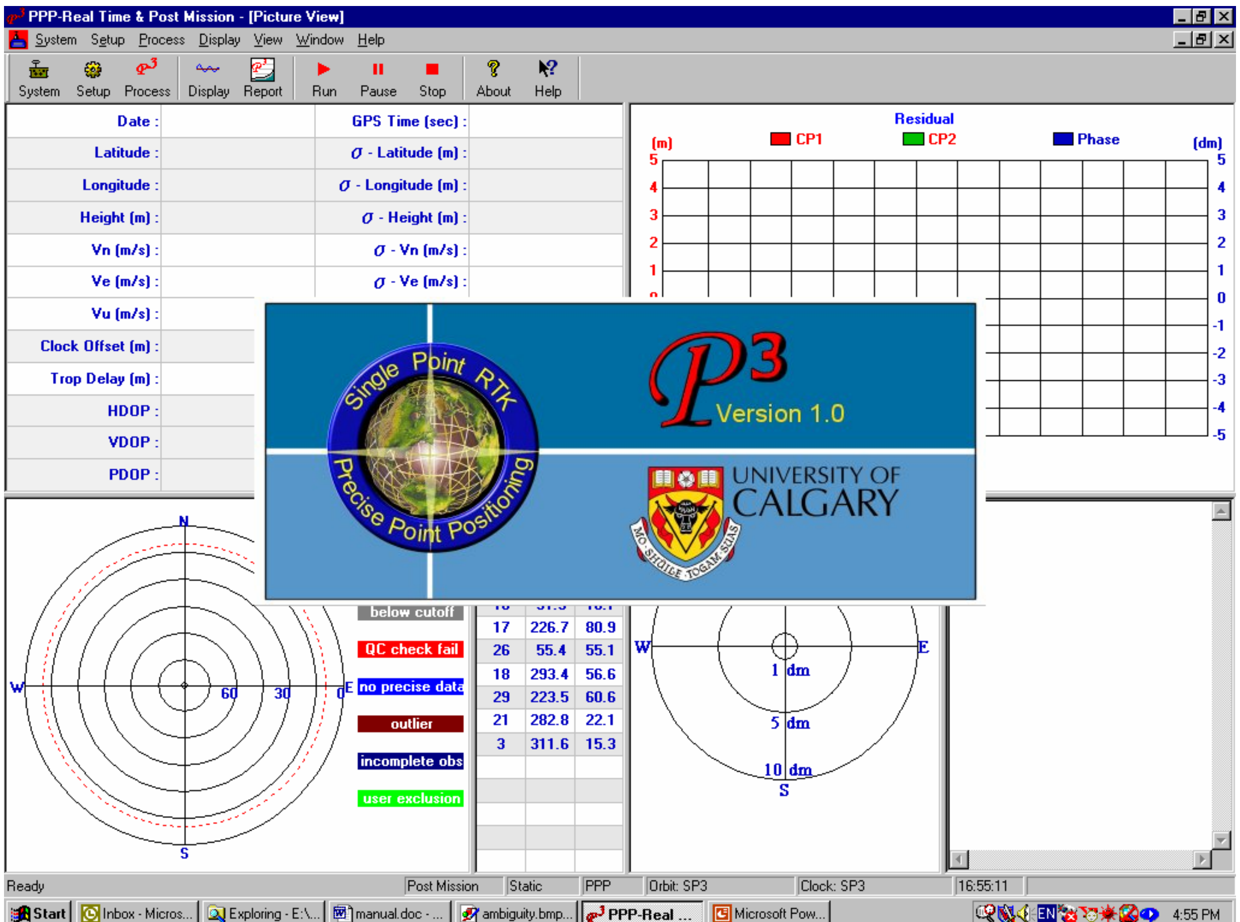
GEOMATICS ENGINEERING

SCHULICH School of Engineering

Outline

- **GNSS-based PPP Software Development**
- **Water Vapor Sensing System Using PPP**
- **Engineering Application Using PPP**
- **Ambiguity Resolution in PPP**
- **GNSS Biases**

A Window-based Software System for GPS-based Precise Point Positioning



GNSS-based PPP Software Development

Functions

- Undifferenced code/carrier processing
- Different observation model implementations (traditional and UC)
- Precise tropospheric delay and receiver clock estimation
- Static and kinematic positioning
- Forward and backward data processing
- Post-mission PPP using IGS Precise ephemeris and clock products
- Real-time PPP using JPL and NRCan real-time precise orbit/clock products
- Easy-to-use interface
- On-line view of processing results
- Various utilities

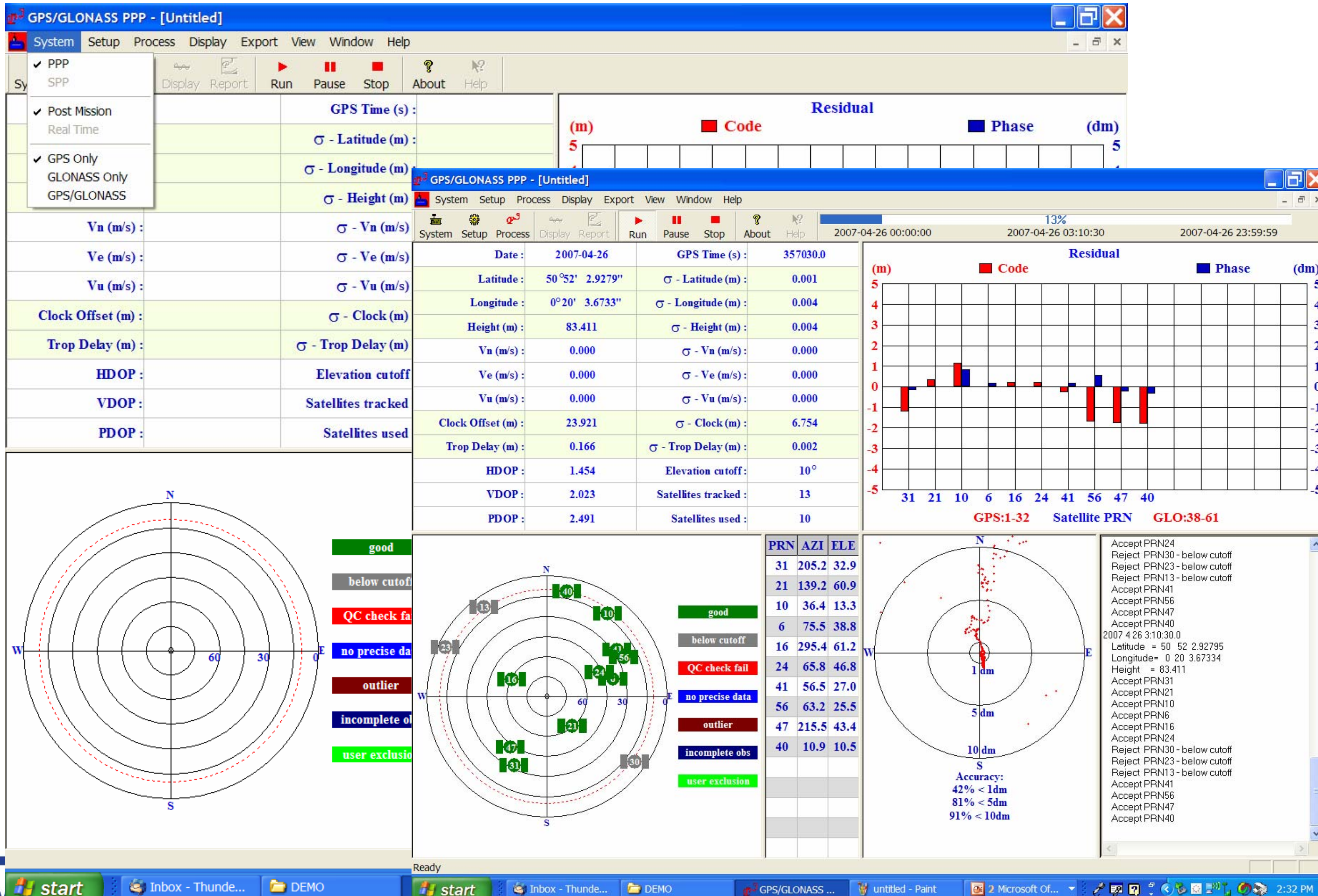
Performance

- Static PPP: mm ~ cm
- Kinematic PPP: cm ~ dm
- Zenith Trop: mm-cm
- Receiver clock: 0.1 ns

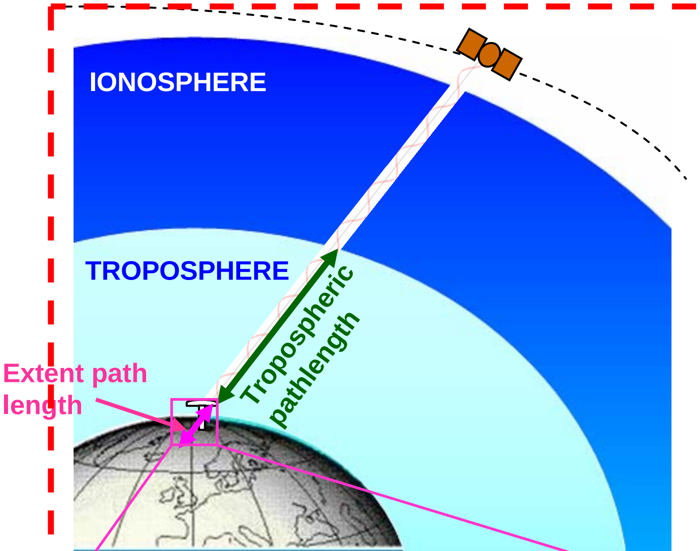
P3 has been licensed to worldwide users including commercial product development

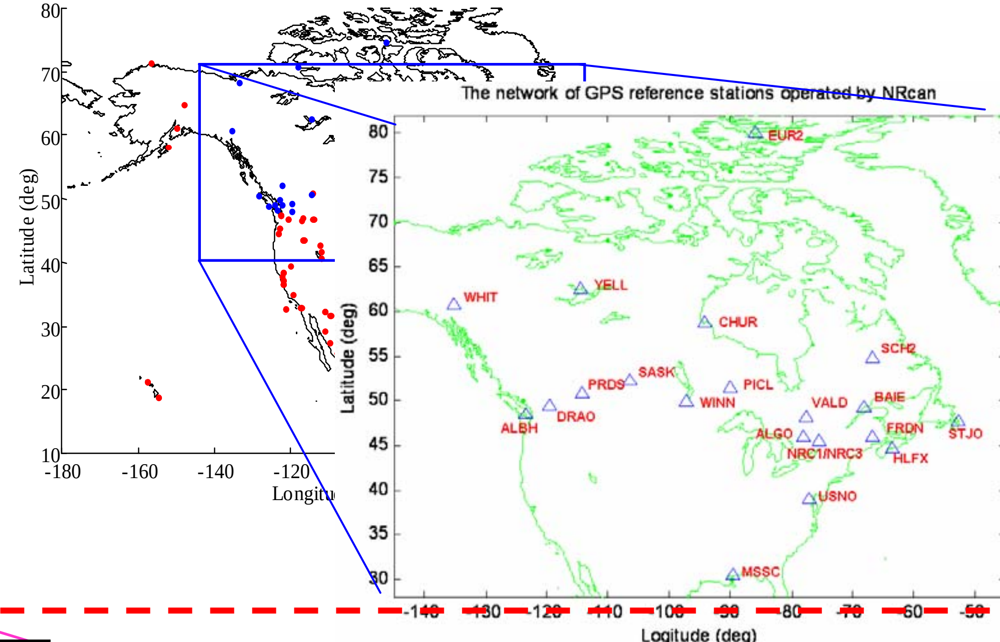
GNSS-based PPP Software Development

A Window-based Software System for GPS/GLONASS-based Precise Point Positioning



Real-time Water Vapor Sensing Network Using PPP



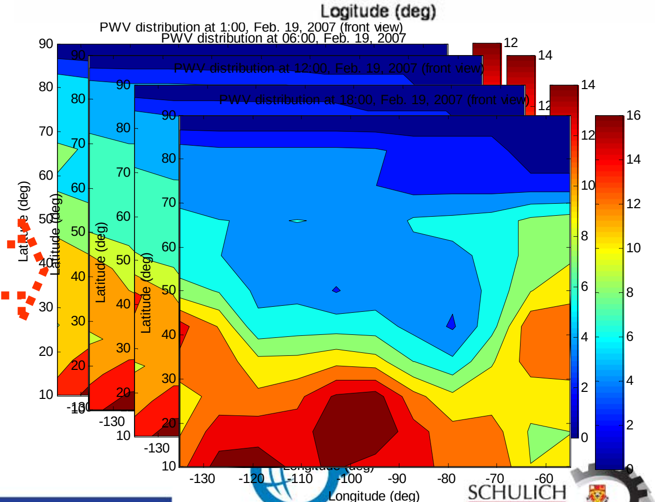


GPS Signal Delay Structure

TOTAL ATMOSPHERIC DELAY
- IONOSPHERIC DELAY → TEC
- *TROPOSPHERIC DELAY*
  - HYDROSTATIC DELAY
  - *WET DELAY* →

Objective

Real-time PWV Database

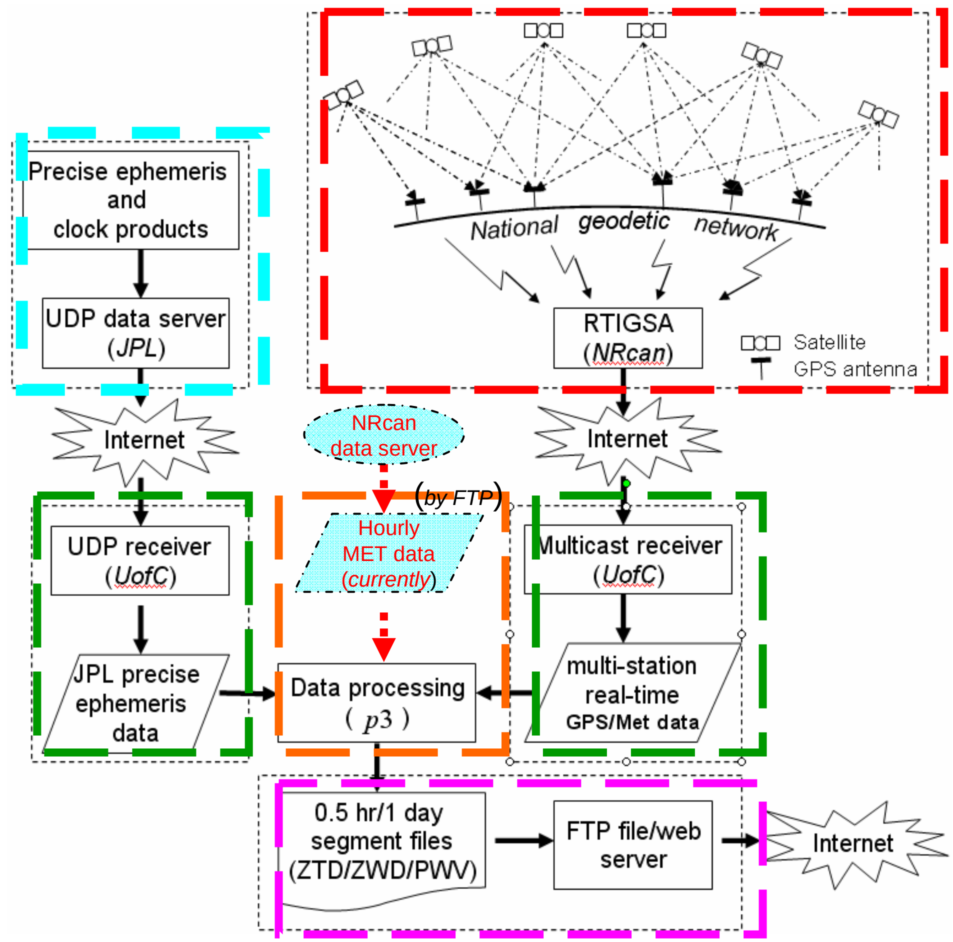


Objective

Develop a Real-time GPS Data Acquisition and Water Vapor Database System based on a network of permanent GPS tracking stations

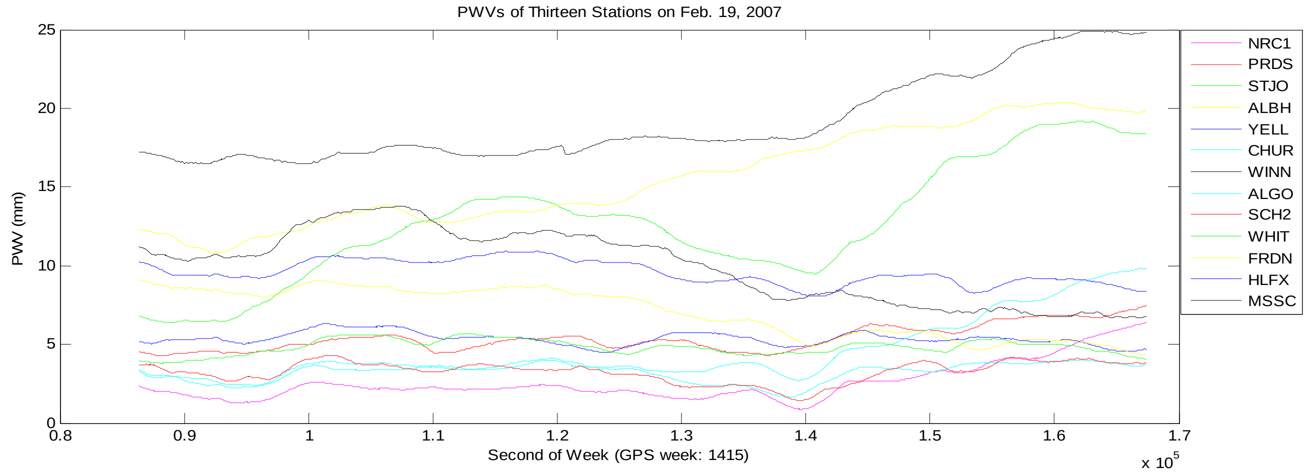
System infrastructure

- Nation-wide network of GPS reference
- Precise GPS satellite orbit and clock product
- Data communication
- Data processing server
- Database server

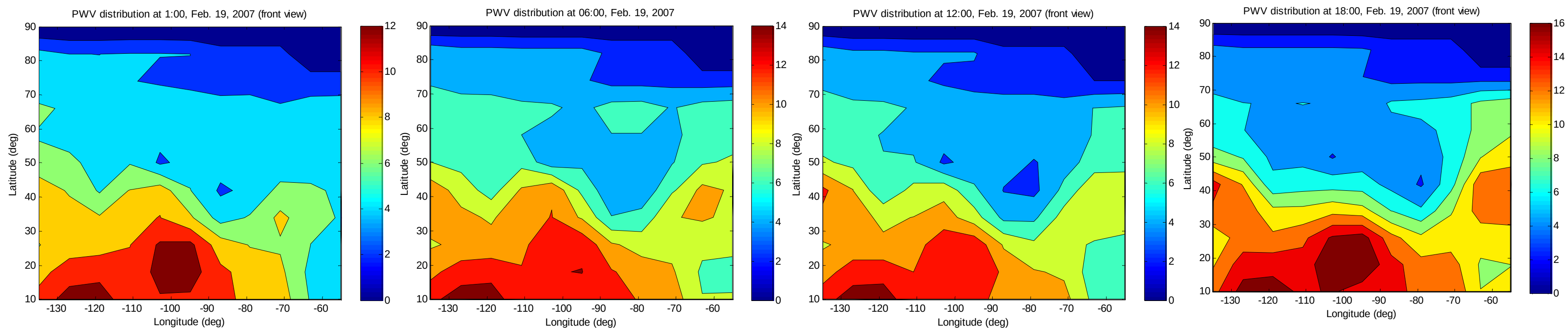


System infrastructure and data flow

Real-time Water Vapor Sensing Network Using PPP

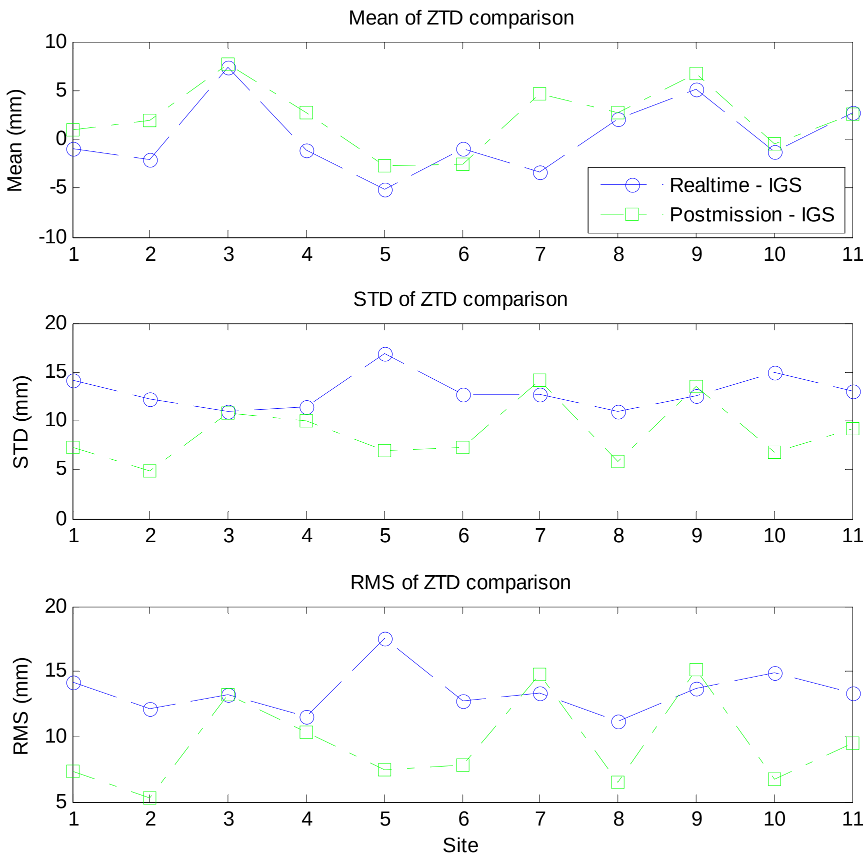


All stations' daily PWV's



Hourly PWV distribution

Real-time Water Vapor Sensing Network Using PPP



	Mean of PWV Comparison		STD of PWV Comparison		RMS of PWV Comparison	
	R.T.	P.M.	R.T.	P.M.	R.T.	P.M.
Mean	0.14	0.36	2.05	1.37	2.10	1.43
Std	0.57	0.50	0.26	0.46	0.26	0.55
RMS	0.58	0.61	2.07	1.45	2.12	1.53

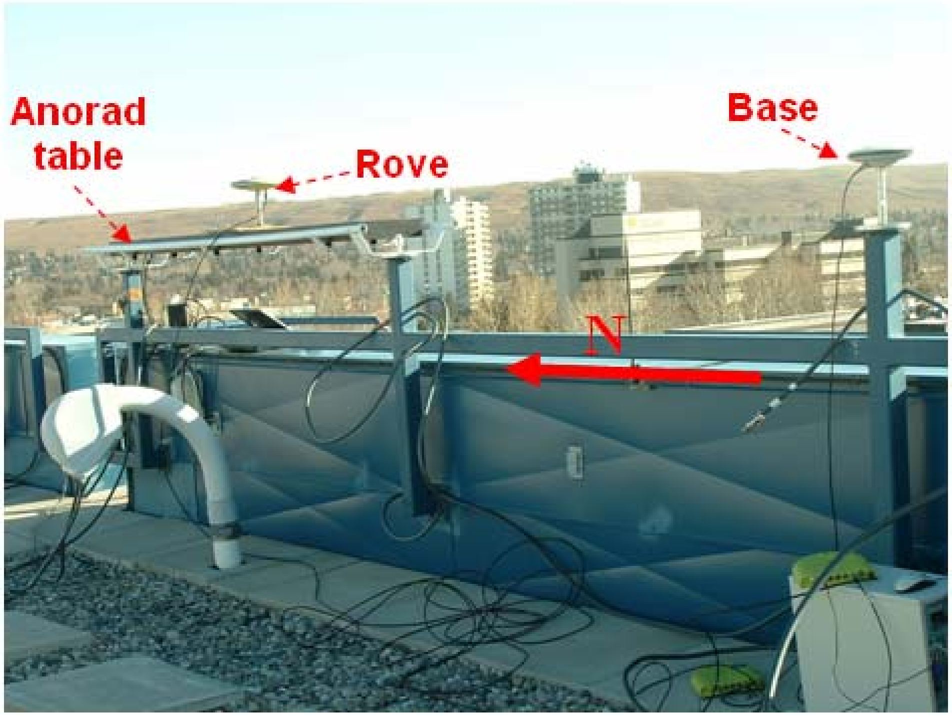
- Real-time system PWV has an difference of ~2 mm from IGS PWV.
- Real-time PWV is greater than post-mission result by ~0.5 mm, which can be 'overcome' through improvement of system and real-time Met data.
- Real-time system could be improved by real-time Met data.

- Real-time ZDT agrees to IGS's within ~10 mm
- Post-time shows the potential accuracy level which real-time system can achieved

Engineering Application Using PPP

Deformation detection experiment

- ✓ March 23, 2007, on the roof of CCIT Building at University of Calgary
- ✓ Two Javad Legacy receivers, 3.5 m baseline
- ✓ The rove antenna was set up on the Anorad linear table
- ✓ Data acquired: 3 hours static data for the base receiver, 2 hours static and then 1 hour kinematic data with controlled movements
- ✓ Truth reference: ambiguity resolved double-difference baseline solutions



- ✓ 6 controlled movement scenarios
- ✓ Vibration motions along the North/South direction
- ✓ 20 times for each movement scenario (always start at the central point but finish at the stop point in the north)

#	Range (cm)	Speed (cm/s)
1	[-0.4 0.4]	0.1
2	[-0.8 0.8]	0.2
3	[-1 1]	0.25
4	[-2 2]	0.5
5	[-5 5]	1.25
6	[-8 8]	2

Engineering Application Using PPP

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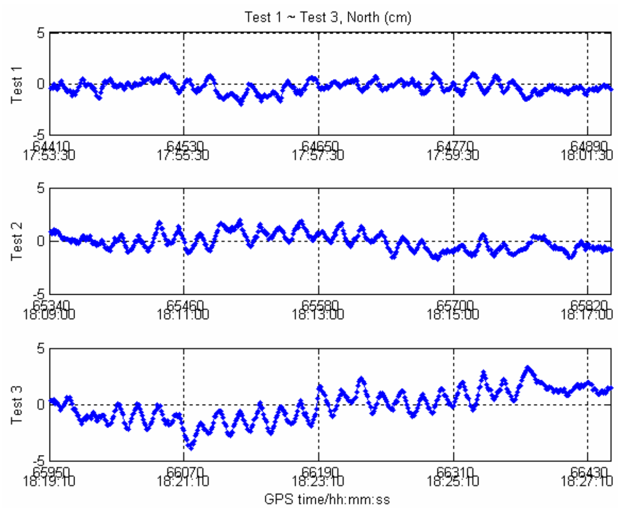
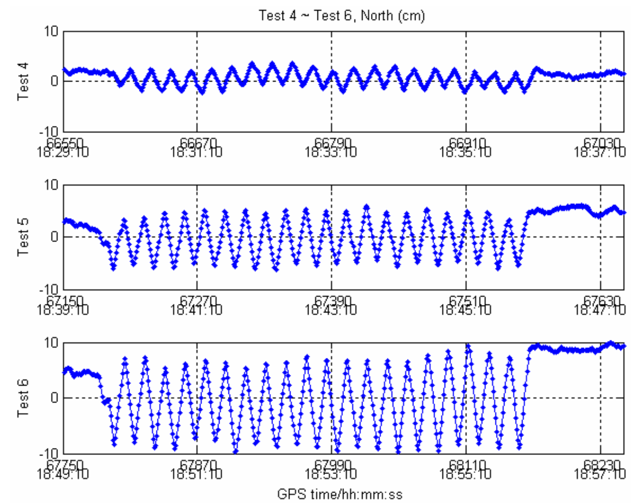
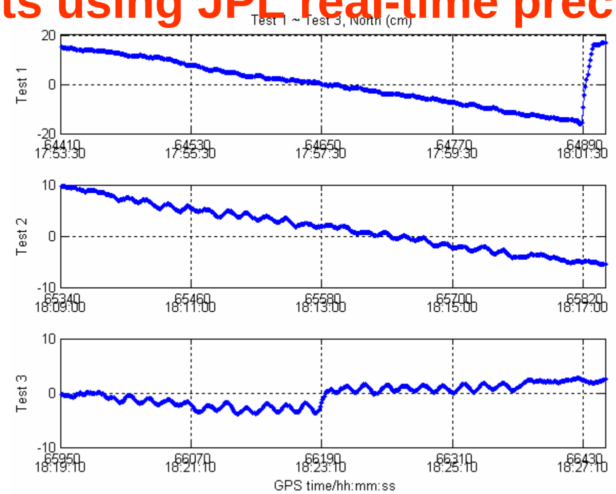
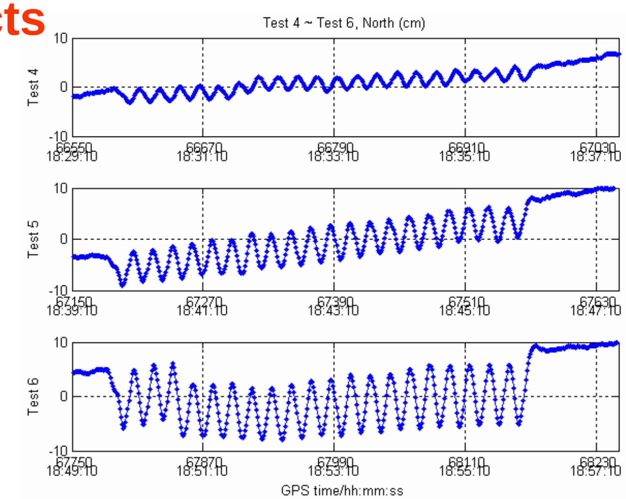
Results using IGS final orbit and JPL final clock



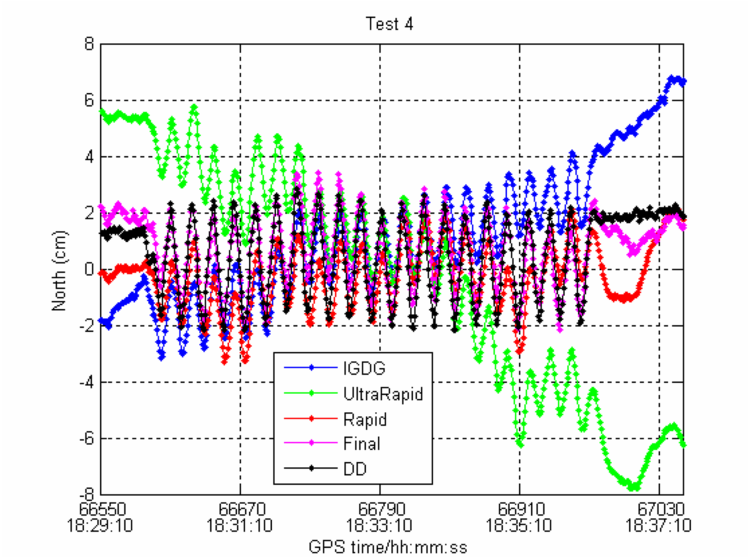


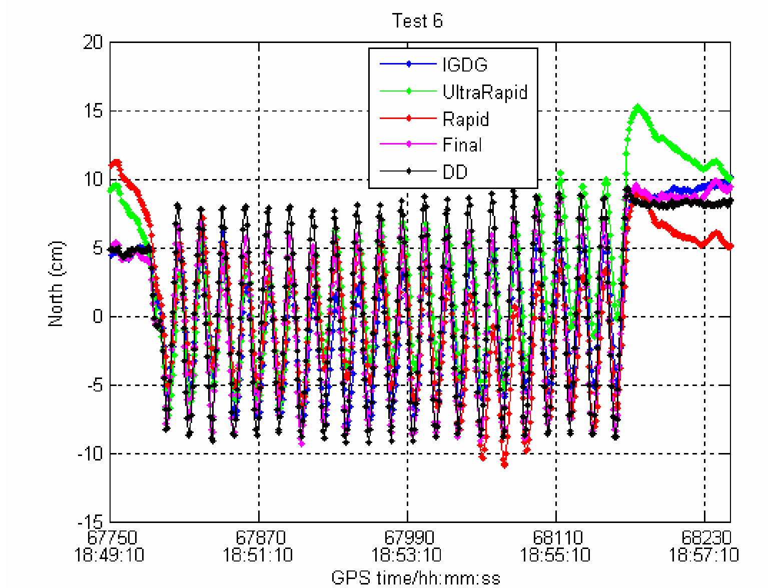
Results using JPL real-time precise products

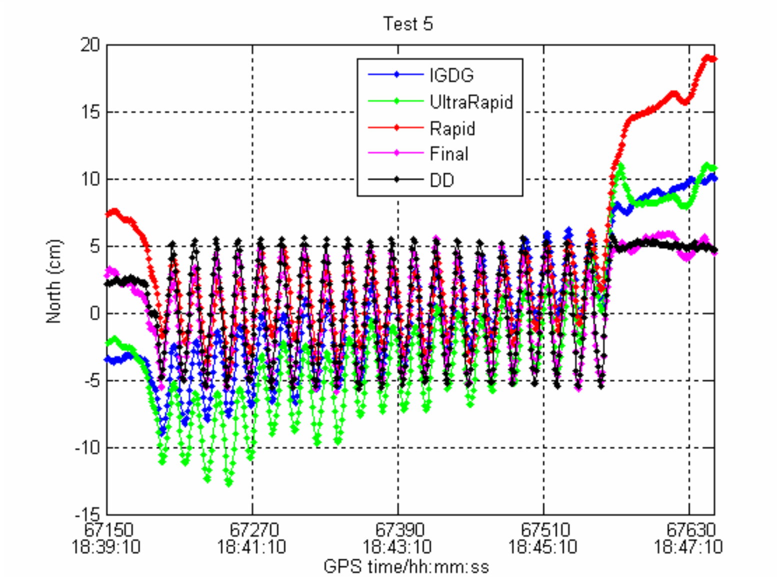




Engineering Application Using PPP







#	Range (cm)	Speed (cm/s)
1	[-0.4 0.4]	0.1
2	[-0.8 0.8]	0.2
3	[-1 1]	0.25
4	**[-2 2]**	**0.5**
5	**[-5 5]**	**1.25**
6	**[-8 8]**	**2**

Engineering Application Using PPP

- **cm level deformation can be detected and determined by precise point positioning method using post-mission Final Product**
- **cm level deformation can be detected but can't be accurately determined by precise point positioning method using real-time precise product**
- **Quality of precise products is a limiting factor for the detection of mm level deformation and accurate deformation determination**
- **Ambiguity resolution method should be investigated to further improve PPP performance**

Ambiguity Resolution in PPP

initial phase bias

- ✓ **Residual orbit and clock errors**
- ✓ **Unmodeled errors**

$$N_i + \phi_r(t_0, L_i) - \phi_s(t_0, L_i)$$

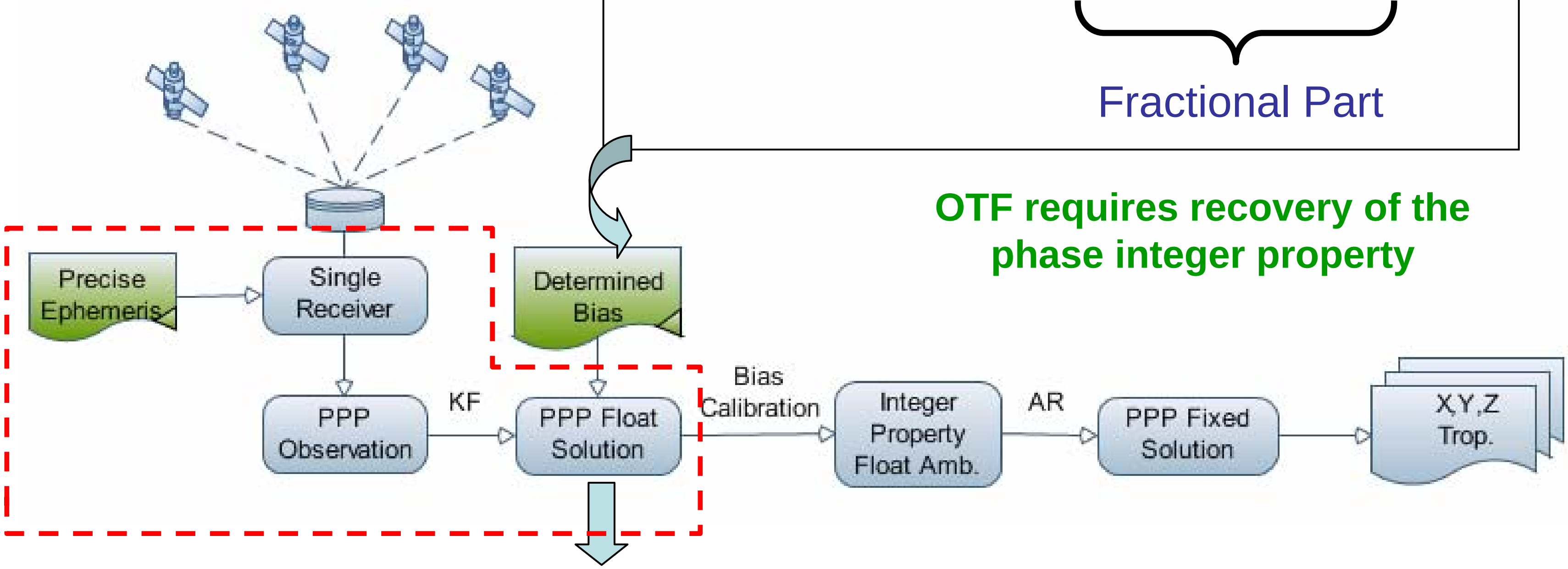
Integer Part

Receiver initial phase bias

Satellite initial phase bias

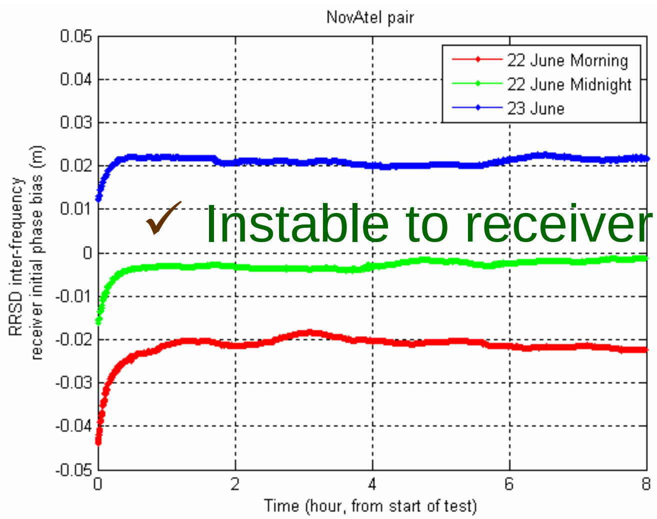
Fractional Part

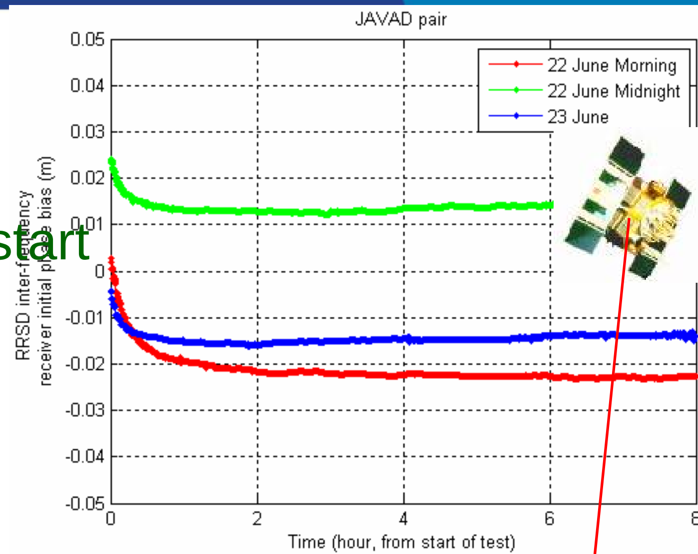
OTF requires recovery of the phase integer property



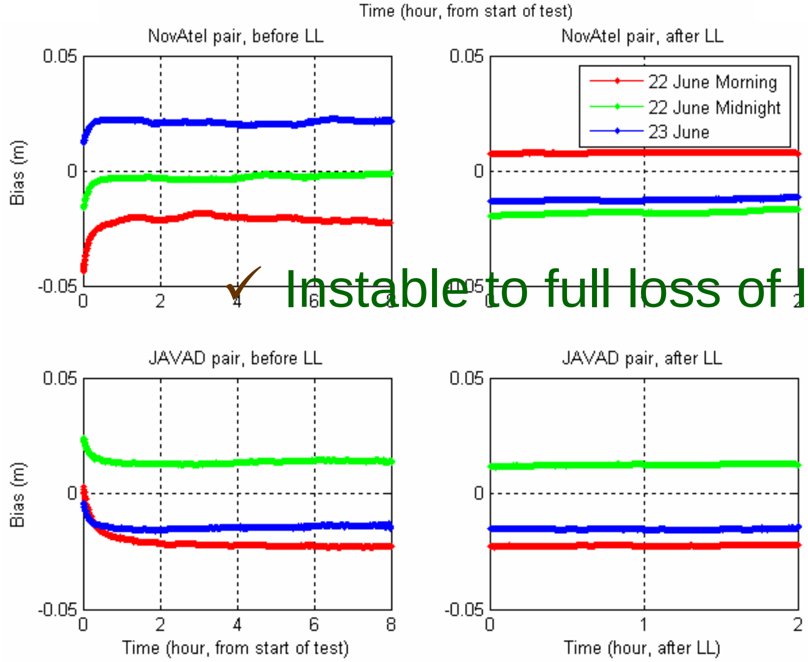
Long initialization time

Ambiguity Resolution in PPP





✓ Instable to receiver restart



✓ Instable to full loss of lock

Receiver Initial Phase Bias

Ambiguity Resolution in PPP

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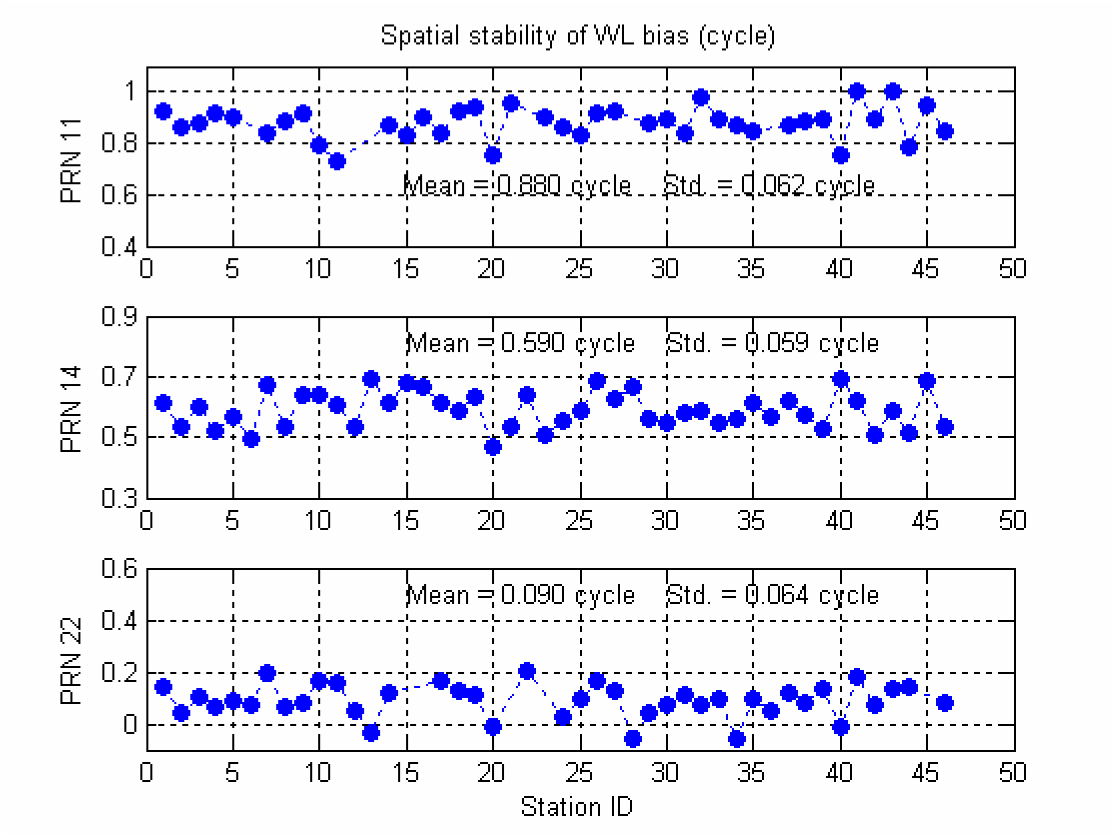
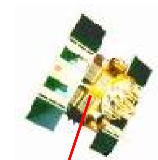
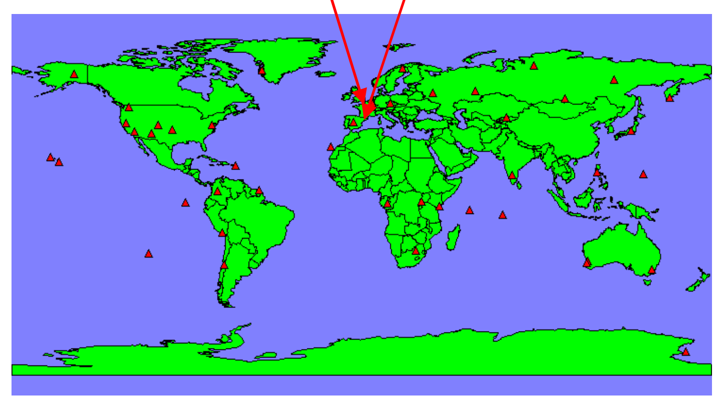


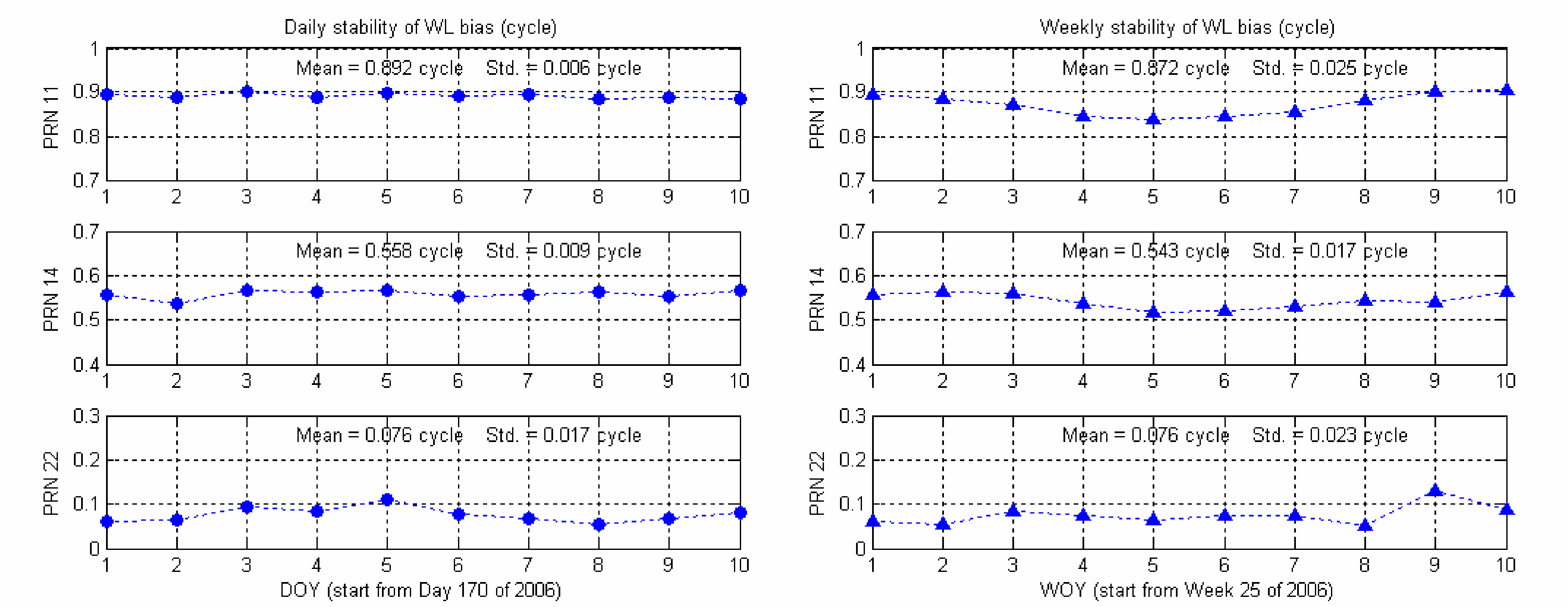
Spatially stable (wide-lane results)



Satellite Initial Phase Bias



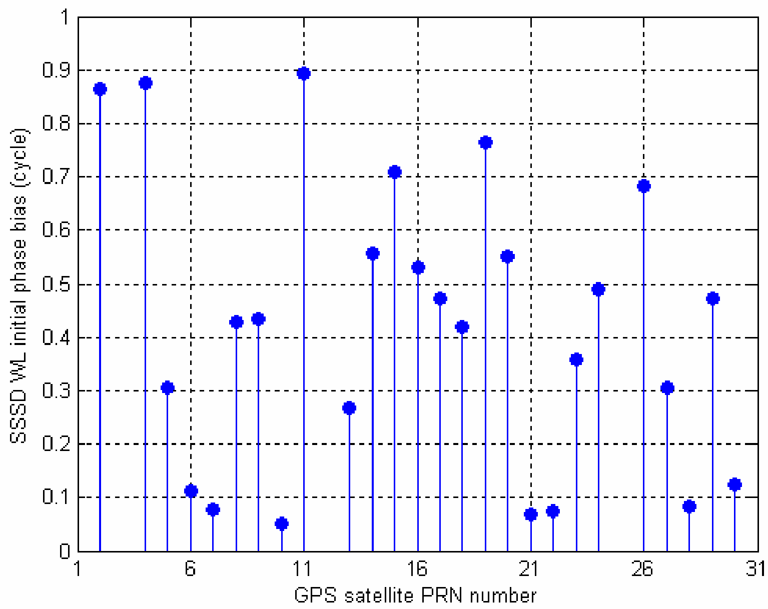
Ambiguity Resolution in PPP

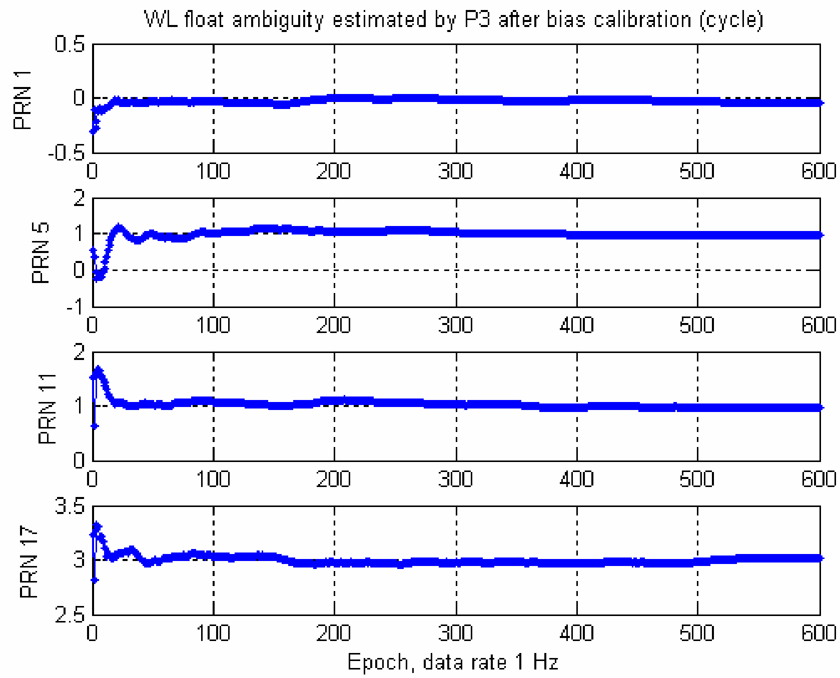


Temporally stable (wide-lane results)

- ✓ Daily stability, 10 days from Day of Year 170 in 2006
- ✓ Weekly stability, 10 weeks from Week 25 of Year 2006

Ambiguity Resolution in PPP





The integer property can be recovered after the removal of the initial phase bias (wide-lane results)!

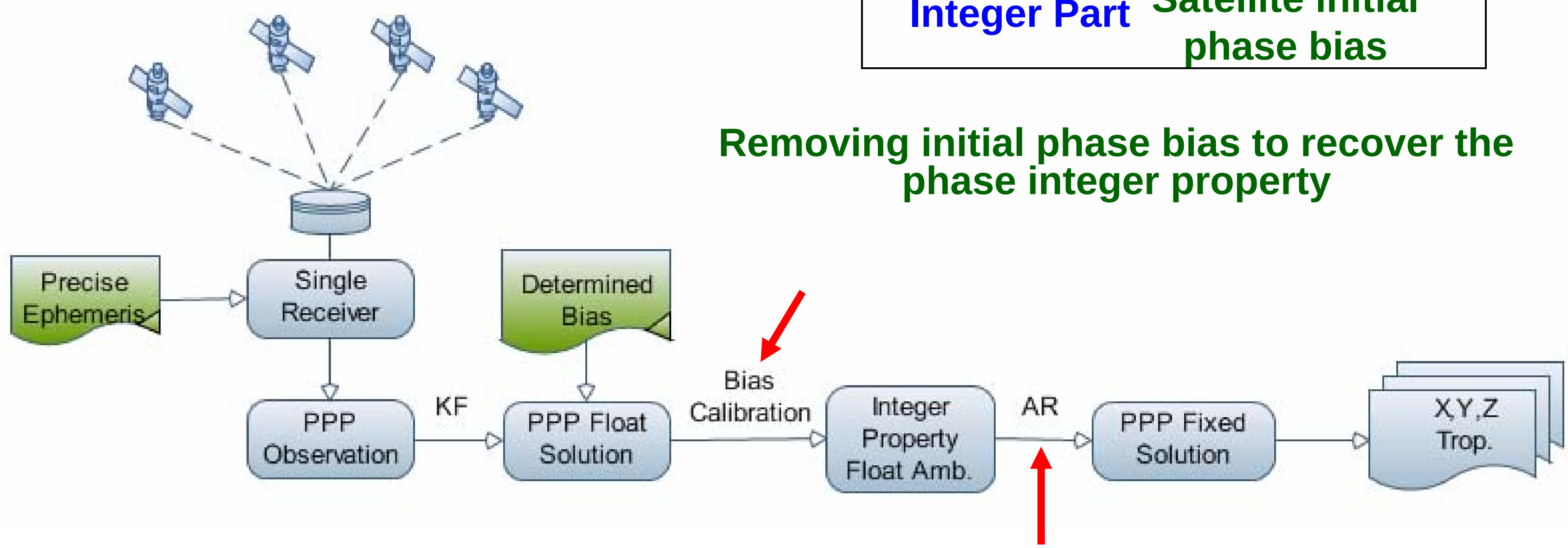
$$\nabla P_{Pi,\Phi i} = 0.5\left[\nabla P_i + \nabla \Phi_i\right] = \nabla\rho + \nabla d_{trop} + 0.5\,\lambda_i\,[\nabla N_i - \nabla\phi_s(t_0, L_i)] + \varepsilon\,(\nabla P_{Pi,\Phi i})$$

$$\nabla\Phi_{IF} = \nabla\rho + \nabla d_{trop} + \frac{f_1^2\lambda_1[\nabla N_1 - \nabla\phi_s(t_0, L_1)]}{f_1^2 - f_2^2} - \frac{f_2^2\lambda_2[\nabla N_2 - \nabla\phi_s(t_0, L_2)]}{f_1^2 - f_2^2} + \varepsilon\,(\nabla\Phi_{IF})$$

$$\nabla N_i - \nabla\phi_s(t_0, L_i)$$

Integer Part **Satellite initial phase bias**

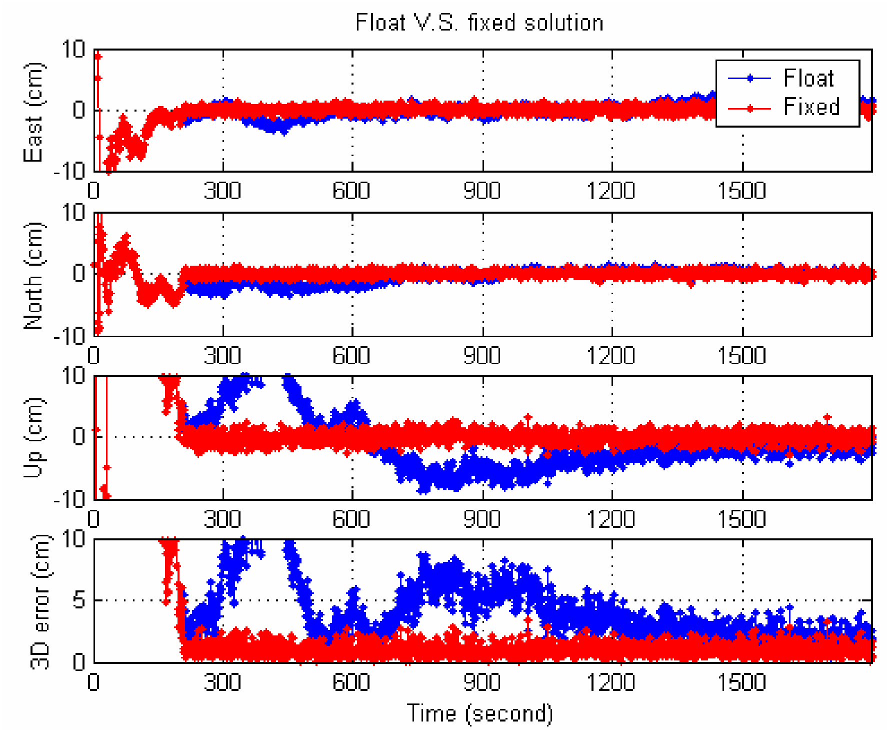
Removing initial phase bias to recover the phase integer property



OTF integer ambiguity resolution

Ambiguity Resolution in PPP

Float v.s. Fixed Solution

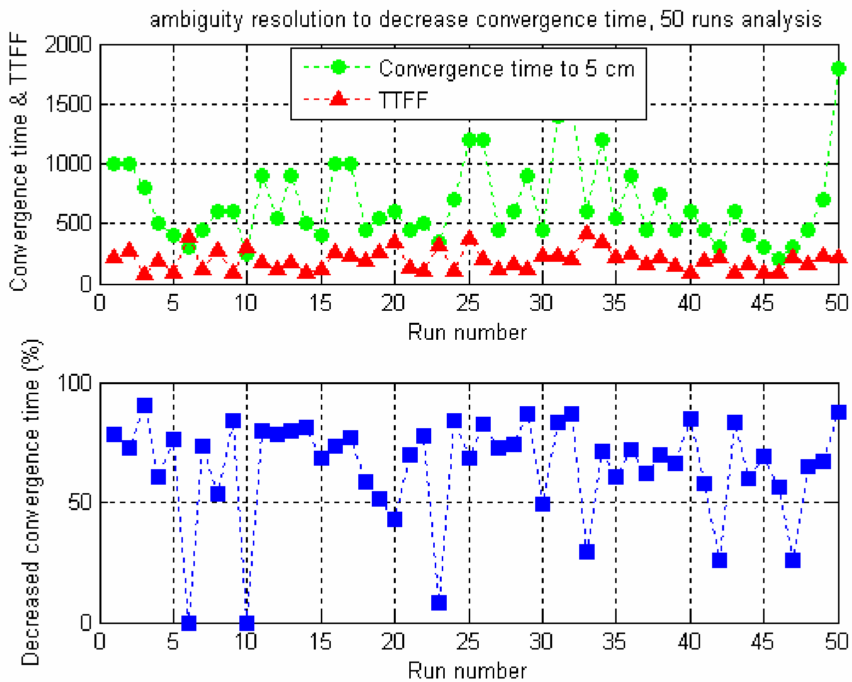


Estimated results	Float (after converged)		Fixed (after TTFF)	
	Mean (cm)	Std. (cm)	Mean (cm)	Std. (cm)
East	0.47	0.73	-0.01	0.48
North	0.19	0.42	0.00	0.42
Up	-2.43	1.43	-0.06	0.90
3D	2.71	1.26	0.99	0.49
Trop. wet	0.12	0.11	0.01	0.04

- ✓ Convergence time is decreased (Converge to 5cm from more than 1000 s -> 200 s TTFF)
- ✓ 3D position and tropospheric zenith wet estimation accuracy dramatically enhanced

Ambiguity Resolution in PPP

Fifty scenarios analysis of AR with PPP

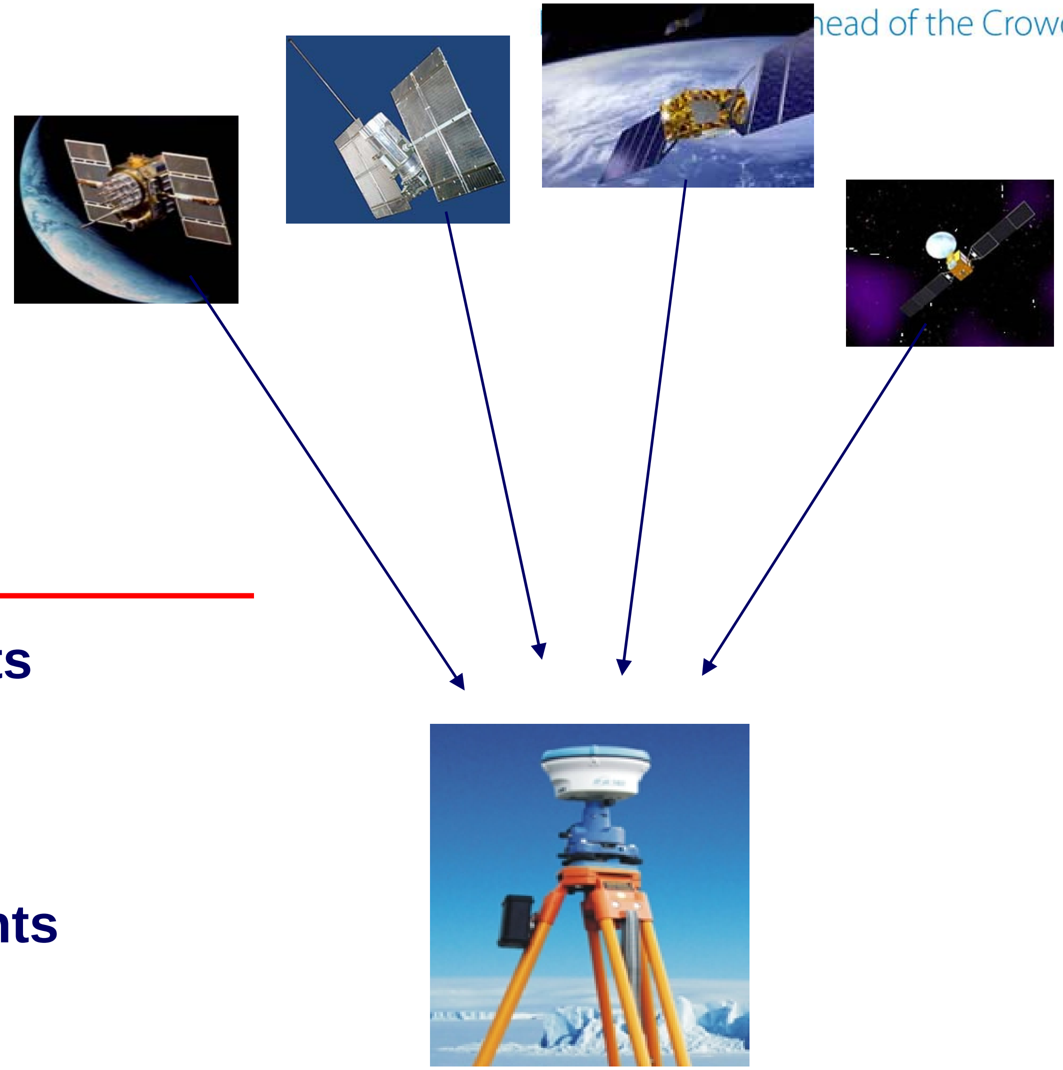


- ✓ Convergence time reduced from 669 s to 198 s
- ✓ Convergence improvement, average 64.7%, maximum 90.2%

GNSS Biases

- **Hardware Bias**
  - ✓ **Satellite hardware bias**
  - ✓ **Receiver hardware bias**
- **Software Bias**
  - ✓ **Satellite software bias**
  - ✓ **Receiver software bias**

- **Bias in Code Measurements**
  - ✓ **Satellite related bias**
  - ✓ **Receiver related bias**
- **Bias in Phase measurements**
  - ✓ **Satellite related bias**
  - ✓ **Receiver related bias**



GNSS Biases

Relative
(inter-frequency bias)

- **Inter-Frequency Bias (IFB)**
  - ✓ Satellite IFB
  - ✓ Receiver IFB
- **Differential Code Bias (DCB)**
  - ✓ Satellite DCB
  - ✓ Receiver DCB
- **Differential Phase Bias (DPB)**
  - ✓ Satellite DPB
  - ✓ Receiver DPB

Inter-System Biases

- **Inter-system Time System Offset (ITB)**
  - ✓ GPS/GLONASS
  - ✓ GPS/GALILEO
  - ✓ GPS/COMPASS
- **Inter-system Coordinate System Offset (ICB)**
  - ✓ GPS/GLONASS
  - ✓ GPS/GALILEO
  - ✓ GPS/COMPASS

GPS Biases in Observation Equations

$$C_1 = \rho + c(dT - dt) + d_{orb} + d_{trop} + d_{ion/L1} + c(b^r_{C1} - b^s_{C1}) + \varepsilon(C_1)$$

$$P_1 = \rho + c(dT - dt) + d_{orb} + d_{trop} + d_{ion/L1} + c(b^r_{P1} - b^s_{P1}) + \varepsilon(P_1)$$

$$P_2 = \rho + c(dT - dt) + d_{orb} + d_{trop} + d_{ion/L2} + c(b^r_{P2} - b^s_{P2}) + \varepsilon(P_2)$$

$$\Phi_1 = \rho + c(dT - dt) + d_{orb} + d_{trop} - d_{ion/L1} + c(b^r_{\Phi 1} - b^s_{\Phi 1}) + \lambda_1 N_1 + \varepsilon(\Phi_1)$$

$$\Phi_2 = \rho + c(dT - dt) + d_{orb} + d_{trop} - d_{ion/L2} + c(b^r_{\Phi 2} - b^s_{\Phi 2}) + \lambda_2 N_2 + \varepsilon(\Phi_2)$$

$$C_2 = \rho + c(dT - dt) + d_{orb} + d_{trop} + d_{ion/L2} + c(b^r_{C2} - b^s_{C2}) + \varepsilon(C_2)$$

$$P_2^{'} = \rho + c(dT - dt) + d_{orb} + d_{trop} + d_{ion/L2} + c(b^r_{P2'} - b^s_{P2'}) + \varepsilon(P_2^{'})$$

$$\Phi_2^{'} = \rho + c(dT - dt) + d_{orb} + d_{trop} - d_{ion/L2} + c(b^r_{\Phi 2'} - b^s_{\Phi 2'}) + \lambda_2 N_2 + \varepsilon(\Phi_2^{'})$$

Hardware biases are not estimable in absolute sense

IGS Product Convention and effect of biases on IGS products

$$P_{IF} = \frac{f_1^2 \cdot P_1 - f_2^2 \cdot P_2}{f_1^2 - f_2^2} = \rho + c(dT - dt) + d_{orb} + d_{trop} + c(b_{IFP}^r - b_{IFP}^s) + \varepsilon(P_{IF})$$

$$\Phi_{IF} = \frac{f_1^2 \cdot \Phi_1 - f_2^2 \cdot \Phi_2}{f_1^2 - f_2^2} = \rho + c(dT - dt) + d_{orb} + d_{trop} + c(b_{IF\Phi}^r - b_{IF\Phi}^s) + \lambda_{IF} N_{IF} + \varepsilon(\Phi_{IF})$$

$$P_{IF} = \frac{f_1^2 \cdot P_1 - f_2^2 \cdot P_2}{f_1^2 - f_2^2} = \rho + c[(dT + b_{IFP}^r) - (dt + b_{IFP}^s)] + d_{orb} + d_{trop} + \varepsilon(P_{IF})$$

$$\Phi_{IF} = \frac{f_1^2 \cdot \Phi_1 - f_2^2 \cdot \Phi_2}{f_1^2 - f_2^2} = \rho + c[(dT + b_{IF\Phi}^r) - (dt + b_{IF\Phi}^s)] + d_{orb} + d_{trop} + \lambda_{IF} N_{IF} + \varepsilon(\Phi_{IF})$$

$$P_{IF} = \frac{f_1^2 \cdot P_1 - f_2^2 \cdot P_2}{f_1^2 - f_2^2} = \rho + c[(dT + b_{IFP}^r) - (dt + b_{IFP}^s)] + d_{orb} + d_{trop} + \varepsilon(P_{IF})$$

$$\Phi_{IF} = \frac{f_1^2 \cdot \Phi_1 - f_2^2 \cdot \Phi_2}{f_1^2 - f_2^2} = \rho + c[(dT + b_{IFP}^r) - (dt + b_{IFP}^s)] + d_{orb} + d_{trop} + c[(b_{IF\Phi}^r - b_{IFP}^r) + (b_{IF\Phi}^s - b_{IFP}^s)] + \lambda_{IF} N_{IF} + \varepsilon(\Phi_{IF})$$

Bias Issue in PPP

Traditional model (Zumberge et al., 1997)

Ionospheric-Free code and phase combinations

$$P_{IF} = \frac{f_1^2 \cdot P_1 - f_2^2 \cdot P_2}{f_1^2 - f_2^2} = \rho + c(dT + b_{IFP}^r) + d_{trop} + \varepsilon(P_{IF})$$

Receiver clock term in the estimates

$$\Phi_{IF} = \frac{f_1^2 \cdot \Phi_1 - f_2^2 \cdot \Phi_2}{f_1^2 - f_2^2} = \rho + c(dT + b_{IFP}^r) + d_{trop}$$
$$+ c[(b_{IF\Phi}^r - b_{IFP}^r) + (b_{IF\Phi}^s - b_{IFP}^s)] + \lambda_{IF} N_{IF} + \varepsilon(\Phi_{IF})$$

Ambiguity term in the estimates

Bias Issue in PPP

Traditional model (Zumberge et al., 1997)

Ionospheric-Free code and phase combinations

✓ based on C1 and P2

$$C_1 = \rho + cdT + d_{trop} + d_{ion/L1} + cb^s_{IFP} + c(b^r_{C1} - b^s_{C1}) + \varepsilon(C_1)$$

$$= \rho + c(dT + b^r_{IFCP}) + d_{trop} + d_{ion/L1} + c(b^s_{IFP} - b^s_{IFCP}) + \frac{c}{1-\gamma}(DCB^r_{C1,P2} - DCB^s_{C1,P2}) + \varepsilon(C_1)$$

$$P_2 = \rho + cdT + d_{trop} + d_{ion/L2} + cb^s_{IFP} + c(b^r_{P2} - b^s_{P2}) + \varepsilon(P_2)$$

$$= \rho + c(dT + b^r_{IFCP}) + d_{trop} + d_{ion/L2} + c(b^s_{IFP} - b^s_{IFCP}) + \frac{c\gamma}{1-\gamma}(DCB^r_{C1,P2} - DCB^s_{C1,P2}) + \varepsilon(P_2)$$

$$P_{IFCP} = \frac{f_1^2 \cdot C_1 - f_2^2 \cdot P_2}{f_1^2 - f_2^2}$$

Receiver clock term in the estimates

$$= \rho + c(dT + b^r_{IFCP}) + d_{trop} - c\frac{\gamma}{1-\gamma}DCB^s_{C1,P1} + \varepsilon(P_{IFCP})$$

must be calibrated

$$\Phi_{IF} = \frac{f_1^2 \cdot \Phi_1 - f_2^2 \cdot \Phi_2}{f_1^2 - f_2^2} = \rho + c(dT + b^r_{IFCP}) + d_{trop}$$

$$+ c[(b^r_{IF\Phi} - b^r_{IFCP}) + (b^s_{IF\Phi} - b^s_{IFP})] + \lambda_{IF}N_{IF} + \varepsilon(\Phi_{IF})$$

Ambiguity term in the estimates

Bias Issue in PPP

UofC model (Gao and Shen, 2002)

Average of code and phase + IF phase combination

$$P_{P1,\Phi1} = \rho + c(dT + b^{r}_{IFP}) + d_{trop} + 0.5[c(b^{r}_{P1} + b^{r}_{\Phi1}) - c(b^{s}_{P1} + b^{s}_{\Phi1}) - 2c(b^{r}_{IFP} - cb^{s}_{IFP}) + \lambda_1 N_1] + \varepsilon\ (P_{P1,\Phi1})$$

$$P_{P2,\Phi2} = \rho + c(dT + b^{r}_{IFP}) + d_{trop} + 0.5[c(b^{r}_{P2} + b^{r}_{\Phi2}) - c(b^{s}_{P2} + b^{s}_{\Phi2}) - 2c(b^{r}_{IFP} - b^{s}_{IFP}) + \lambda_2 N_2] + \varepsilon\ (P_{P2,\Phi2})$$

$$\Phi_{IF} = \rho + c(dT + d^{r}_{IFP}) + d_{trop} + \frac{f_1^2[c(b^{r}_{\Phi1} - b^{s}_{\Phi1}) - c(b^{r}_{P1} - b^{s}_{P1}) - 2c(b^{r}_{IFP} - b^{s}_{IFP}) + \lambda_1 N_1]}{f_1^2 - f_2^2} - \frac{f_2^2[c(b^{r}_{\Phi2} - b^{s}_{\Phi2}) - c(b^{r}_{P2} - b^{s}_{P2}) - 2c(b^{r}_{IFP} - b^{s}_{IFP}) + \lambda_2 N_2]}{f_1^2 - f_2^2} + \varepsilon\ (\Phi_{IF})$$

- ✓ L1 ambiguity term in the estimates

$$c(b^{r}_{P1} + b^{r}_{\Phi1}) - c(b^{s}_{P1} + b^{s}_{\Phi1}) - 2c(b^{r}_{IFP} - cb^{s}_{IFP}) + \lambda_1 N_1$$

- ✓ L2 ambiguity term in the estimates

$$c(b^{r}_{P2} + b^{r}_{\Phi2}) - c(b^{s}_{P2} + b^{s}_{\Phi2}) - 2c(b^{r}_{IFP} - b^{s}_{IFP}) + \lambda_2 N_2$$

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