Session on Calibration and Future Receiver Developments

Part I: Calibration

- Yang Gao - Bias catalog, effect and calibration….
- Gerard Petit - Absolute receiver bias calibration, stability…..
- Stefan Schaer - IGS bias estimates, data format issue…

GNSS Biases, their Effect and Calibration

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IGS Workshop 2008
2-6 June 2008, Miami Beach, Florida, USA

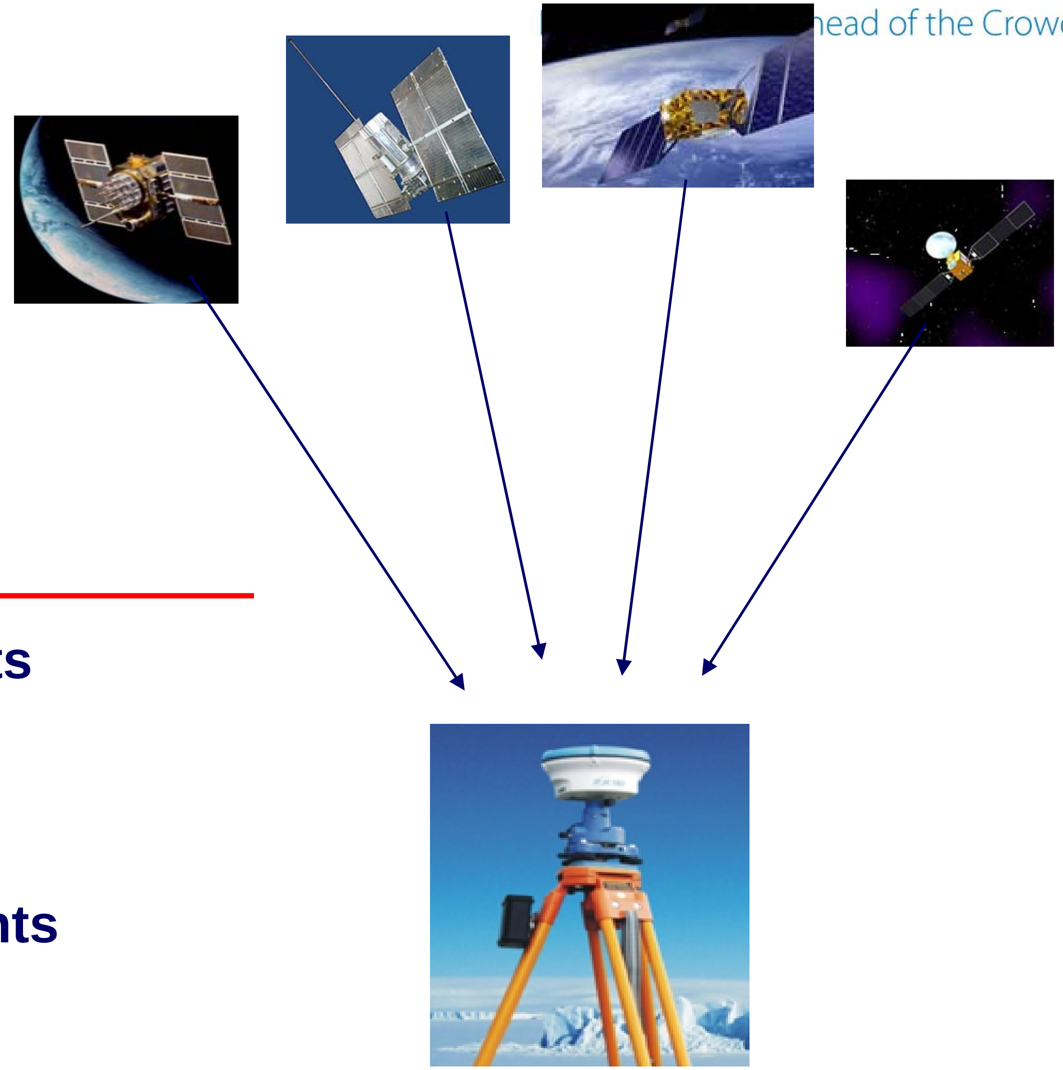
Outline

- **Catalog of GNSS Biases**
- **Effect of Biases on IGS Products**
- **Bias Calibration**
- **Bias Issue in PPP**
- **GNSS Biases**
- **Recommendations/Actions for Discussions**

Catalog of GNSS Biases

- **Hardware Bias**
  - ✓ **Satellite related bias**
  - ✓ **Receiver related bias**
- **Firmware Bias**
  - ✓ **Satellite related bias**
  - ✓ **Receiver related bias**

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



GPS Biases in Observation Equations

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

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

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

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

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

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

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

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

Catalog of GNSS Biases

Biases are not estimable in absolute sense

Relative
(fix a reference such as a ground receiver)

- **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 (multi-constellations)

- **Inter-system Time System Offset**
  - ✓ GPS/GLONASS
  - ✓ GPS/GALILEO
  - ✓ GPS/COMPASS
- **Inter-system Coordinate System Offset**
  - ✓ GPS/GLONASS
  - ✓ GPS/GALILEO
  - ✓ GPS/COMPASS

Absolute receiver bias calibration

- ✓ **BIPM (see Petit's slides)**
- ✓ **JPL (see below from Larry Young)**

JPL had 4 generations of receiver calibration used since 1980.

1. SERIES (pretty much the same as for #4 below)

2. SERIES-X: codeless dual frequency
This was calibrated by generating PN codes at 1.023 MHz and 10.23 MHz, and modulating both onto a L1 carrier, and the 10,23 MHz code onto the L2 carrier, and coupling them into the receiver data stream. An interesting feature is they were swept across the signal doppler range to measure phase shifts across each filter.

3. ROGUE
This receiver used the CA, P1, and P2 codes, and was designed for ionospheric measurements, and so needed accurate L1-L2 delay calibrations. There was a 'clever trick" which proved very accurate. The receiver was designed with very symmetric paths for P1 and P2. For calibration, the operator used the L1 LO frequency to drive both L1 andL2 mixers, so the receiver tracked the P1 signal on both channels. This provided TEC calibrations to about 100 ps, which translates to a TEC error of about 0.3E-16 e-/m2.

4 Turborogue: Codeless or semicodeless tracking CA, P(Y)1, and P(Y)2
The calibrator generated a GLONASS code at 10.23 MHz, and mixed that with the sum of L1 and L2 LOs in a single mixer. The modulated L1 and L2 carriers were cupled into the receiver signal path near the antenna. This provided ~200 ps to 300 ps L1 - L2 calibration accuracy when it worked, but there were problems with some of the directional couplers which added differential delay to the calibration signal.

Lesson: It is not easy to get better than 1 ns calibration!

IGS Product Convention and Bias Effect on IGS products

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

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

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

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

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

Bias Calibration

GPS Observation Equations using IGS Products

$$C_1 = \rho + cdT + d_{trop} + d_{ion/L1} + c(T_{gd} + DCB_{P1/C1}) + cb^r_{C1} + \varepsilon(C_1)$$

$$P_1 = \rho + cdT + d_{trop} + d_{ion/L1} + cT_{gd} + cb^r_{P1} + \varepsilon(P_1)$$

$$P_2 = \rho + cdT + d_{trop} + d_{ion/L2} + c\gamma T_{gd} + cb^r_{P2} + \varepsilon(P_2)$$

$$C_2 = \rho + cdT + d_{trop} + d_{ion/L2} + c(T_{gd} + DCB_{P2/C2}) + cb^r_{C2} + \varepsilon(C_2)$$

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

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

$$P_2' = \rho + cdT + d_{trop} + d_{ion/L2} + c\gamma T_{gd} + c \cdot DCB_{P1/C1} + b^r_{P2'} + \varepsilon(P_2')$$

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

Bias Calibration

✓ **DCB (P1, P2) and Tgd**

$$\begin{cases} b_{P1}^{s} = b_{IFP}^{s} - \dfrac{1}{1-\gamma} DCB_{P1/P2}^{s} = b_{IFP}^{s} - T_{gd} \\ b_{P2}^{s} = b_{IFP}^{s} - \gamma \dfrac{1}{1-\gamma} DCB_{P1/P2}^{s} = b_{IFP}^{s} - \gamma T_{gd} \end{cases}$$

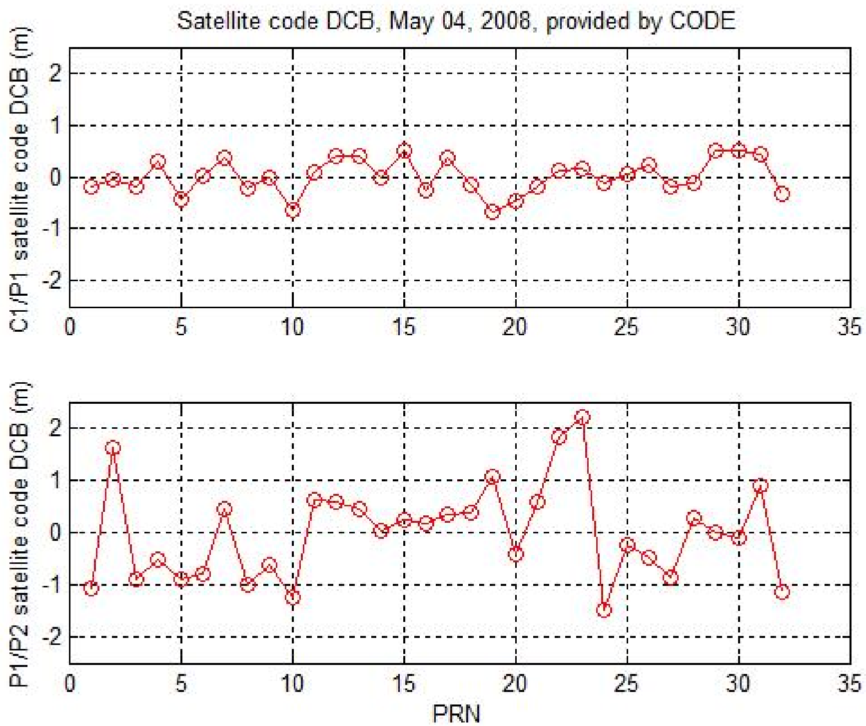
$$b_{IFP}^{s} = \frac{f_1^{\,2} b_{P1}^{s} - f_2^{\,2} b_{P2}^{s}}{f_1^{\,2} - f_2^{\,2}} \qquad \gamma = \left(\frac{f_1}{f_2}\right)^2$$

$$T_{gd} = \frac{b_{P2}^{s} - b_{P1}^{s}}{1-\gamma} = \frac{DCB_{P1/P2}^{s}}{1-\gamma}$$

$$DCB_{P1/P2}^{s} = (1-\gamma) T_{gd}$$

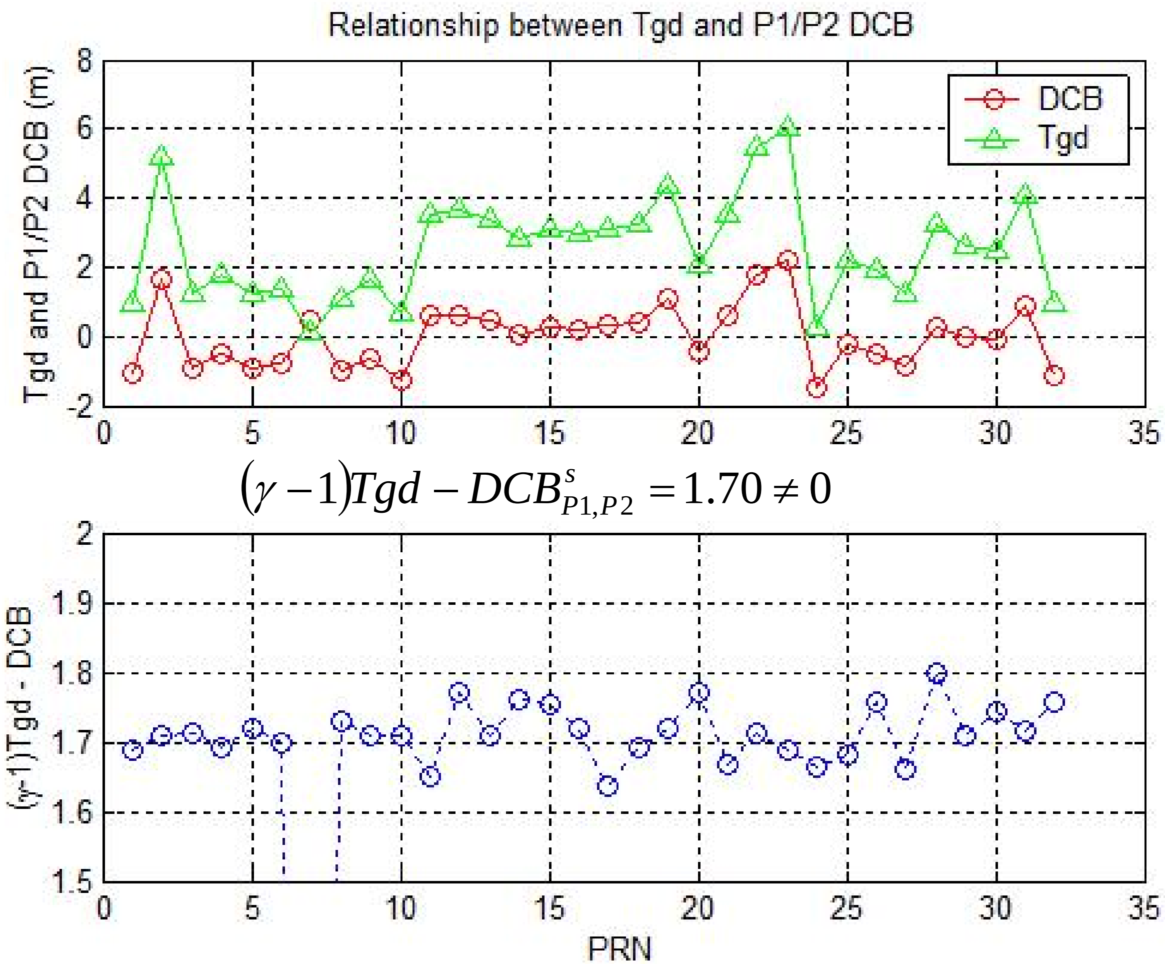
✓ **DCB (C1, P1)**

$$DCB_{C1/P1}^{s} = b_{P1}^{s} - b_{C1}^{s}$$



IGS bias estimates (see Schaer's slides)

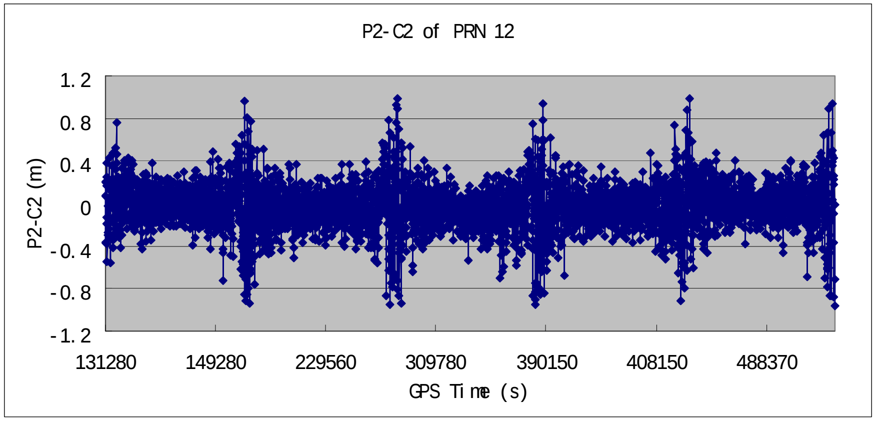
Bias Calibration

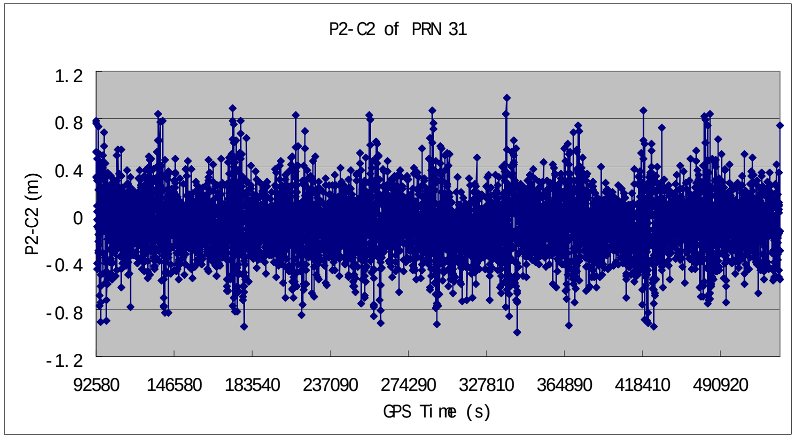


$$(\gamma - 1)Tgd - DCB^{s}_{P1,P2} = 1.70 \neq 0$$

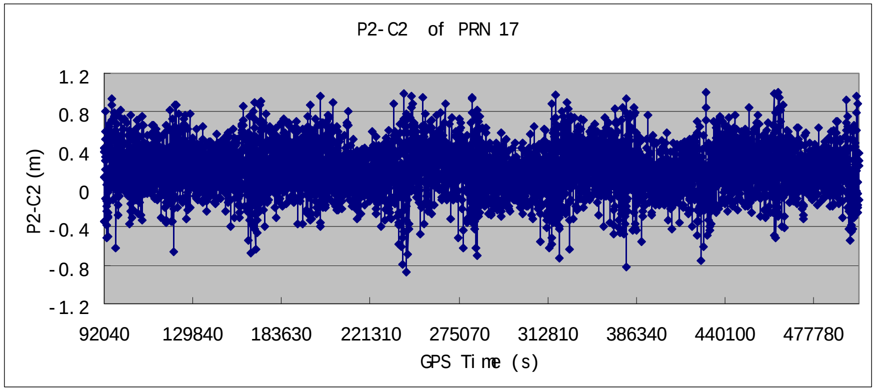
CODE DCB(P1, P2) and broadcast Tgd

Bias Calibration





PRN	Mean (cm)	STD (cm)
12	-2.9	21.9
17	19.3	24.9
31	-8.6	25.4



✓ **DCB (C2, P2)**

$$DCB_{C1/P1} = (b_{P1}^{r} - b_{C1}^{r}) - (b_{P1}^{s} - b_{C1}^{s})$$

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

$$P_{P1,\Phi 1} = \frac{P_1 + \Phi_1}{2}$$
$$= \rho + cdT + d_{trop} + cb^s_{IFP} + 0.5[c\left(b^r_{P1} + b^r_{\Phi 1}\right) - c\left(b^s_{P1} + b^s_{\Phi 1}\right) + \lambda_1 N_1] + \varepsilon\ (P_{P1,\Phi 1})$$

$$P_{P2,\Phi 2} = \frac{P_2 + \Phi_2}{2}$$
$$= \rho + cdT + d_{trop} + cb^s_{IFP} + 0.5[c\left(b^r_{P2} + b^r_{\Phi 2}\right) - c\left(b^s_{P2} + b^s_{\Phi 2}\right) + \lambda_2 N_2] + \varepsilon\ (P_{P2,\Phi 2})$$

$$\Phi_{IF} = \rho + c(dT + d^r_{IFP}) + d_{trop} + \frac{f_1^2[c(b^r_{\Phi 1} - b^s_{\Phi 1}) - c(b^r_{P1} - b^s_{P1}) + \lambda_1 N_1]}{f_1^2 - f_2^2}$$
$$- \frac{f_2^2[c(b^r_{\Phi 2} - b^s_{\Phi 2}) - c(b^r_{P2} - b^s_{P2}) + \lambda_2 N_2]}{f_1^2 - f_2^2} + \varepsilon\ (\Phi_{IF})$$

Bias Issue in PPP

UofC model (Gao and Shen, 2002)

Average of code and phase + IF phase combination

$$P_{P1,\Phi 1} = \rho + c(dT + b^{r}_{IFP}) + d_{trop} + 0.5[c(b^{r}_{P1} + b^{r}_{\Phi 1}) - c(b^{s}_{P1} + b^{s}_{\Phi 1}) - 2c(b^{r}_{IFP} - cb^{s}_{IFP}) + \lambda_1 N_1] + \varepsilon\ (P_{P1,\Phi 1})$$

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

$$\Phi_{IF} = \rho + c(dT + d^{r}_{IFP}) + d_{trop} + \frac{f_1^2[c(b^{r}_{\Phi 1} - b^{s}_{\Phi 1}) - c(b^{r}_{P1} - b^{s}_{P1}) - 2c(b^{r}_{IFP} - b^{s}_{IFP}) + \lambda_1 N_1]}{f_1^2 - f_2^2} - \frac{f_2^2[c(b^{r}_{\Phi 2} - b^{s}_{\Phi 2}) - c(b^{r}_{P2} - b^{s}_{P2}) - 2c(b^{r}_{IFP} - b^{s}_{IFP}) + \lambda_2 N_2]}{f_1^2 - f_2^2} + \varepsilon\ (\Phi_{IF})$$

- ✓ L1 ambiguity term in the estimates

$$c(b^{r}_{P1} + b^{r}_{\Phi 1}) - c(b^{s}_{P1} + b^{s}_{\Phi 1}) - 2c(b^{r}_{IFP} - cb^{s}_{IFP}) + \lambda_1 N_1$$

- ✓ L2 ambiguity term in the estimates

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

Bias Issue in PPP

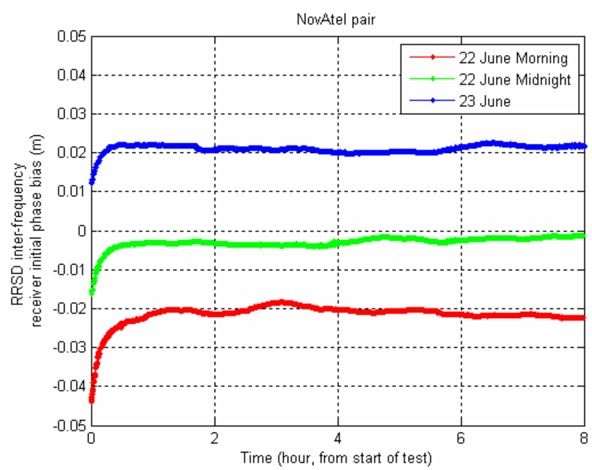
Receiver fractional phase bias

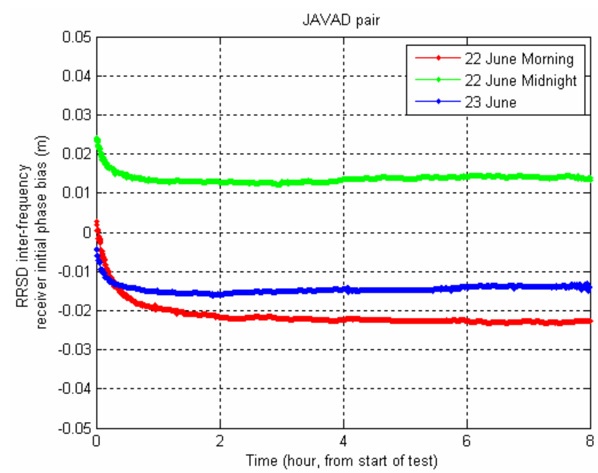
- ✓ Zero-baseline approach
- ✓ Receiver fractional phase bias is not stable
- ✓ The bias value changes after each power-cycle of receiver

$$\Phi_1 - \Phi_2 = (-d_{ion/L1} + b^r_{\Phi 1} - b^s_{\Phi 1} + \lambda_1 N_1) - (-d_{ion/L2} + b^r_{\Phi 2} - b^s_{\Phi 2} + \lambda_2 N_2)$$

$$\Delta(\Phi_1 - \Phi_2) = (\Delta b^r_{\Phi 1} - \Delta b^r_{\Phi 2}) + \left(\lambda_1 \Delta N_1 - \lambda_2 \Delta N_2\right)$$

$$\Delta b^r_{\Phi 1} - \Delta b^r_{\Phi 2} = \Delta(\Phi_1 - \Phi_2) - \left(\lambda_1 \Delta N_1 - \lambda_2 \Delta N_2\right)$$

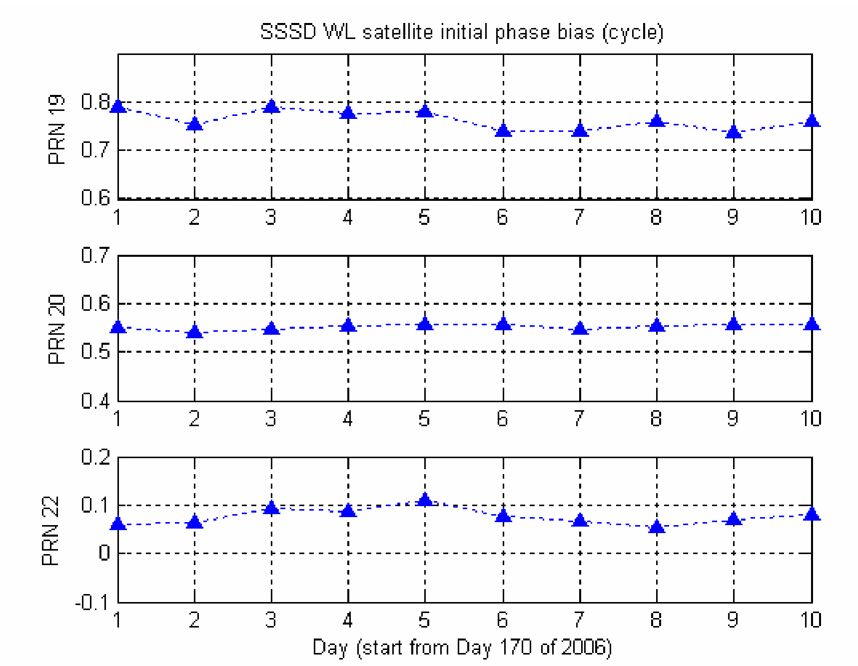


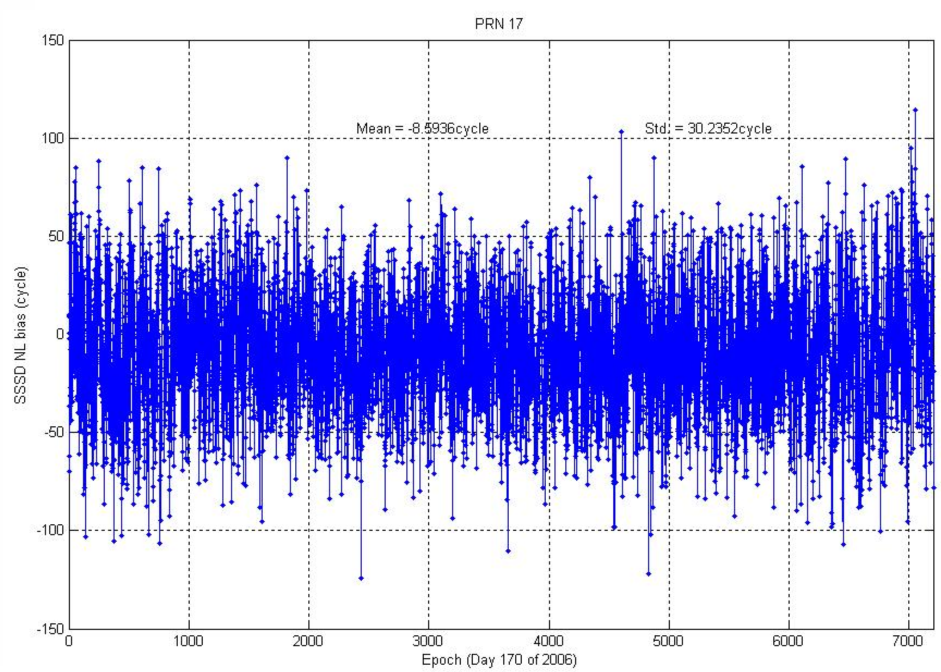


Bias Issue in PPP

Satellite fractional phase bias

- ✓ Wide-lane phase bias value is stable
- ✓ Narrow-lane bias value is very hard to determine (noise std is 30 cycle and NL wavelength is only 10 cm)

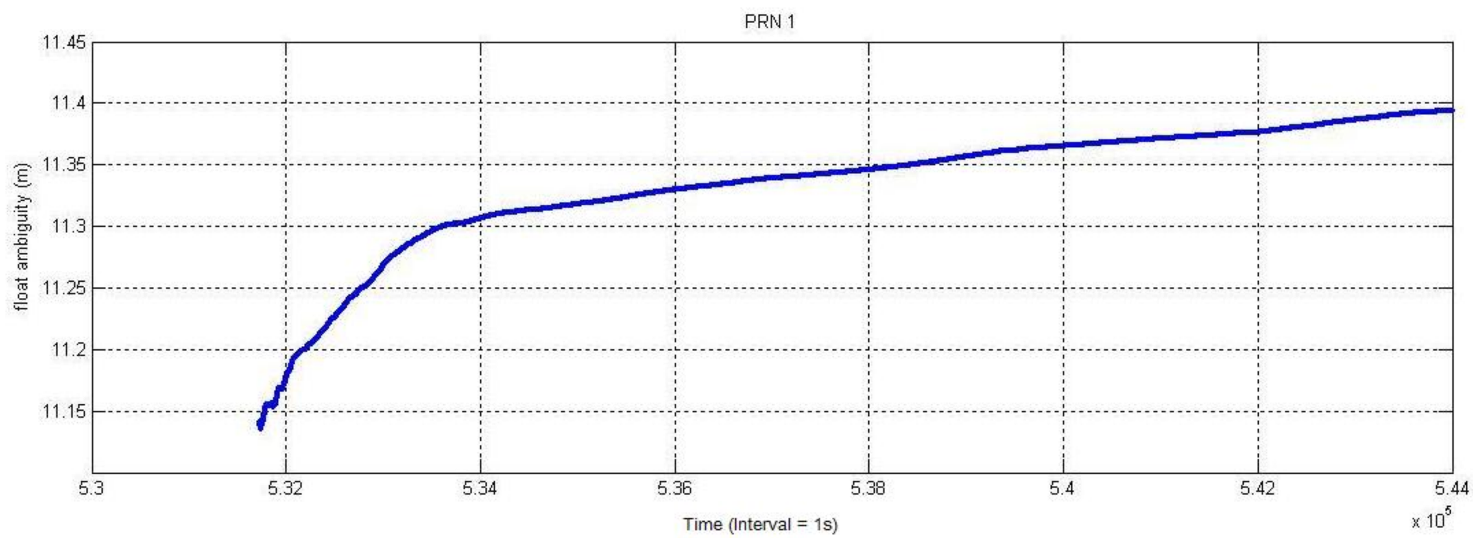




Bias Issue in PPP

Challenges for integer ambiguity resolution in PPP

- ✓ Ambiguity term in PPP is affected by many residual errors and biases including those due to satellite orbit/clock products
- ✓ Float ambiguity solutions usually not converge to a constant



GNSS Biases

PRN	Bias (cm)	STD (cm)	Epochs
38	−62.06	16.91	95866
41	−62.18	9.65	103658
43	−52.15	9.93	64476
45	−67.21	14.14	72705
46	−53.43	7.21	91423
47	−50.39	8.3	109083
48	−53.02	8.17	81015
50	−53.56	8.23	72067
51	−45.56	10	93959
52	−54.83	9.3	96608
54	−53.72	10.38	70726
56	−48.83	9.14	85059
57	−50.45	11.45	90261
60	−50.74	11.6	96119
61	−50.4	9.63	88684

GLONASS DCB (G1, G2) (zero-baseline)

$$\Delta DCB^{r}_{G1/G2}$$

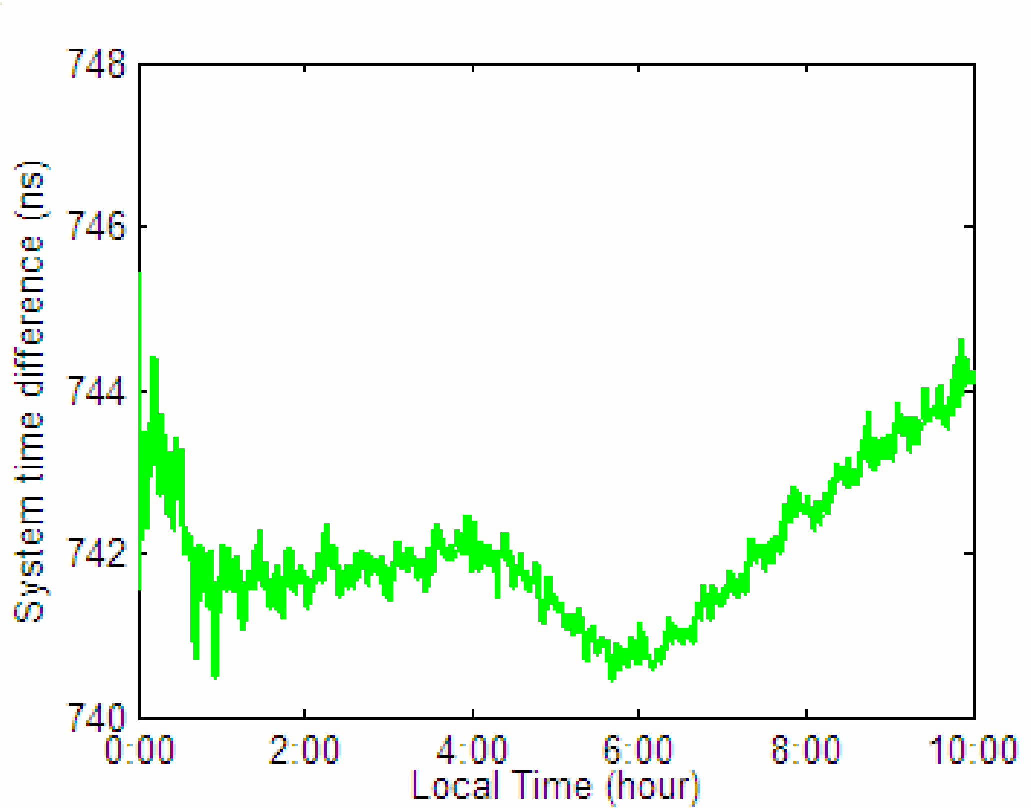
GNSS Biases

PRN	Bias (cm)	STD (cm)	Epochs
38	32.31	16.87	95899
41	32.57	9.64	103721
43	19.99	9.69	64506
45	37.69	14.14	72759
46	16.07	7.22	91543
47	21.14	8.17	109141
48	19.12	7.98	81063
50	15.65	8.29	72098
51	16.07	10.02	93980
52	20.51	9.31	96631
54	18.43	10.41	70737
56	18.68	9.06	85079
57	19.16	11.57	90287
60	20.89	11.53	96185
61	20.17	9.54	88708

GLONASS G1-GPS C1 (zero-baseline)

$$\Delta DCB^{r}_{C1/G1}$$

✓ Timing System Difference



System time difference between GPS and GLONASS

Discussions

- **IGS Convention and user guideline development**
  - Convention on observation combinations (modernized GPS signals, Galileo) and products (orbit/clock, iono/trop….)
  - Convention on bias estimates (products)
  - User community need to understand the convention and proper use of IGS products
  - Increased user community participation should be considered
  - Stable or able to monitor reference should be established for bias estimates
- **Absolute receiver bias calibration is becoming increasingly important as the increase of GNSS signals along with biases**
  - Current effort should be continued and increased to develop standard and convention
  - In-receiver bias calibration should be investigated, long-term stability is more important if removal is difficult
  - Firmware bias should be given special attention
- **Multi-constellation bias determination**
  - GLONASS products (some confusion….)
  - Bias estimates for GLONASS
  - Inter-system bias/offset estimates
- **Actions should be taken to further improve IGS products to support demanding applications**
  - These applications don't tolerate current small systematic biases in IGS products
  - Basic research efforts are needed to understand better GNSS biases and develop new modeling methodologies
  - Phase bias determination and real-time products should be investigated to support real-time OTF PPP

Discussions

Modeling issue for iono-free P1/P2

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

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

Decoupling clock model (Collins, 2008)

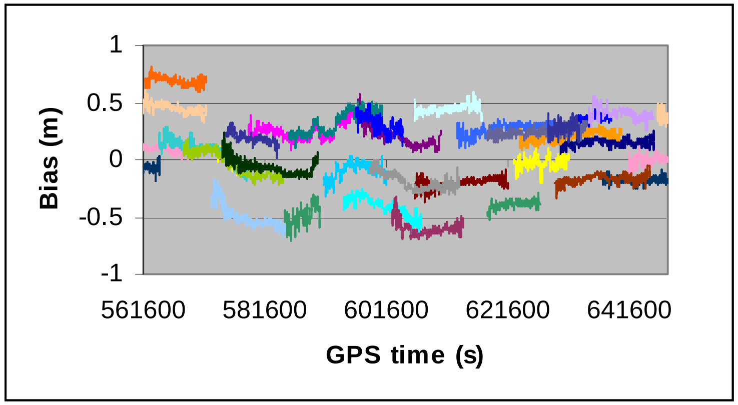
$$P_{IF} = \frac{f_1^2 \cdot P_1 - f_2^2 \cdot P_2}{f_1^2 - f_2^2} = \rho + c[(dT + b_{IFP}^r) - (dt + b_{IFP}^s)] + d_{orb} + d_{trop} + \varepsilon(P_{IF})$$

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

Discussions

Modeling issue for C1-P1 bias determination

$$C_1^i(j) - P_1^i(j) = d^i_{sat/C1} - d^i_{sat/P1} + d_{rcv/C1}(j) - d_{rcv/P1}(j) + \varepsilon(C_1^i(j) - P_1^i(j)) = d^i_{sat/C1-P1} + d_{rcv/C1-P1}(j) + \varepsilon(C_1^i(j) - P_1^i(j))$$



Modeling the effect of common signal (Gao et al., 2001)

$$C_1^i(j) - P_1^i(j) = d^i_{sat/C1} - d^i_{sat/P1} + d_{rcv/C1}(j) - d_{rcv/P1}(j) + S_{C1} - S_{P1} + \varepsilon(C_1^i(j) - P_1^i(j)) = d^i_{sat/C1-P1} + d_{rcv/C1-P1}(j) + S_{C1-P1} + \varepsilon(C_1^i(j) - P_1^i(j))$$

$$[C_1^i(j) - P_1^i(j)] - [C_1^k(j) - P_1^k(j)] = \Delta d^{i,r}_{sat/C1-P1} - \Delta d^{k,r}_{sat/C1-P1} + \varepsilon\left\{[C_1^i(j) - P_1^i(j)] - [C_1^k(j) - P_1^k(j)]\right\}$$