Multi-Constellation GNSS Precise Point Positioning using GPS, GLONASS and BeiDou in Australia

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Outline

- Multi-Constellation GNSS
- PPP for multi-GNSS
- Static PPP Test
- Kinematic PPP Test
- Summary

The Multi-GNSS

- Long solution convergence time and low accuracy when **the number of visible satellites is small** in GNSS-challenged environment
  - ✓ urban canyons
  - ✓ open pits
  - ✓ mountains
- Multi-Constellation GNSS
  - ✓ Improved availability and reliability
  - ✓ Improved accuracy and convergence time?

The multi-GNSS era

- Constellations
  - ✓ GPS and GLONASS: full constellation
  - ✓ Galileo:4 IOVS
  - ✓ BeiDou: 5GEOs/ 5 IGSOs/ 4 MEOs
  - ✓ …
- More satellites, more frequencies
  - ✓ New signals with higher power
  - ✓ Better tracking performance
  - ✓ Speed up ambiguity resolution process
  - ✓ Eliminate higher-order ionosphere path delay
  - ✓ …

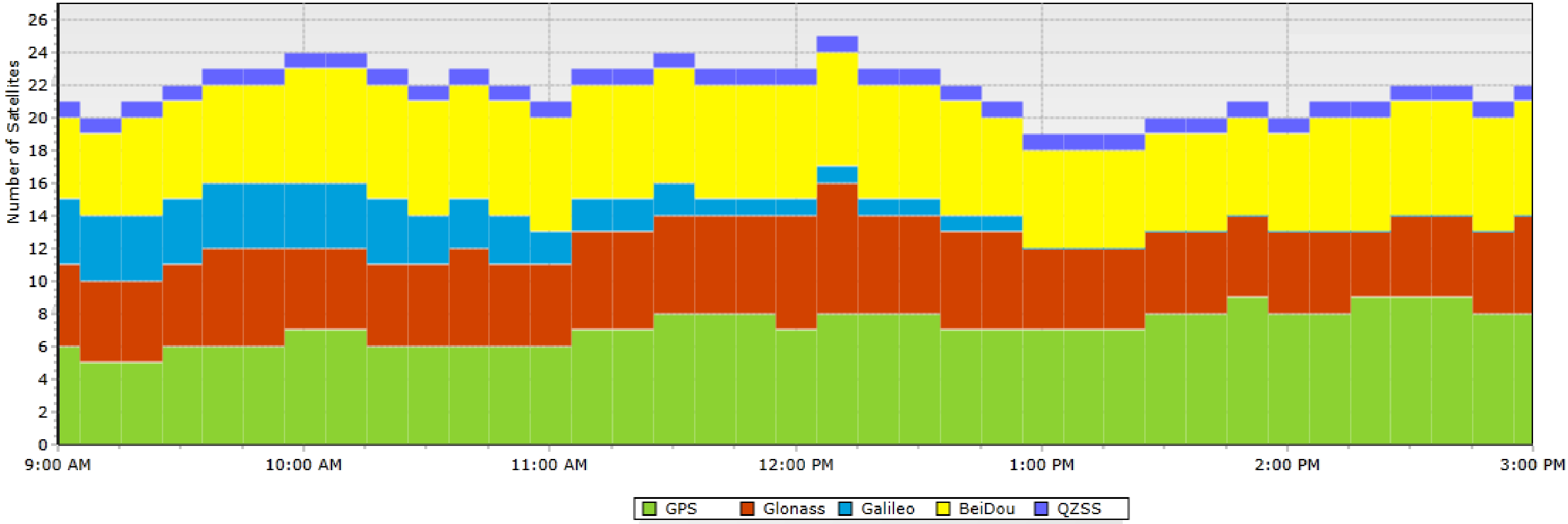


Figure 1. The number of SVs in Gold Coast on 16/07/15 (Trimble planning)

IGS Multi-GNSS Experiment

- IGS has set up the Multi-GNSS Experiment (MGEX - http://igs.org/mgex ,2011)
- MGEX network: More than 90 stations

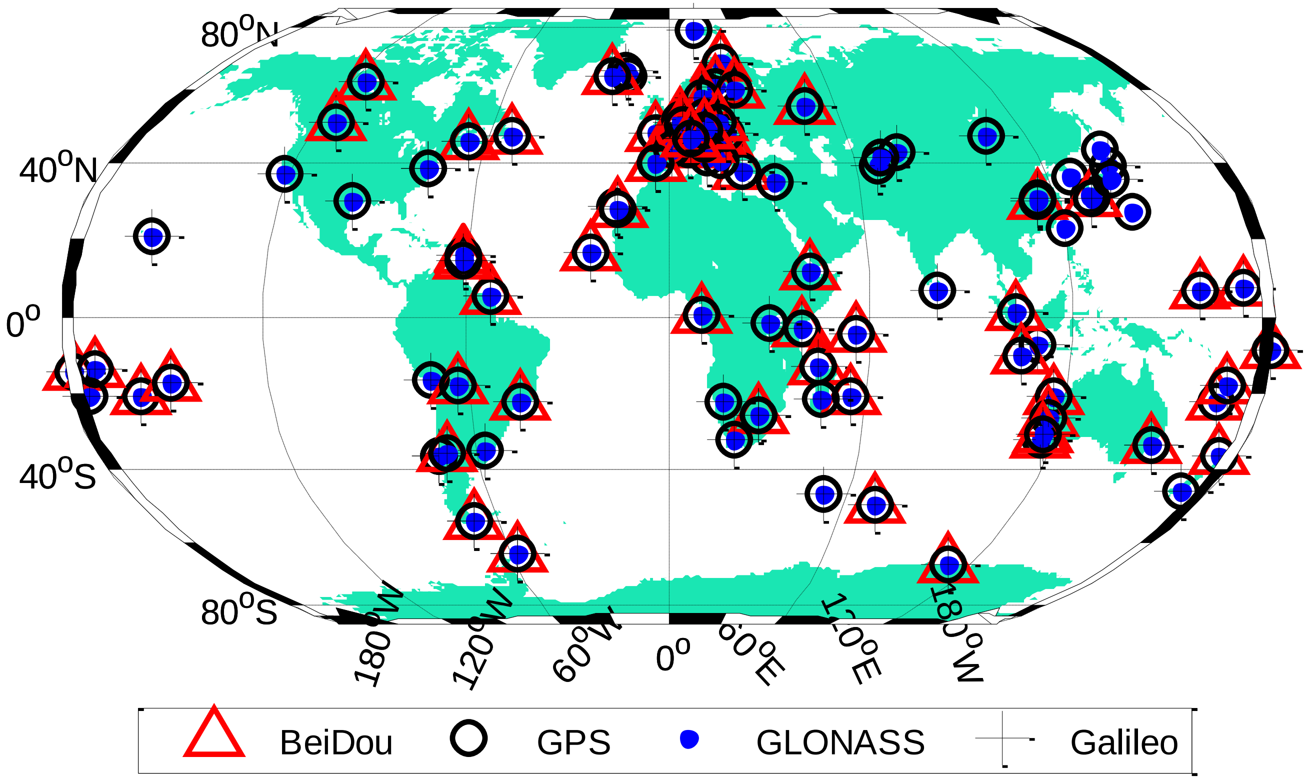


Figure 2. The IGS MGEX tracking stations network. Reference station tracking BeiDou are indicated as red triangle, GPS as hollow black circle, GLONASS as blue dot and Galileo as cross.

IGS MGEX Products

Table 1. The information of multi-GNSS precise orbit and clock products are provided from different MGEX analysis centres (http://igs.org/mgex/products).

Institution	Products		Constellation	Availability (week/day)
CNES/CLS	grmyyyyd.sp3	Orbits and Clocks (15 min)	GAL	Since 1692/1
CODE	comyyyyd.sp3	Orbits and Clocks (15 min)	GPS+GLO+ GAL/GIO	Since 1689/5
	comyyyyd.clk	Clocks (5 min)		
GFZ	gfmyyyyd.sp3	Orbits (15 min)	GPS+GAL	1680/0-1683/0
	gfmyyyyd.clk	Clocks (5 min)		
	gfbyyyyd.sp3	Orbits (15 min)	GPS+BDS	Since 1777/2-1781/5
	gfbyyyyd.clk	Clocks (5 min)		
JAXA	qzfyyyyd.sp3	Orbits and Clocks (5min)	GPS+QZS	Since 1751/6
TUM	tumyyyyd.sp3	Orbits and Clocks (5min)	GAL+QZS	Since 1711/1
Wuhan Univ	wumyyyyd.sp3	Orbits (15min)	BDS	since 1721/2
	wumyyyyd.clk	Clocks(5min)		

Evaluating the potential of PPP

- Available GNSS constellations
  - ✓ GPS
  - ✓ GLONASS
  - ✓ BeiDou
  - ✓ …
- Available Precise products
  - ✓ Precise Orbit
  - ✓ Precise Clock
  - ✓ …

Evaluation of the Multi-GNSS PPP

- Related studies
  - ✓ Tegedor, 2014;
  - ✓ Chen and Zhang, 2015;
  - ✓ Li and Zhang et al., 2015
  - ✓ …

Precise Point Positioning

- The ionosphere-free linear combinations equations:

$$P_{r,IF}^{j} = \frac{f_1^2 P_{r,1}^{j}}{f_1^2 - f_2^2} - \frac{f_2^2 P_{r,2}^{j}}{f_1^2 - f_2^2} = c_1 \cdot P_{r,1}^{j} + c_2 \cdot P_{r,2}^{j}$$

$$= \rho_r^j + c\cdot(dt_r - dt^j) + d_{orb}^j + m_r^j \cdot ZTD + B_{r,IF} - B_{IF}^j + \varepsilon_{r,P_{IF}}^j \quad (1)$$

$$L_{r,IF}^{j} = \frac{\lambda_2^2 L_{r,1}^{j}}{\lambda_2^2 - \lambda_1^2} - \frac{\lambda_1^2 L_{r,2}^{j}}{\lambda_2^2 - \lambda_1^2} = c_1 \cdot L_{r,1}^{j} + c_2 \cdot L_{r,2}^{j}$$

$$= \rho_r^j + c\cdot(dt_r - dt^j) + d_{orb}^j + m_r^j \cdot ZTD + \mathrm{N}_{r,IF}^j + b_{r,IF} - b_{IF}^j + \varepsilon_{r,L_{IF}}^j \quad (2)$$

- L_{IF} *and* P_{IF} are the ionospere-free phase and code pseudorange observable in meters, respectively;
- receiver “*r*” and satellite “*j*” ;
- $B_{r,IF}$ and B_{IF}^{j} are the receiver and satellite hardware code biases(m) on ionosphere-free pseudorange combined P_{IF} . $b_{r,IF}$ and b_{IF}^{j} denote those on L_{IF} *(m)*
- m_r^j *and ZTD* are mapping function and zenith tropospheric delay, respectively

Precise Point Positioning (cont.)

IGS precise ephemeris products include the ionosphere free satellite clock ($c\overline{dt}_{IF}^{j} = cdt^{j} + B_{IF}^{j}$) and precise satellite orbits. When corrected for these products, equations (1) and (2) becomes

$$P_{r,IF}^{j} + c\overline{dt}_{IF}^{j} = \bar{\rho}_{r}^{j} + c\overline{dt}_{r,IF} + m_{r}^{j} \cdot ZTD + \varepsilon_{r,P_{IF}}^{j} \quad (3)$$

$$L_{r,IF}^{j} + c\overline{dt}_{IF}^{j} = \bar{\rho}_{r}^{j} + c\overline{dt}_{r,IF} + m_{r}^{j} \cdot ZTD + \bar{N}_{r,IF}^{j} + \varepsilon_{r,L_{IF}}^{j} \quad (4)$$

Where $c\overline{dt}_{r,IF} = cdt_{r} + B_{r,IF}$ is the iono-free receiver clock, obit errors are considered insignificant when using IGS precise orbits, and

$$\bar{N}_{r,IF}^{j} = c_{1}N_{r,1}^{j} + c_{2}N_{r,2}^{j} + b_{r,IF} - b_{IF}^{j} + B_{IF}^{j} - B_{r,IF}$$

is the “float ambiguity” which is estimated as an additional parameter.

PPP in Multi-GNSS scenario

- If GPS time is used as the reference time, Equations (3) and (4) can be expanded to multi-constellation PPP observations model for GPS+GLONASS +BeiDou,

$$P_{r,IF}^{j,G} + cd\bar{t}_{IF}^{j,G} = \bar{\rho}_r^{j,G} + c \cdot d\bar{t}_r^{G} + m_r^{j,G} \cdot ZTD + \varepsilon_{r,P_{IF}}^{j,G}$$

$$L_{r,IF}^{j,G} + cd\bar{t}_{IF}^{j,G} = \bar{\rho}_r^{j,G} + c \cdot d\bar{t}_r^{G} + m_r^{j,G} \cdot ZTD + \bar{N}_{r,IF}^{j,G} + \varepsilon_{r,L_{IF}}^{j,G}$$

$$P_{r,IF}^{j,R} + cd\bar{t}_{IF}^{j,R} = \bar{\rho}_r^{j,R} + (c \cdot d\bar{t}_r^{G} + ISB_r^{j,GR}) + m_r^{j,R} \cdot ZTD + \varepsilon_{r,P_{IF}}^{j,R}$$

$$L_{r,IF}^{j,R} + cd\bar{t}_{IF}^{j,R} = \bar{\rho}_r^{j,R} + (c \cdot d\bar{t}_r^{G} + ISB_r^{j,GR}) + m_r^{j,R} \cdot ZTD + \bar{N}_{r,IF}^{j,R} + \varepsilon_{r,L_{IF}}^{j,R}$$

$$P_{r,IF}^{j,B} + cd\bar{t}_{IF}^{j,B} = \bar{\rho}_r^{j,B} + (c \cdot d\bar{t}_r^{G} + ISB_r^{GB}) + m_r^{j,G} \cdot ZTD + \varepsilon_{r,P_{IF}}^{j,B}$$

$$L_{r,IF}^{j,B} + cd\bar{t}_{IF}^{j,B} = \bar{\rho}_r^{j,B} + (c \cdot d\bar{t}_r^{G} + ISB_r^{GB}) + m_r^{j,B} \cdot ZTD + \bar{N}_{r,IF}^{j,B} + \varepsilon_{r,L_{IF}}^{j,B}$$

Where ISB_r^{SYS} denote the Inter System Biases in this case between GPS and the other systems. In the case of Beidou these biases can be considered unique for all satellites, whereas for GLONASS the phase biases ae different for each satellite.

Multi-GNSS test in Victoria, Australia

- The three GNSS reference stations equipped with dual frequency receiver capable of multi-GNSS tracking from the Victorian Continuously Operating Reference Stations (CORS) network – GPSnet.

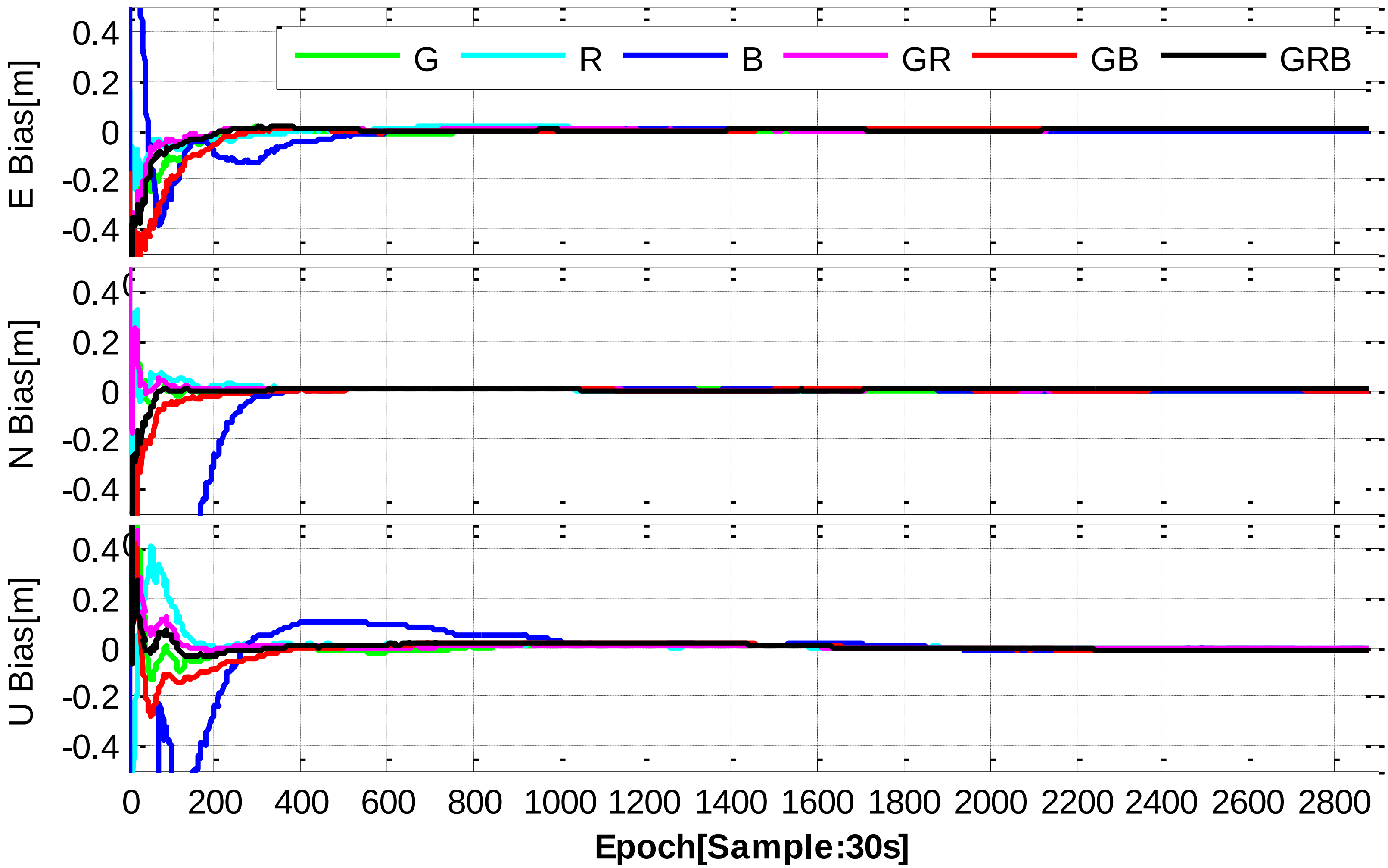
Table 2. Information of the GNSS stations.

Station	Receiver Type	Antenna	ITRF08 Coordinates (dd.mmsssssss)		
			Latitude	Longitude	Ellipsoidal Height
BNLA	TRIMBLE NETR9	TRM57971.00	-36.323789799	146.002148938	187.452
MNGO	TRIMBLE NETR9	TRM59800.00	-38.464726718	143.390618770	62.694
WORI	TRIMBLE NETR9	TRM57971.00	-37.463748052	145.314810106	117.955

PPP processing

Item	Models/Constraints
Observations	- Ionosphere-free combination measurements - GPS: L1/L2; GLONASS: L1/L2; BeiDou: B1/B2 - Elevation-dependent weighting strategy
Elevation Angle Cut-off	- 7°
Sampling Rate	- 30s
Precise Satellite Orbit	- GFZ precise orbit products（gfmyyyyd.sp3：15min）
Precise Satellite Clock	- GFZ precise clock products（gfmyyyyd.clk：5min）
Satellite PCO	- GPS+GLONASS：IGS antenna products（IGS08.atx） - BeiDou: Conventional Antenna Offsets (http://igs.org/mgex/status-BDS）
Satellite PCV	- GPS + GLONASS: IGS antenna products (IGS08.atx) - BeiDou: not applied
Receiver PCO and PCV	- GPS + GLONASS: IGS antenna products (IGS08.atx) - BeiDou: Not applied.
Phase wind-up	- Corrected (Wu et al.,1993)
Ionosphere	- First order effect removed by ionosphere-free combination
Troposphere model	- Saastamoinen model
Displacement	- Solid earth tides, solid earth pole tides ,ocean tides and relativistic effects modelling by IERS Convention 2010
Reference time system	- GPS Time
Station position	- Static: Constant - Kinematic: A Random Walk process for each epoch at a rate of 100m/s - An initial uncertainty of 100m
Receiver clock error	- A Random Walk process for each epoch at a rate of 100m/s - An initial uncertainty of 300km
Troposphere delay	- A Random Walk process for each epoch at a rate of 36cm/h - An initial uncertainty of 0.15 m
Ambiguity	- Constant for each satellite arc
Inter system biases	- A Random Walk process for each epoch at a rate of 100m/s

Static PPP Results



• **BNLA**

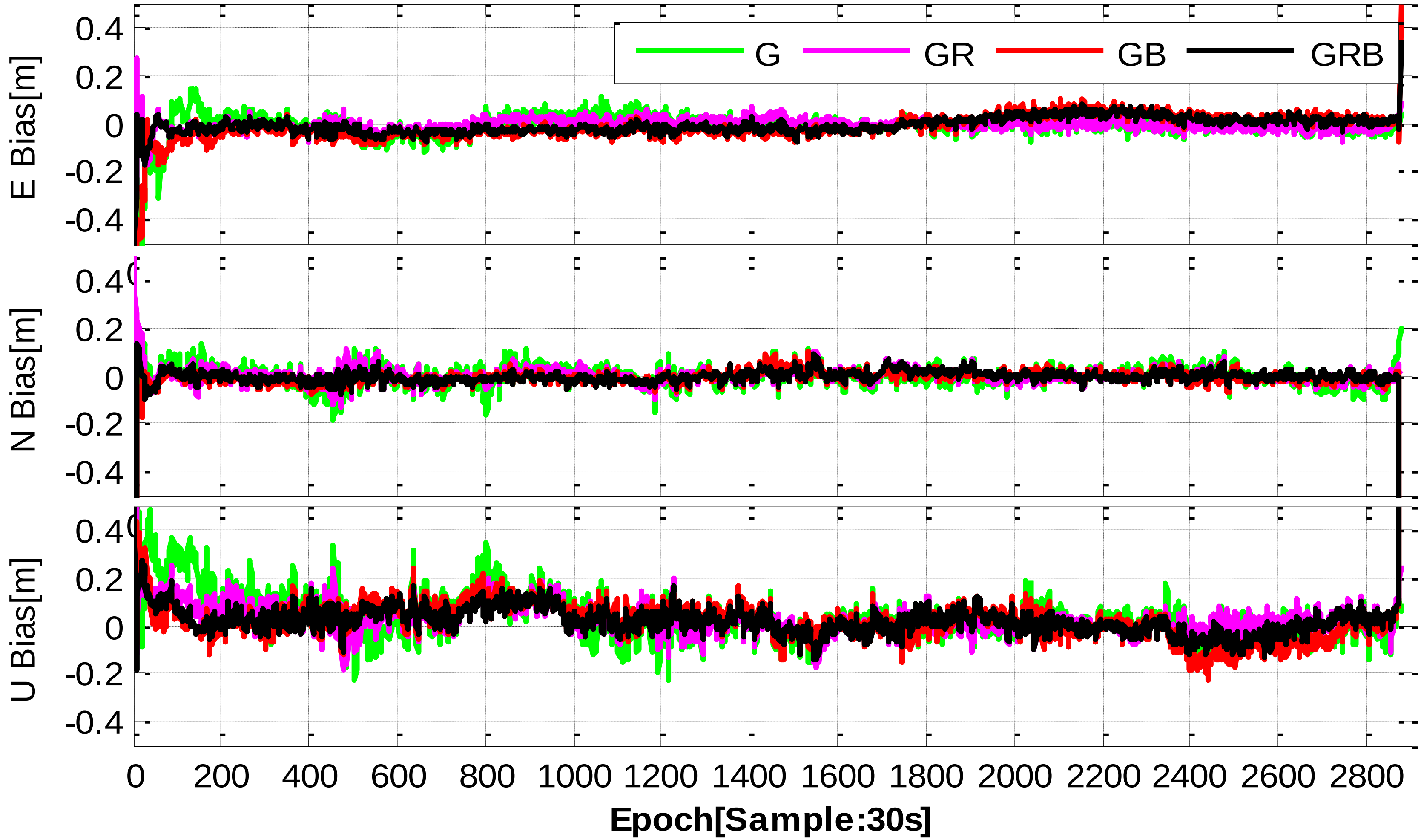
Static PPP Results

- The static position filter is considered to have converged when the positioning errors in all directions reach ±0.05 m and remain within **±0.05 m**.

Table 4. RMS (**3 sigma**) in centimetres and convergence time

Station	Item	GPS	GLO	BDS	GPS+GLO	GPS+BDS	GPS+GLO+BDS
BNLA	Time (<5cm)	58min	100min	502min	53min	60min	51min
	East	1.1	1.2	0.7	0.4	0.6	0.3
	North	0.3	0.3	0.6	0.3	0.1	0.2
	Up	1.5	1.0	5.7	1.1	2.4	2.1
	2-D	1.1	1.2	0.9	0.5	0.6	0.3
	3-D	1.9	1.6	5.7	1.2	2.5	2.1
MNGO	Time (<5cm)	65min	105min	400min	51min	66min	50min
	East	0.5	1.7	0.7	0.6	0.5	0.4
	North	0.6	0.3	0.6	0.5	0.5	0.4
	Up	1.3	0.6	5.5	0.7	2.2	1.5
	2-D	0.8	1.7	0.9	0.7	0.6	0.6
	3-D	1.5	1.8	5.5	1.0	2.3	1.6
WORI	Time (<5cm)	51min	101min	412min	52min	74min	37min
	East	0.5	1.6	0.6	0.9	0.6	0.5
	North	0.3	0.2	0.2	0.2	0.2	0.2
	Up	1.2	1.0	1.8	0.7	1.8	1.6
	2-D	0.5	1.6	0.6	0.9	0.6	0.5
	3-D	1.3	1.9	1.9	1.1	1.9	1.6

Kinematic PPP Results



•**BNLA**

Kinematic PPP Results

- The Kinematic position filter is considered to have converged when the positioning errors in all directions reach ±**0.20 m** and remain within ±**0.20 m**.

Table 4. RMS (**3 sigma**) in centimetres and convergence time

Station	Item	GPS	GPS+BDS	GPS+GLO	GPS+GLO+BDS
BNLA	Time (<20cm)	85min	68min	42min	41min
	East	5.4	6.7	3.6	5.3
	North	5.9	3.7	4.3	3.4
	Up	12.8	12.4	9.5	9.0
	2-D	8.0	7.6	5.7	6.3
	3-D	15.1	14.6	11.0	11.0
MNGO	Time (<20cm)	89min	62.5min	45min	48min
	East	8.7	7.0	3.2	6.5
	North	6.3	3.4	3.9	3.0
	Up	15.1	10.8	8.5	8.0
	2-D	10.8	7.7	5.0	6.5
	3-D	18.6	13.3	9.9	10.3
WORI	Time (<20cm)	74min	65min	35min	32min
	East	4.8	6.9	3.2	5.6
	North	5.8	3.7	4.1	3.0
	Up	10.6	10.2	8.3	8.3
	2-D	7.5	7.8	5.2	6.3
	3-D	13.0	10.2	9.8	10.4

Summary

- The performance and the benefits of a combined GPS+GLONASS+BeiDou system PPP were evaluated and compared
- Strengthen the positioning model and improve the accuracy and convergence time
  - ✓ For the static PPP solution, the positioning accuracy and convergence time of the combined system is marginally improved compared to the GPS-only static PPP solution.
  - ✓ For the kinematic PPP solution, the positioning accuracy was improved by approximately 20% and 30% in the horizontal and vertical components, respectively. shorten the convergence time by more than 20%

Thank you for your attention