Real-time Time and Frequency Transfer based on GNSS Network Solution

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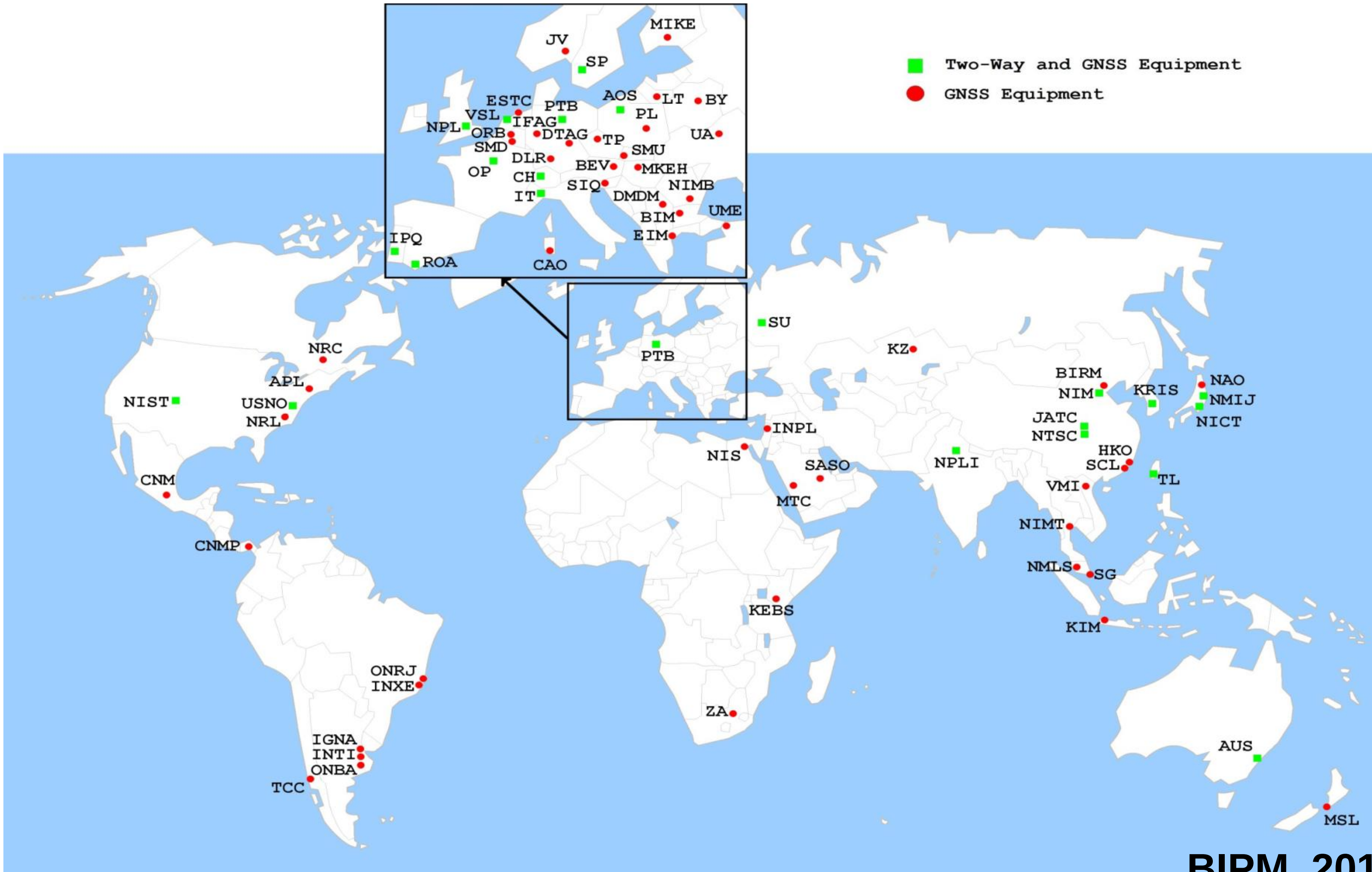
Content

- **Background**
- **New development in Time and Frequency Transfer(TFT)**
- **Multi-GNSS PPP and GNSS Network Solution for TFT**
- **TFT Experiment**
- **Summary**

World wide TAI TFT network

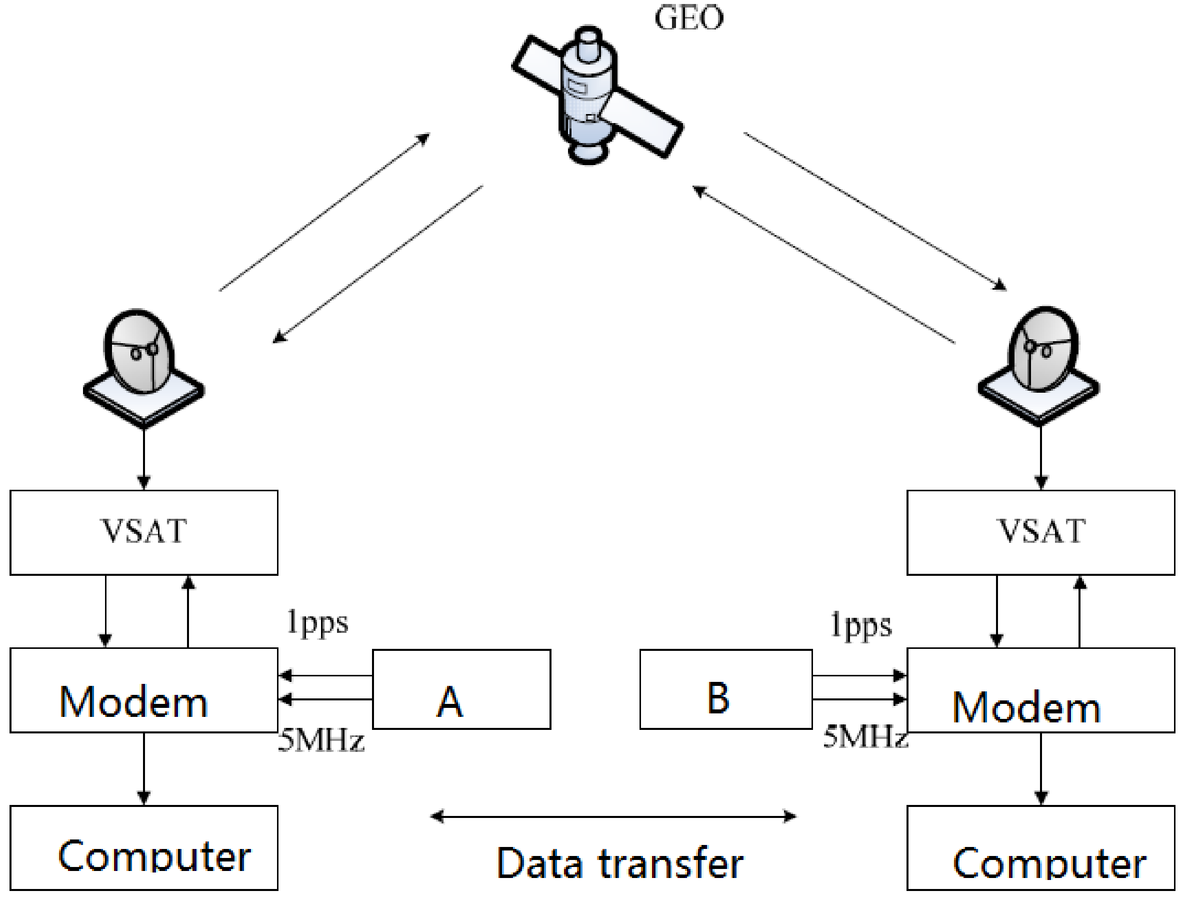
➢**Geographical distribution of the laboratories that contribute to TAI and time transfer equipment**



BIPM, 2014

Techniques for TFT

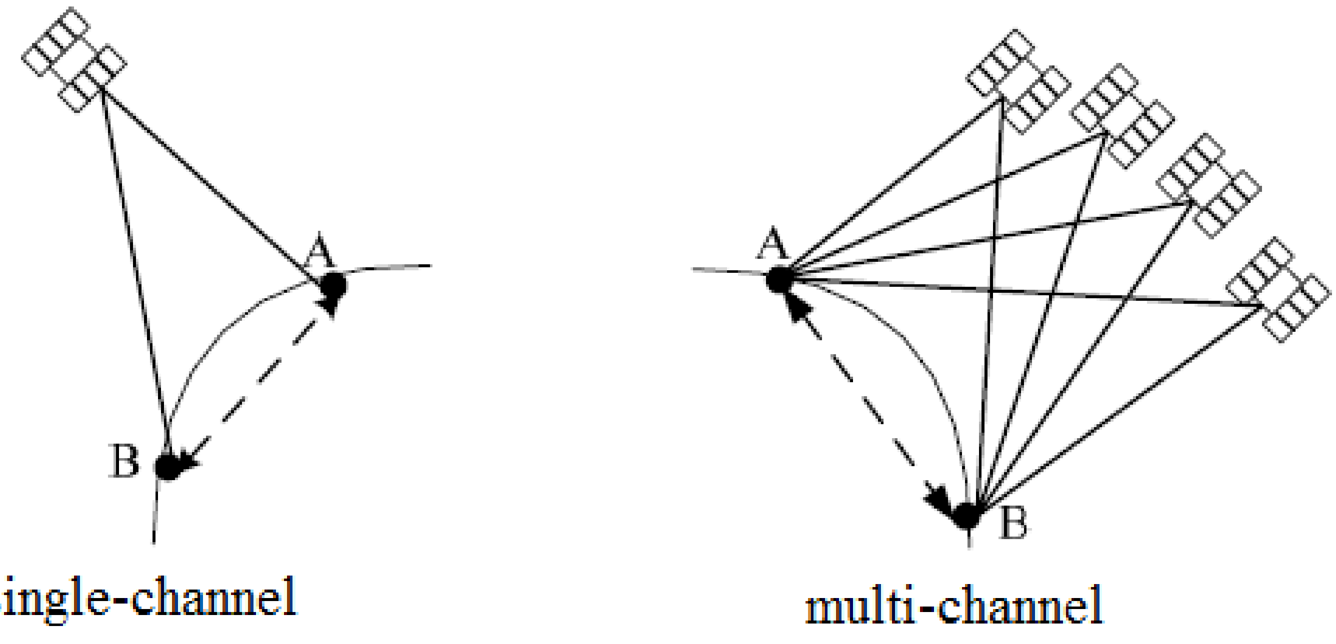
➢**Two Way Satellite Time and Frequency Transfer(TWSTFT):** *Similar paths of two signals; making difference between two records, thus* ***eliminating*** *common satellite errors.*



Techniques for TFT

➢**GPS Common View (CV) :** *Making satellite-differences between two stations, Satellite related error removed.*

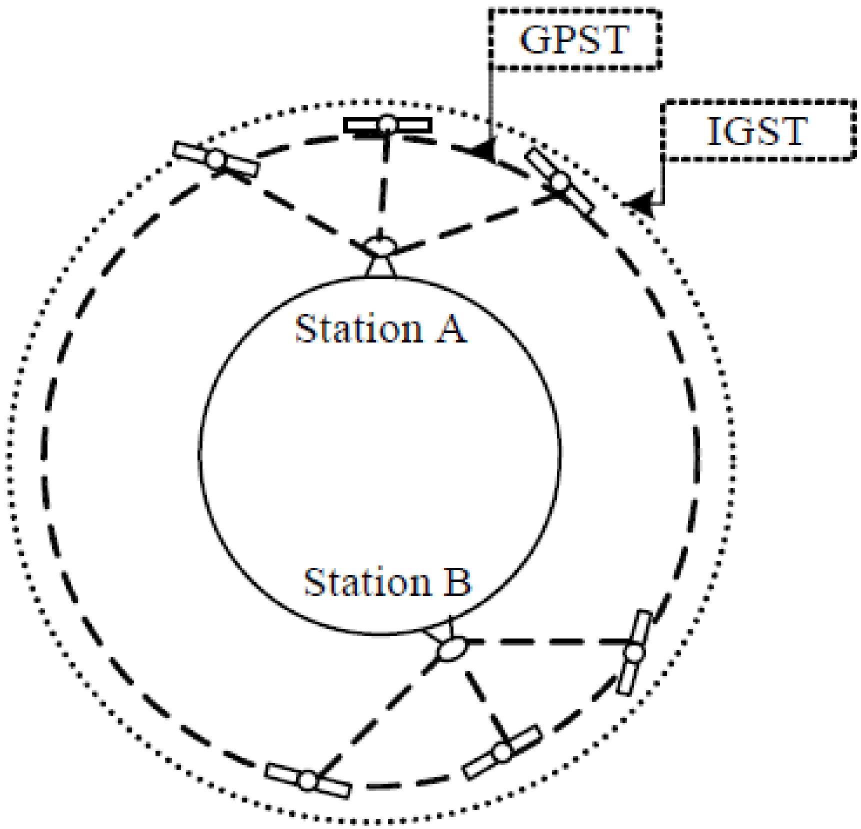
Valid only for stations have common satellites observed
Range data are used, common satellites are used



Techniques for TFT

➢**GPS All in View (AV) :** *Clock estimation using all satellites observed.*

No need for common satellites; Range data are used, Satellite related errors affect results; Could use precise satellite orbit/clock from e.g. the IGS.



Li, 2007

Techniques for TFT

➢**Precise Point Positioning :** *Clock estimation using all satellite observed.*

No need for common satellites; Range+Phase data are used, Satellite related errors affect results; Use precise satellite orbit/clock from e.g. the IGS.

$$\begin{cases} P_i^k = \rho + c\delta_i - c\delta^k + \delta_{trop} - \varepsilon_i \\ L_i^k = \rho + c\delta_i - c\delta^k + \delta_{trop} + \lambda N_i - \varepsilon_i \end{cases}$$

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➢IGS Precise satellite orbit/clock used

$$\delta_i = IGST - UTC(i)$$

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➢TFT obtained through clock comparison

$$\begin{aligned} \Delta T &= \delta_i - \delta_j \\ &= [IGST - \mathrm{UTC}(i)] - [IGST - \mathrm{UTC}(j)] \\ &= \mathrm{UTC}(j) - UTC(i) \end{aligned}$$

Techniques for TFT

➢**Precise Point Positioning :** *For real-time or quasi-real-time application, IGS Ultra-Rapid product (IGU) used, and PPP based TFT are affected.*

Accuracy of IGS product

Product	Orbits	Clocks
IGS Final	<2.5cm	<75ps
IGU(observed)	<3cm	<150ps
IGU(predicted)	<5cm	**<3ns**

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TFT using different IGS products (baseline:TWFT-IENG)

Product	IGS	IGR	IGU(O)	**IGU(P)**
RMS(ns)	0.13	0.16	0.23	**1.39**

New development using current techniques

- **Multi-GNSS constellation:** *Not GPS constellation only, receivers capable of tracking other constellations. More satellites to improve accuracy.*

- **Real-time:** *When TFT goes into real-time, accuracy/precision will much **decrease** using current techniques.*

- ***Combination:*** *Results from different techniques could be combined to generate better results.*

- ***New Application:*** ***system time offset between GNSS satellite systems*** *to improve interoperability.*

Multi-GNSS analysis model

➢**GPS observation:** *Clocks mitigate instrument delay errors.*

$$P_i^j = \rho_i^j + c \cdot (dt_i - dt^j) + DCB_i^j - I_i^j + T_i^j + \varsigma_i^j$$
$$L_i^j = \rho_i^j + c \cdot (dt_i - dt^j) + DPB_i^j + \lambda \cdot N_i^j - I_i^j + T_i^j + \varepsilon_i^j$$

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$$

$$\Downarrow$$

$$
\begin{aligned}
P_i^j &= \rho_i^j + c\cdot(\overline{d}t_i - \overline{d}t^j) - I_i^j + T_i^j + \varsigma_i^j \\
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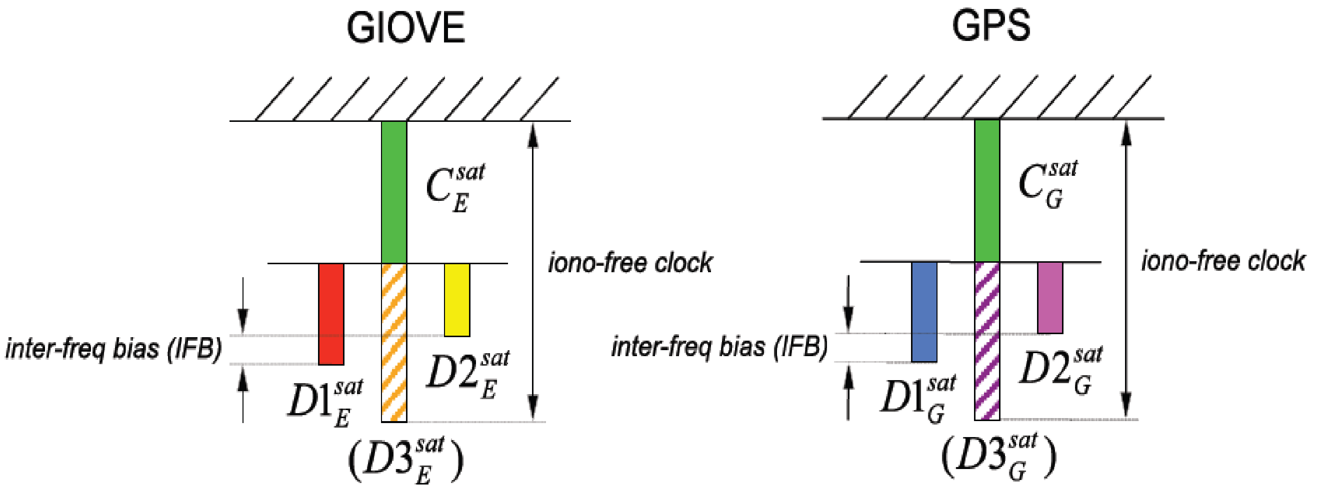
$$

Multi-GNSS analysis model

➢**Multi-GNSS observation:** *Same clocks could be set up, relative instrument delay (inter-system bias) removed or estimated.*



Ricardo Píriz et al., 2008

Multi-GNSS analysis model

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$$\mathrm{L}_{\mathrm{i}}^{kG} = \rho_{\mathrm{i}}^{kG} + \mathrm{c}\cdot(\overline{d}t_i - \overline{d}t^k)^G - I_i^{kG} + T_i^{kG} + \lambda^G \cdot \overline{N}_i^{kG} + \varsigma_i^k$$

$$\mathrm{L}_{\mathrm{i}}^{\mathrm{j}R} = \rho_{\mathrm{i}}^{\mathrm{j}R} + \mathrm{c}\cdot(\overline{d}t_i - \overline{d}t^j)^G + ISB_i^{jk} + \lambda^R \cdot \overline{N}_i^{jR} - I_i^{jR} + T_i^{jR} + \varepsilon_i^j$$

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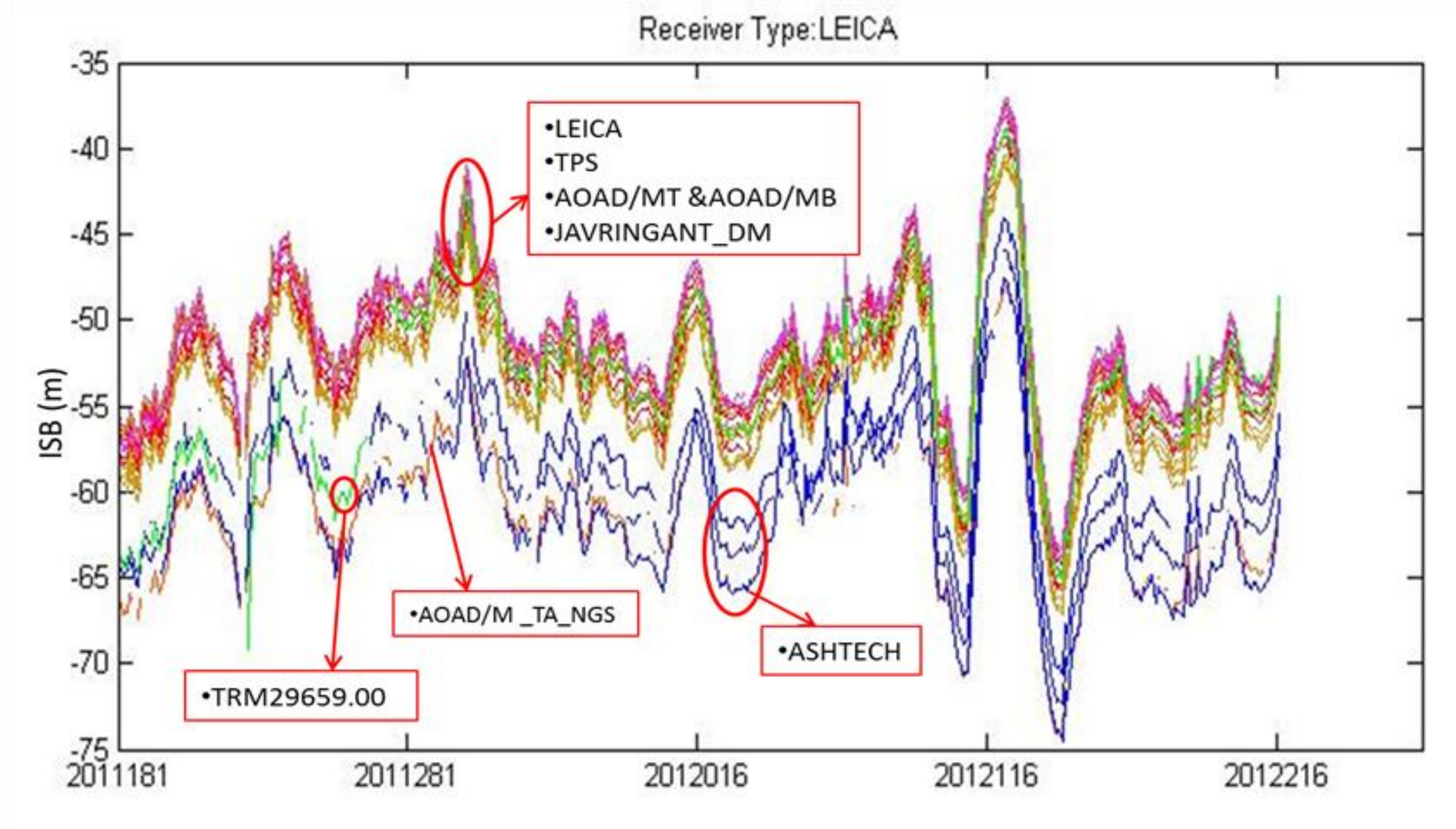
$$ISB_i^{jk} = c\cdot(\bar{d}t_i - \bar{d}t^j)^R - c\cdot(\bar{d}t_i - \bar{d}t^k)^G$$
$$= TO + \Delta DCB_i^{j,k}$$

Multi-GNSS analysis model

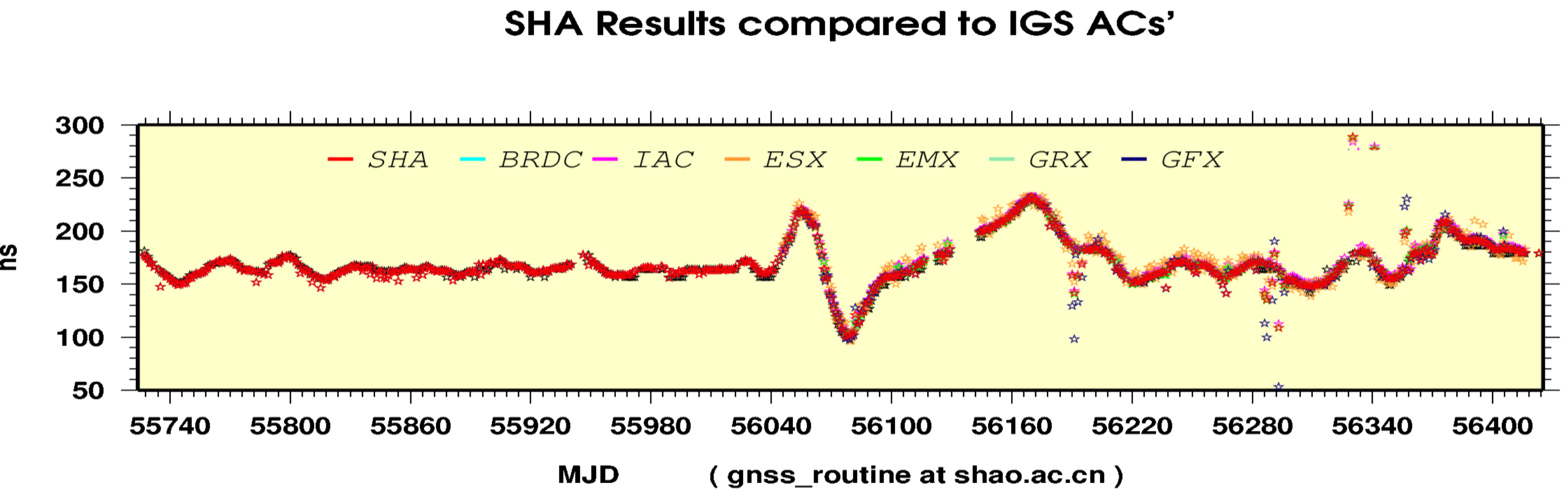
➢**Relative instrument delay:** ***different for each receiver/antenna pair****. Values are provided by SHAO (www.shao.ac.cn/shao_gnss_ac)*



Multi-GNSS analysis model: GNSS Time Offset

➢GPS/GLONASS Time Offset: *provided by SHAO*

(*www.shao.ac.cn/shao_gnss_ac*)



GNSS network solution for TFT

- **Network solution:** *Satellite clock estimated together with station clock.*

$$\begin{cases} P_i^k = \rho + c\delta_i - c\delta^k + \delta_{trop} - \varepsilon_i \\ L_i^k = \rho + c\delta_i - c\delta^k + \delta_{trop} + \lambda N_i - \varepsilon_i \end{cases}$$

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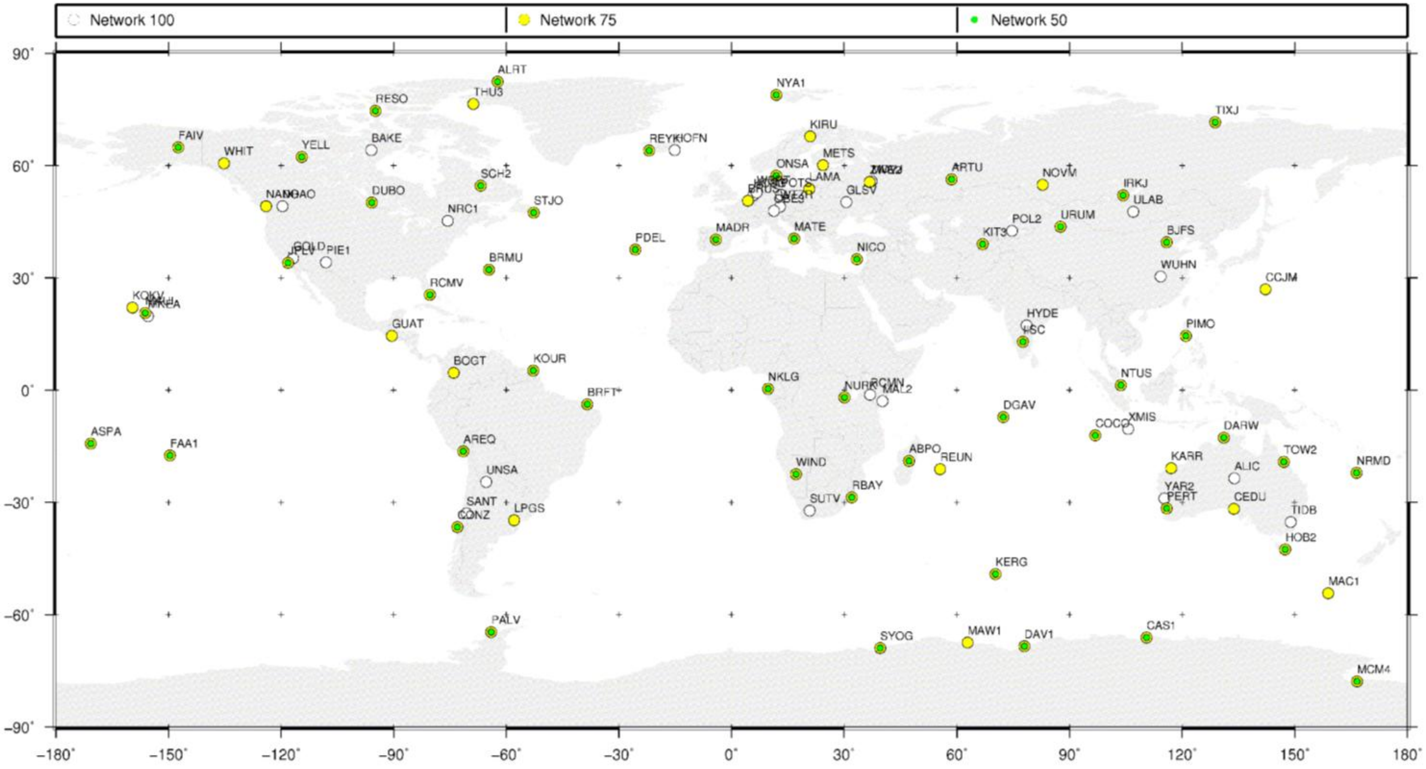
- **One reference clock selected:** *Remove rank-deficiency and relative station/satellite clocks derived.*

- **Satellite orbits fixed to IGS predicted**.

GNSS network solution: Global solution

➢**Global Network solution:** *with 50,75,100 real-time GNSS stations*



GNSS network solution: Global solution

➢**Global Network solution:** *with 50,75,100 real-time GNSS stations,* ***Satellite clock accuracy in ns.***

Number. of Stations	Epoch-Diff.		Mixed-Diff.		Zero-Diff.	
	BIAS	**STD**	**BIAS**	**STD**	**BIAS**	**STD**
50	3.94	0.09	0.26	0.10	0.17	**0.11**
75	3.94	0.09	0.29	0.10	0.17	**0.10**
100	3.94	0.08	0.28	0.09	0.16	**0.09**

GNSS network solution: Global solution

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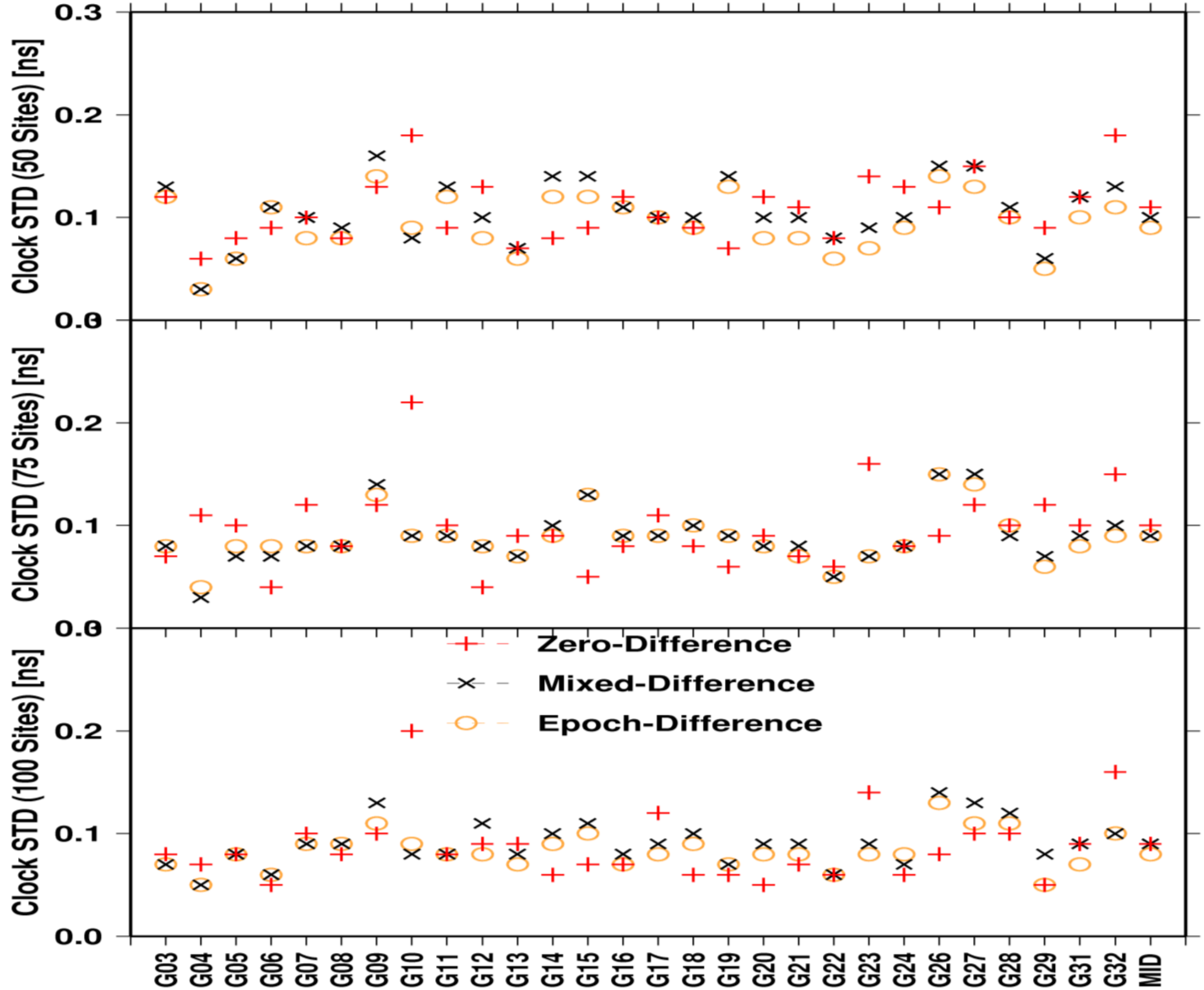
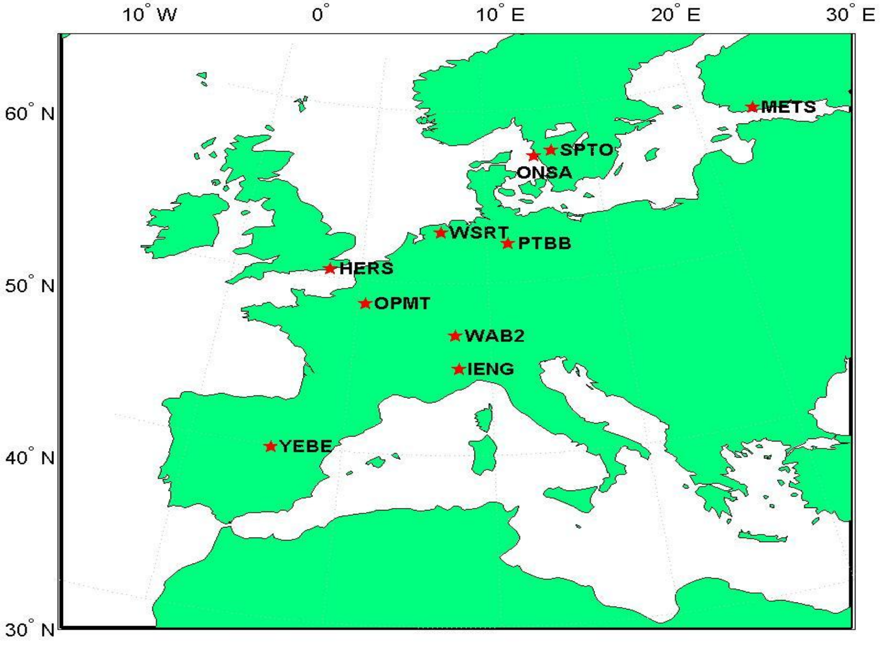


Regional Experiment setup

- **DATA:** *10 regional IGS stations in Europe are selected, they all contributed to BIPM TAI computations. DOY 295 to 301 in the year of 2012.*
- **Input**: *IGU and IGS final products are used for comparison.*
- **Results:** *PPP and Network; Real-time and Post-processing*



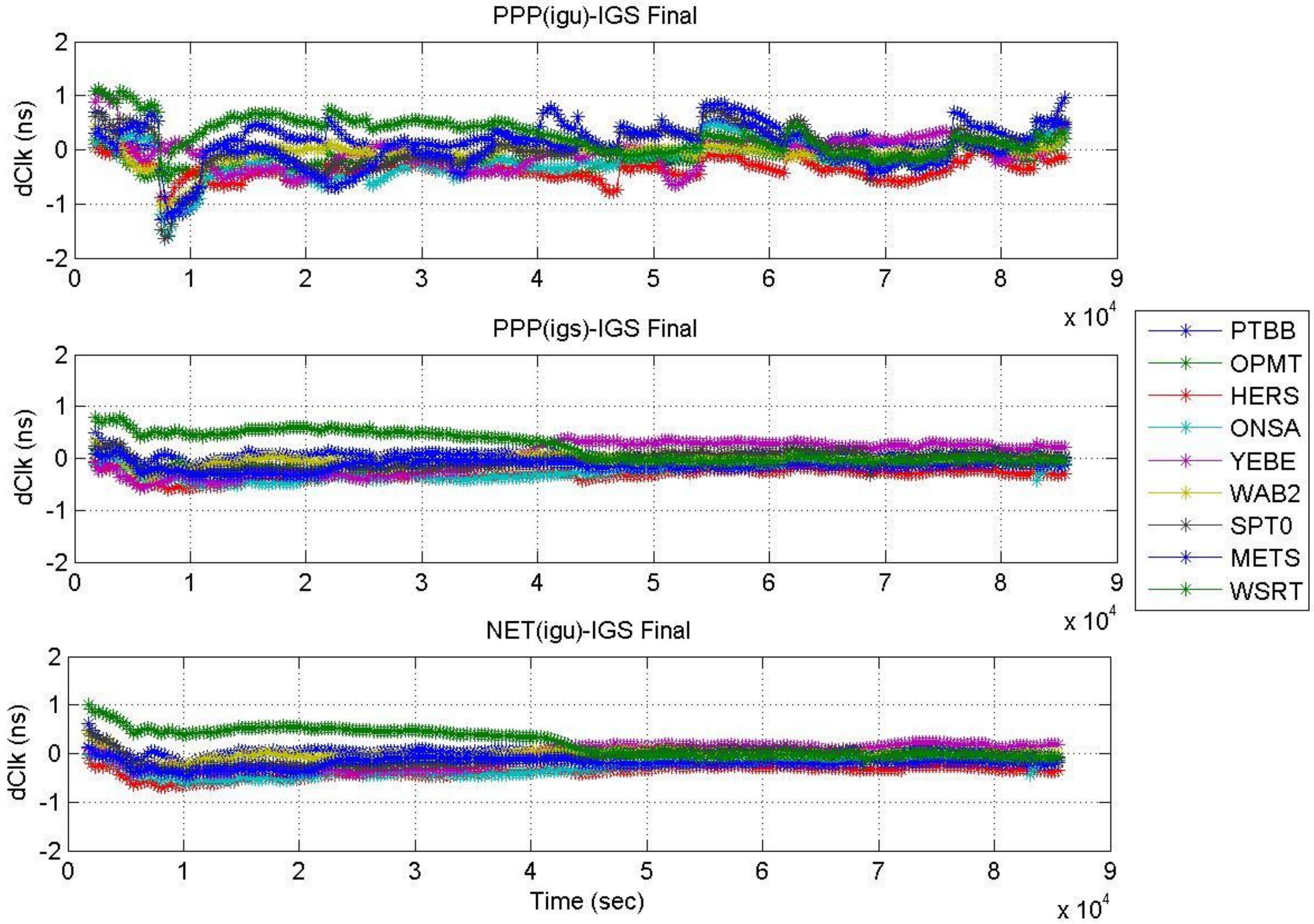
Regional Experiment setup

- **Software LTW_BS**: *developed at SHAO* (*www.shao.ac.cn/shao_gnss_ac*)

Correction	Model
Ionosphere delay	Ionosphere-free combination
Troposphere delay	Saastmoinen+GMF
Satellite clock error	PPP: IGS/IGU product
	Network solution: estimated
Receiver clock error	estimated
Antenna correction	IGS absolute phase center model
Solid tide **Ocean tide** **Polar tide**	IERS 2010 correction model
Relativity effect	IERS standard
Phase wind-up effect	IGS recommended model

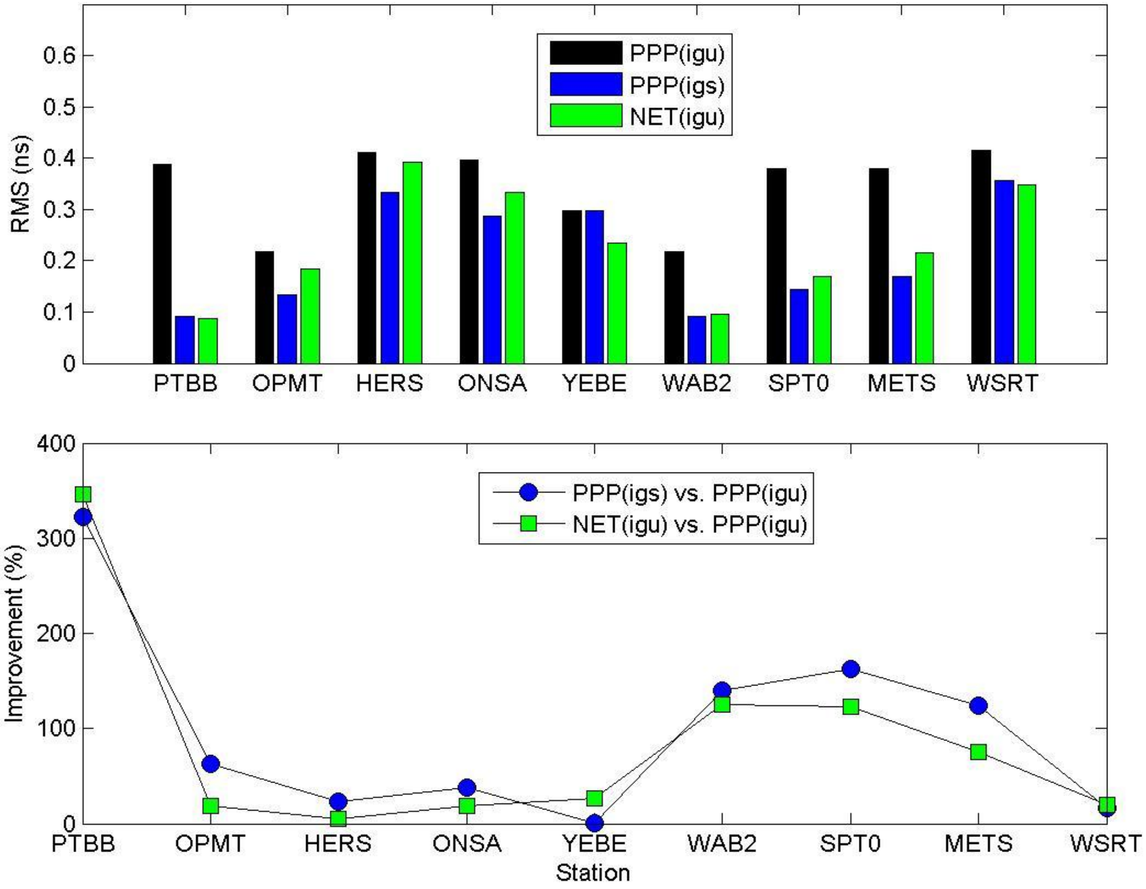
Time transfer results

- **Time transfer result for different approaches:** *epoch-wise clock compared with IGS final clocks.*



Time transfer results

➢ **Time transfer result for different approaches:** ***accuracy*** *and* ***improvement*** *against real-time PPP.*



Time transfer results

- **Time transfer result for different approaches:** ***accuracy*** *and* ***improvement*** *against real-time PPP.*
- *Mean improvement: 99% for post-processing PPP and 84% for real-time network solution.*

Station	Improvement over PPP(igu)	
	PPP (igs)	**Network**
PTBB	322.2%	345.9%
OPMT	62.7%	19.0%
HERS	23.2%	4.8%
ONSA	37.5%	18.6%
YEBE	0.5%	27.6%
WAB2	139.5%	125.7%
SPT0	163.0%	123.1%
METS	123.8%	75.8%
WSRT	16.9%	19.5%

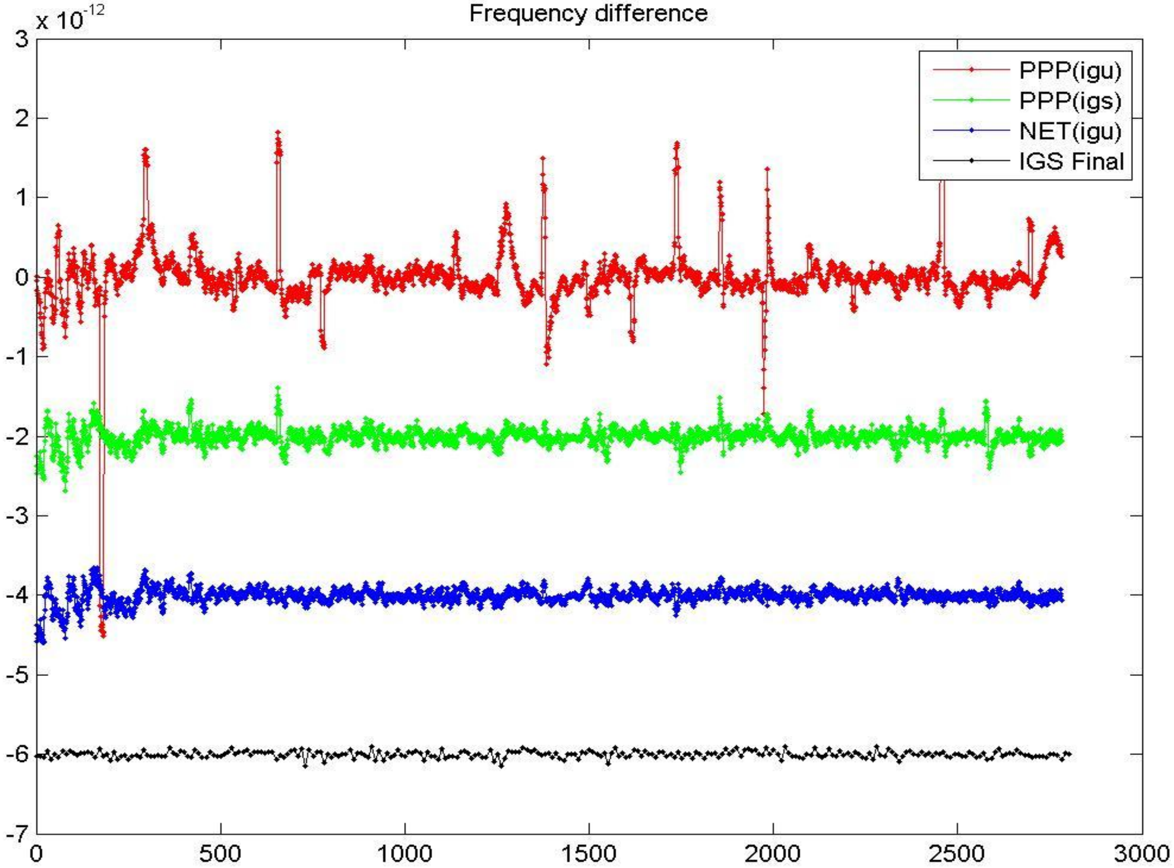
Frequency transfer results

- **Frequency transfer result:**

$$y(t) = [\delta_{ck}(t) - \delta_{ck}(t-T)]/T$$

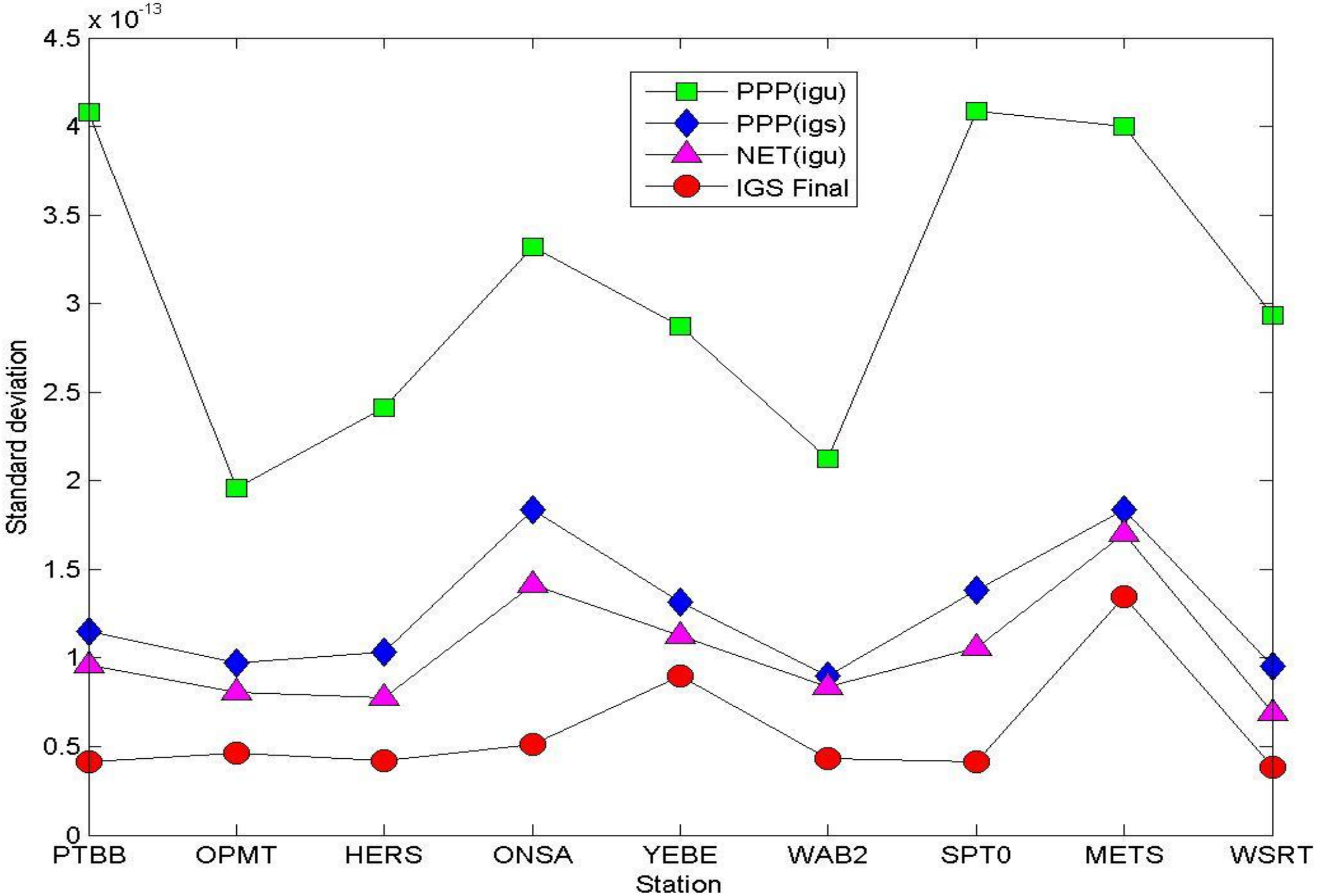
Frequency transfer results

➢**Frequency transfer result:** *Frequency difference for baseline IENG-PTBB (T=300s), the PPP (igs), Network solution, IGS Final are moved by 2e-12, 4e-12, 6e-12 respectively*



Frequency transfer results

➤**Frequency transfer result:** *Standard deviation of baseline frequency difference (reference station: IENG,T=300s), for PPP (igs), PPP(igu), Network solution, and IGS Final.*



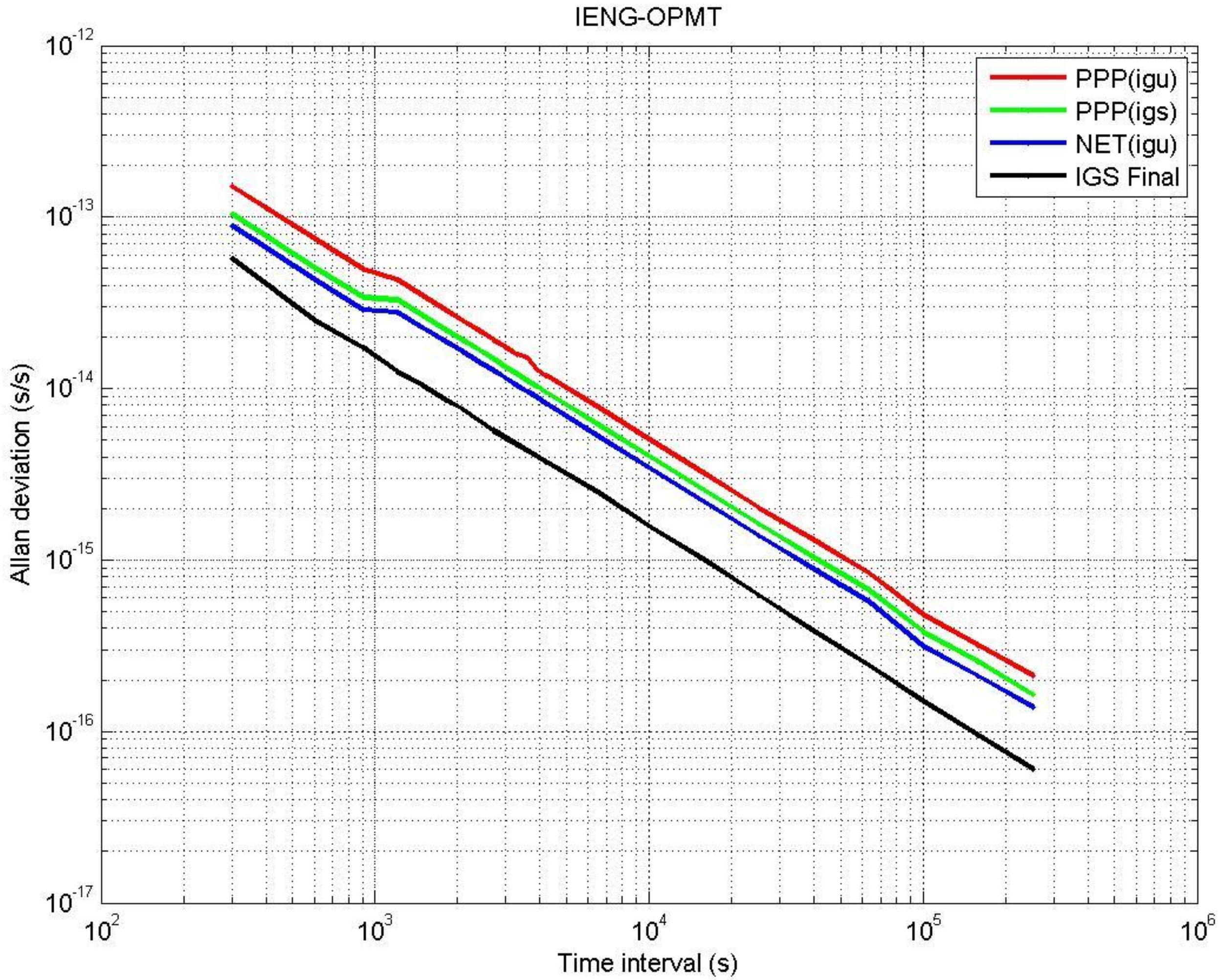
Frequency transfer results

➢**Frequency transfer result:** *Standard deviation of baseline frequency difference (reference station: IENG,T=300s, unit 1.0e-13), for PPP (igs), Net (igu), and IGS Final.*

Station	PPP(igu)	PPP(igs)	Network	IGS Final
PTBB	4.081	1.149	0.962	0.415
OPMT	1.958	0.974	0.804	0.465
HERS	2.411	1.034	0.776	0.422
ONSA	3.320	1.834	1.411	0.514
YEBE	2.875	1.315	1.123	0.899
WAB2	2.124	0.898	0.838	0.429
SPT0	4.086	1.383	1.055	0.414
METS	3.999	1.837	1.698	1.349
WSRT	2.934	0.953	0.689	0.383
Mean	**3.087**	**1.264**	**1.039**	**0.587**

Frequency stability results

➢**Frequency stability result:** *Baseline: IENG-OPMT for PPP (igs), Net (igu), and IGS Final*



Conclusion

- Multi-GNSS PPP provides an enhanced TFT solution with more satellites included.
- GNSS network solution for TFT eliminate the effect of satellite clocks error and is feasible for real-time time and frequency transfer. **Allows for global and regional TFT**
- Experiments show that the strategy is effective for real-time TFT and it can achieve the same precision as post-processed PPP.
- It could be implemented for global GNSS network of timing laboratories.

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http://www.shao.ac.cn/shao_gnss_ac

Thank you!