Interoperable PPP/PPP-AR products and their combination & cross-validation

Jianghui GENG, Zhe YAN, Qiang WEN

GNSS Research Center, Wuhan University, China

IGMA Taskforce Workshop

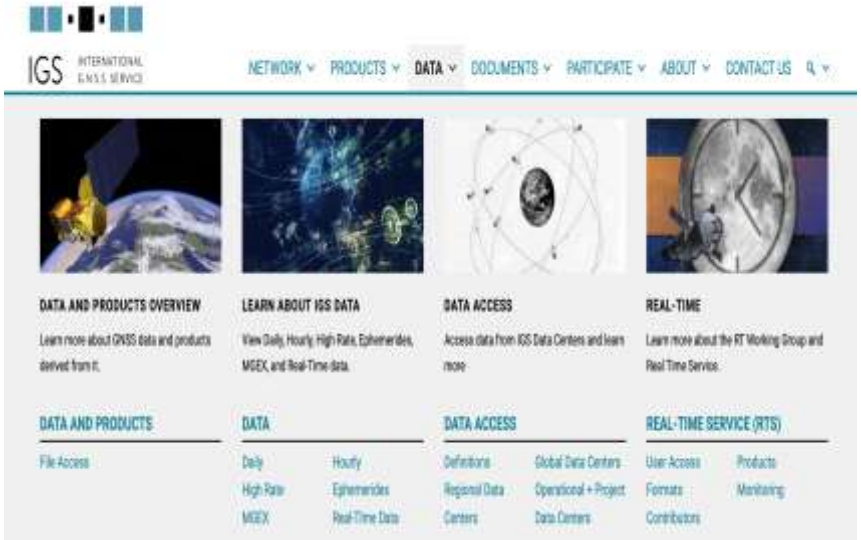
Chiang Rai, Thailand

30 Jan. – 2 Feb, 2024

International GNSS Service (IGS)

- IGS is a voluntary federation founded in 1993 to deliver the highest-quality satellite products as global commons

  - 500+ worldwide GNSS stations
  - 12 Analysis Centers (ACs) to generate independent satellite products including orbits, clocks, biases, etc.

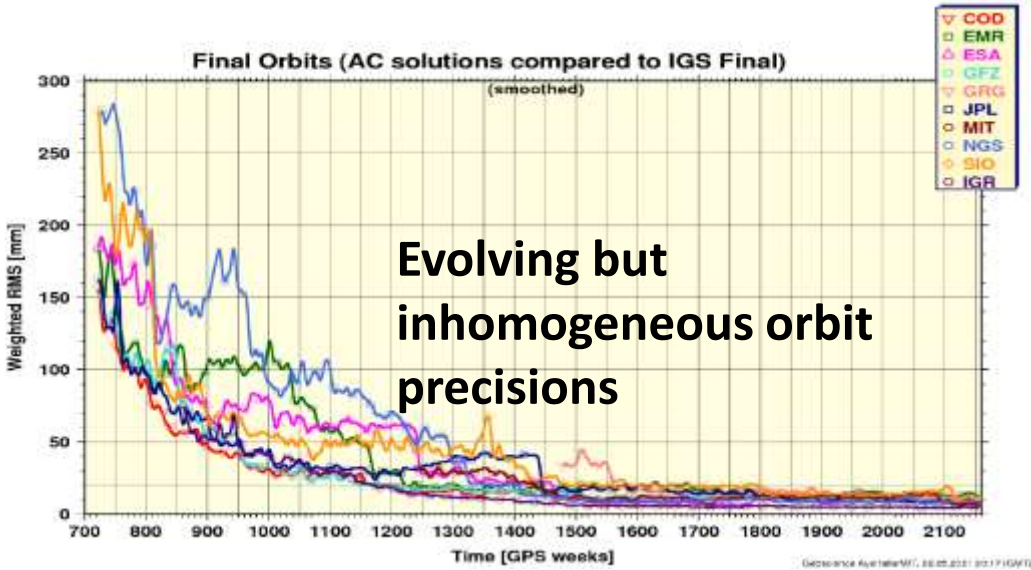


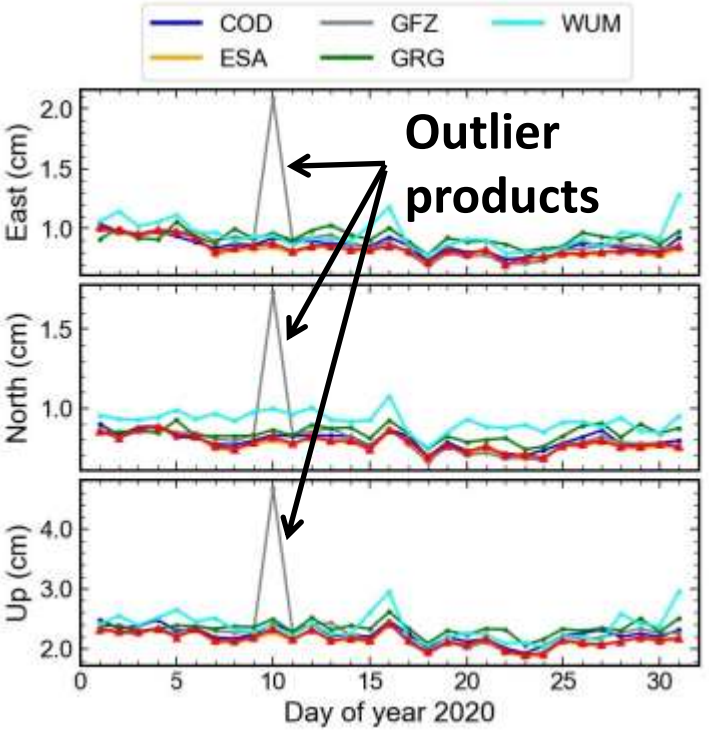
International GNSS Service (IGS)

- Serving the community with facilitation, coordination, incubation, and advocacy for three goals:
  - Achieve multi-GNSS technical excellence
    - Reinforce continuous technical evolution
  - Strengthen outreach and engagement
    - Open access geodetic and GNSS data and products
  - Build sustainability and resilience
    - Foster an expanding and evolving community

Combination & cross-validation for IGS products

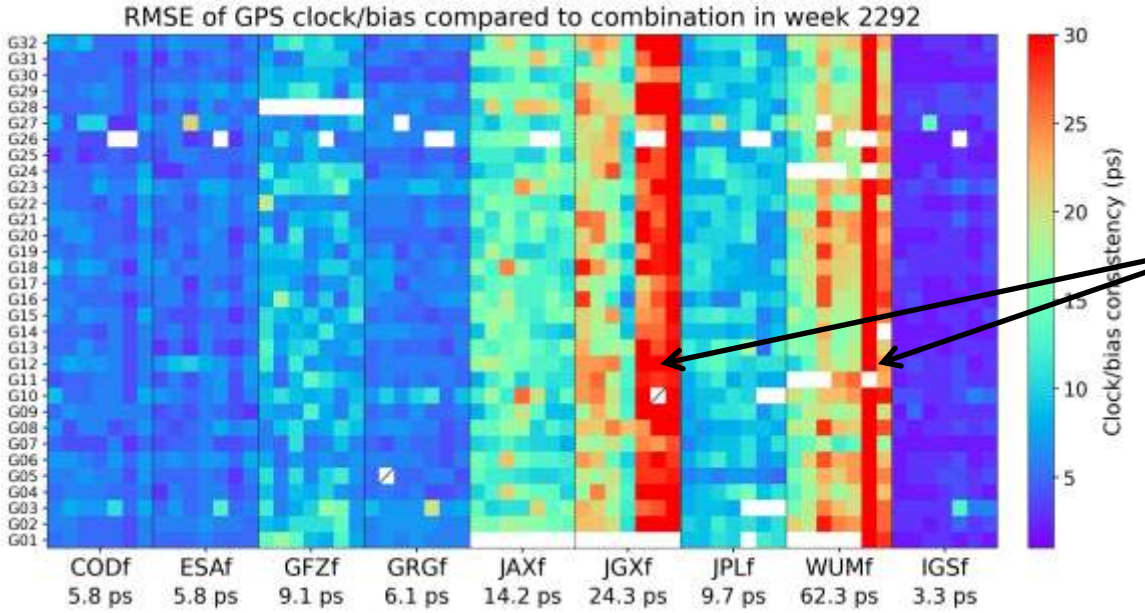
- Generate baseline products by combining AC's contributions
  - Achieve the highest robustness





Combination & cross-validation for IGS products

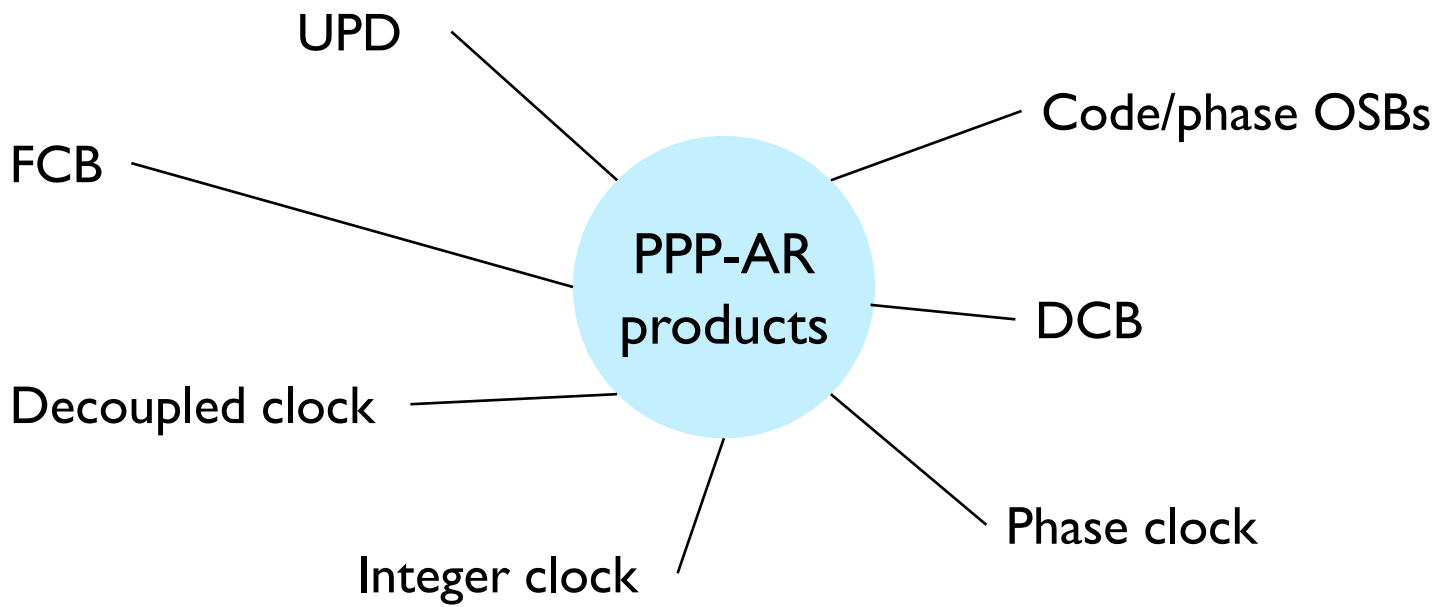
- Generate baseline products by combining AC's contributions
  - ➢ Cross-validate AC-specific products



Some ACs' products show incompatibility and have outliers

Difficulty: disparate PPP-AR products

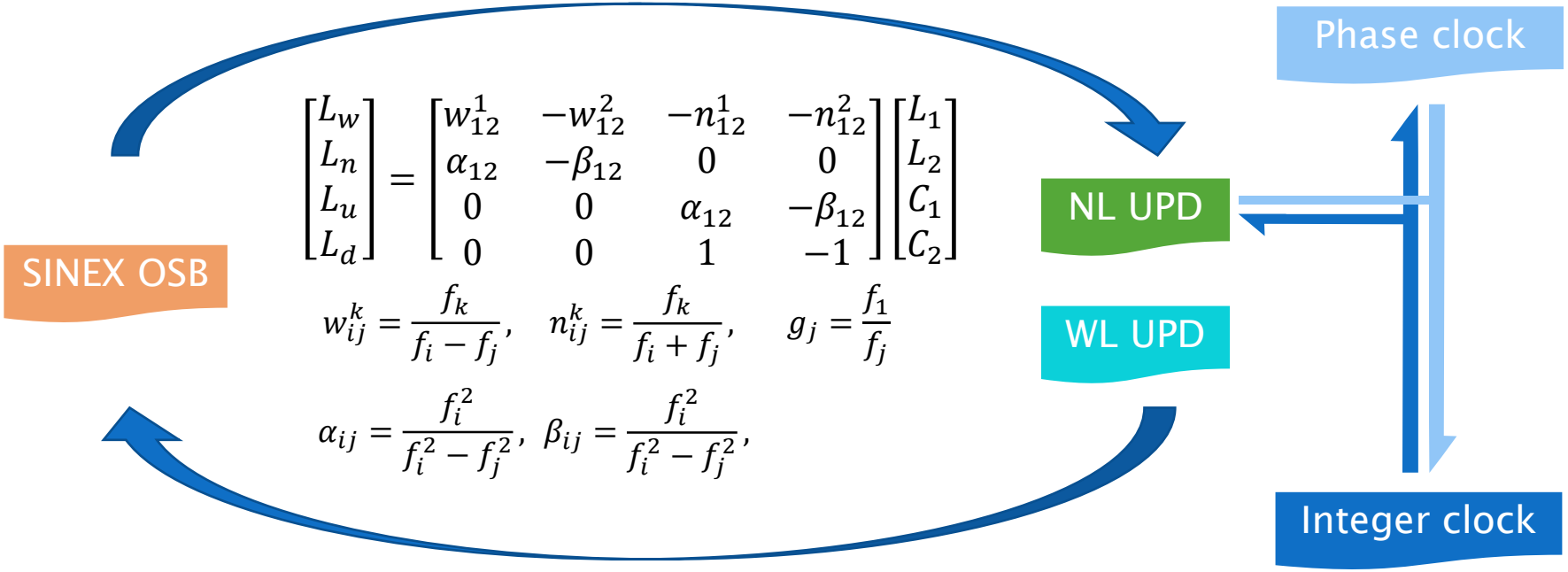
- Products used for PPP-AR



How to recover the interoperability of disparate PPP-AR products for combination?

Recover PPP-AR Interoperability : Quantity conversion

- Integer clock and UPD products converted into OSB products



$$\begin{bmatrix} L_w \\ L_n \\ L_u \\ L_d \end{bmatrix} = \begin{bmatrix} w_{12}^1 & -w_{12}^2 & -n_{12}^1 & -n_{12}^2 \\ \alpha_{12} & -\beta_{12} & 0 & 0 \\ 0 & 0 & \alpha_{12} & -\beta_{12} \\ 0 & 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} L_1 \\ L_2 \\ C_1 \\ C_2 \end{bmatrix}$$

$$w_{ij}^k = \frac{f_k}{f_i - f_j}, \quad n_{ij}^k = \frac{f_k}{f_i + f_j}, \quad g_j = \frac{f_1}{f_j}$$

$$\alpha_{ij} = \frac{f_i^2}{f_i^2 - f_j^2}, \quad \beta_{ij} = \frac{f_i^2}{f_i^2 - f_j^2},$$

Recover PPP-AR Interoperability : Incompatibility calibration

- Antenna phase center calibration
- Quaternions to calibrate satellite attitude inconsistencies

$$\begin{bmatrix} L_w \\ L_n \\ L_u \\ L_d \end{bmatrix} = \begin{bmatrix} w_{12}^1 & -w_{12}^2 & -n_{12}^1 & -n_{12}^2 \\ \alpha_{12} & -\beta_{12} & 0 & 0 \\ 0 & 0 & \alpha_{12} & -\beta_{12} \\ 0 & 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} L_1 \\ L_2 \\ C_1 \\ C_2 \end{bmatrix}$$

SINEX OSB

ATX

$$L'_w = L_w \pm z_w$$

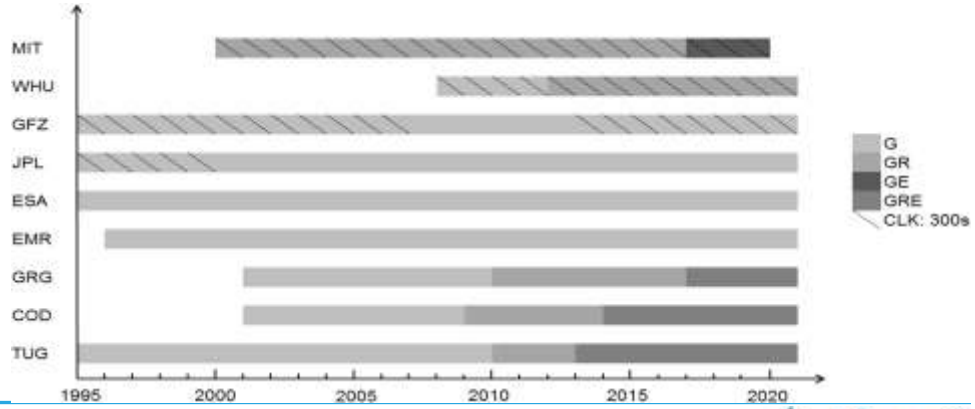
$$\begin{bmatrix} L'_1 \\ L'_2 \\ C'_1 \\ C'_2 \end{bmatrix} = \begin{bmatrix} -(g_2)^{-1} & (n_{12}^1)^{-1} & -(g_2)^{-1} & \beta_{12} \\ -g_2 & (n_{12}^2)^{-1} & -g_2 & \alpha_{12} \\ 0 & 0 & 1 & -\beta_{12} \\ 0 & 0 & 1 & -\alpha_{12} \end{bmatrix} \begin{bmatrix} L'_w \\ L_n \\ L_u \\ L_d \end{bmatrix}$$

Corrected SINEX OSB

IGS repro3 clock/bias combination

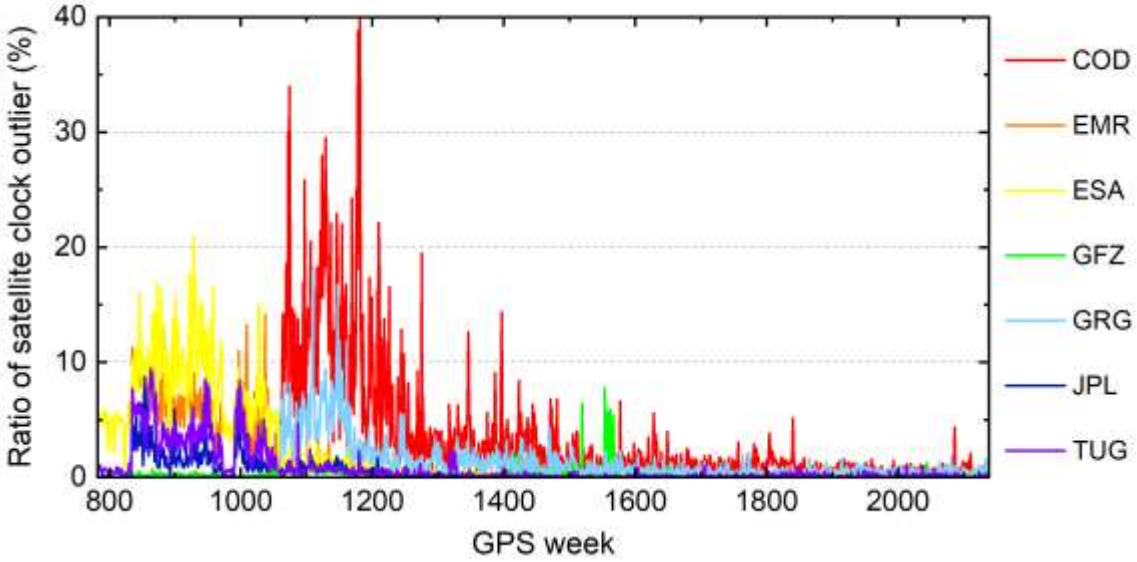
- A brief summary of IGS *Repro3* products
  - 20 years (2000-2020)
  - 10 ACs
  - 4 with phase bias products
  - GPS/Galileo combined

AC	Orbits/Clock	Bias	Quaternion	APC model
COD	GRE	GE	GRE	
EMR/NGS	G	G	G	
ESA	G	N/A	N/A	
GFZ	G	N/A	G	
GRG	GRE	GE	GRE	
JPL	G	N/A	G	
MIT	GE	N/A	N/A	
TUG	GRE	GRE	GRE	YES
WHU	GR	N/A	GR	



Quality control for satellite clocks

- AC-specific satellite clock outlier rates

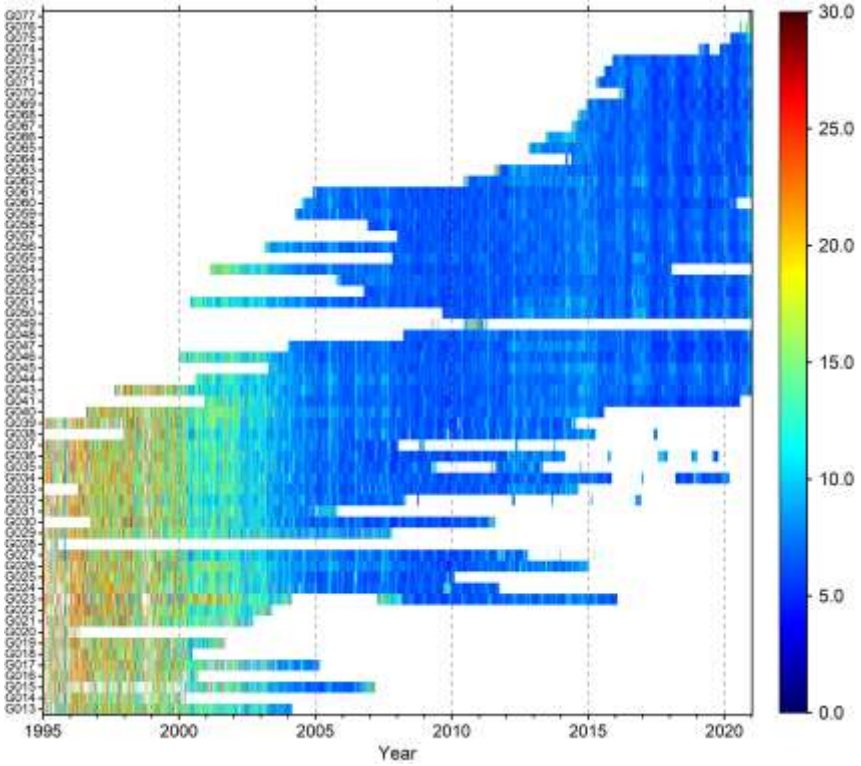


AC	Average ratio (%)
COD	3.2
EMR	1.1
ESA	1.9
GFZ	0.3
GRG	1.3
JPL	0.4
TUG	0.8

ACs occasionally make mistakes in estimating PPP-AR products

Consistency among AC clocks/biases

- GPS from 1995-2020

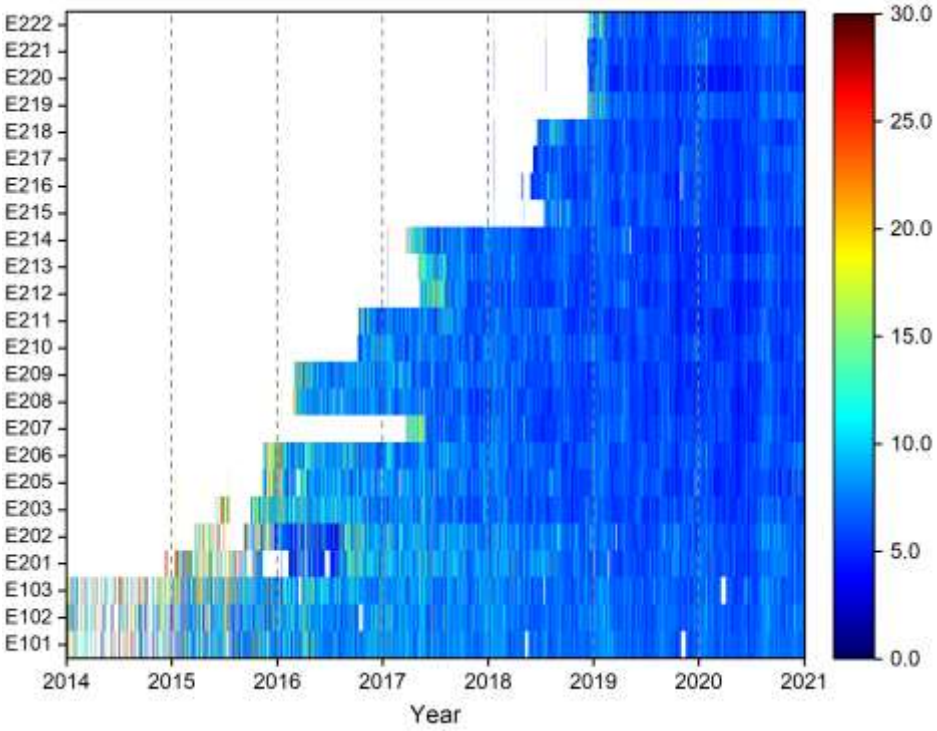


Year	Mean RMS (ps)
1995-1999	22.41
2000-2004	17.43
2005-2009	7.98
2010-2014	7.91
2015-2019	7.06

It has strong time correlation and gradually stabilizes at 7ps.

Consistency among AC clocks/biases

- Galileo from 2014-2020

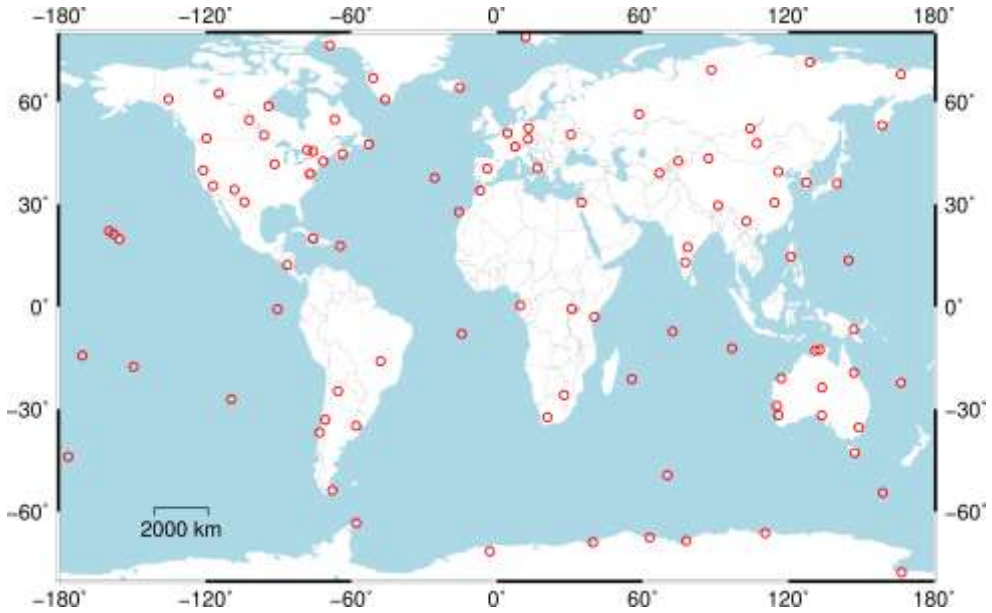


Year	Mean RMS (ps)
2014	20.01
2015	21.17
2016	11.53
2017	8.68
2018	7.39
2029	6.54
2020	7.91

Galileo is similar to GPS, and slightly better than GPS

Overview of PPP-AR validation

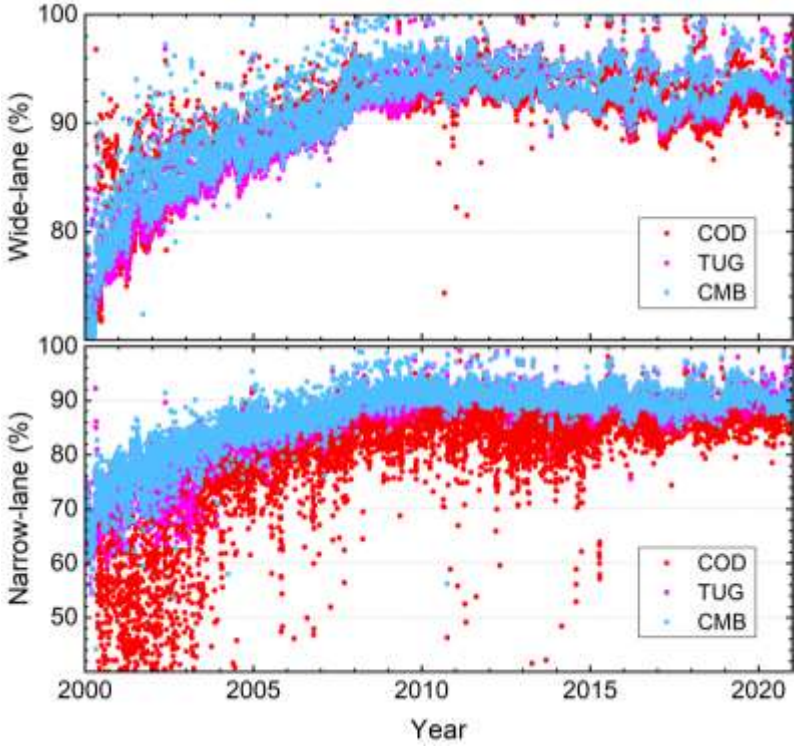
- Software: PRIDE_PPP-AR v2.2
- Mode: Static daily PPP-AR
- 21 years for 3 ACs' products:
  - CMB (2000-2020)
  - COD (2001-2020)
  - TUG (2000-2020)
- 100 global stations
- Results:
  - i. Daily position RMS
  - ii. Ambiguity fixing rates



Distribution of 103 global stations

Static daily PPP-AR solutions

- Ambiguity fixing rate for GPS from 2000 to 2020

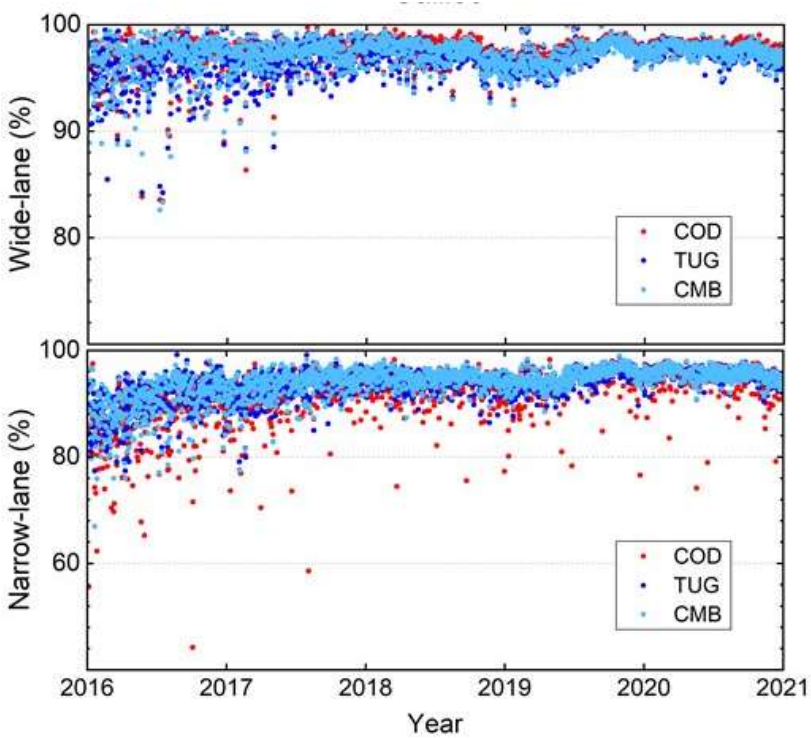


Products	Wide-lane (%)
CMB	90.65
COD	90.27
TUG	89.93

Products	Narrow-lane (%)
CMB	87.18
COD	80.36
TUG	86.38

Static daily PPP-AR solutions

- Ambiguity fixing rate for Galileo from 2016 to 2020

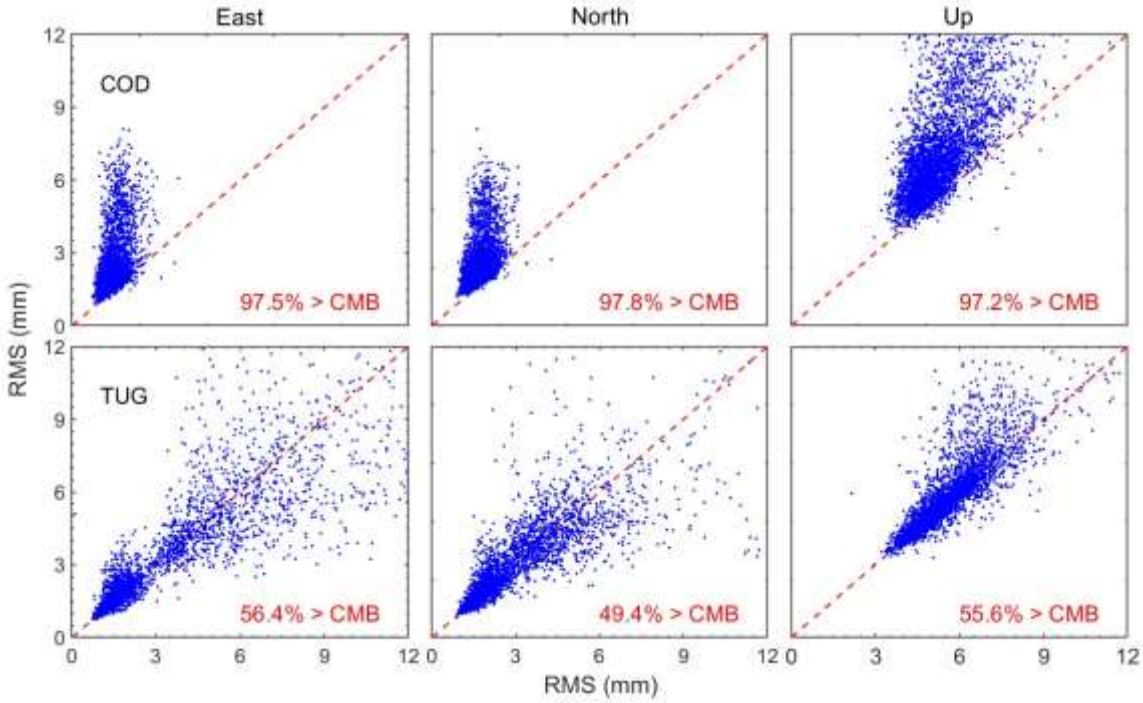


Products	Wide-lane (%)
CMB	97.11
COD	97.37
TUG	96.87

Products	Narrow-lane (%)
CMB	93.77
COD	92.40
TUG	93.62

Static daily PPP-AR solutions

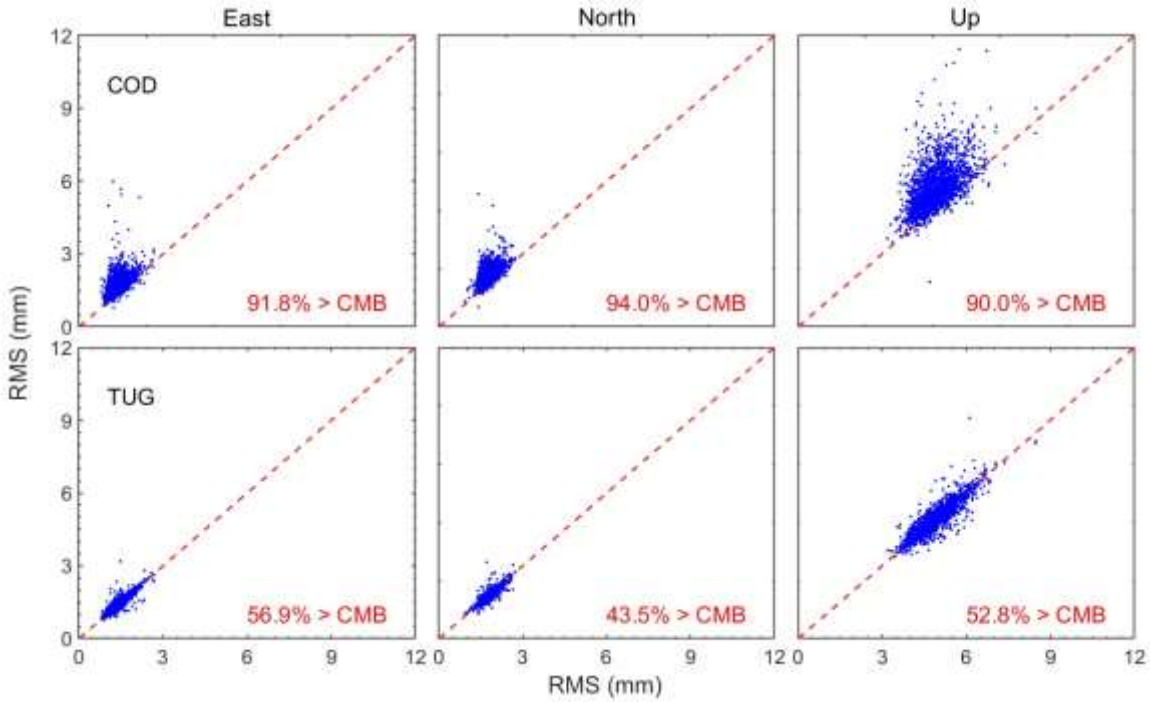
- Daily position RMS (mm) for GPS from 2000 to 2015



mm	CMB	COD	TUG
East	1.49	2.45	1.57
North	1.79	2.58	1.82
Up	5.39	7.17	5.54

Static daily PPP-AR solutions

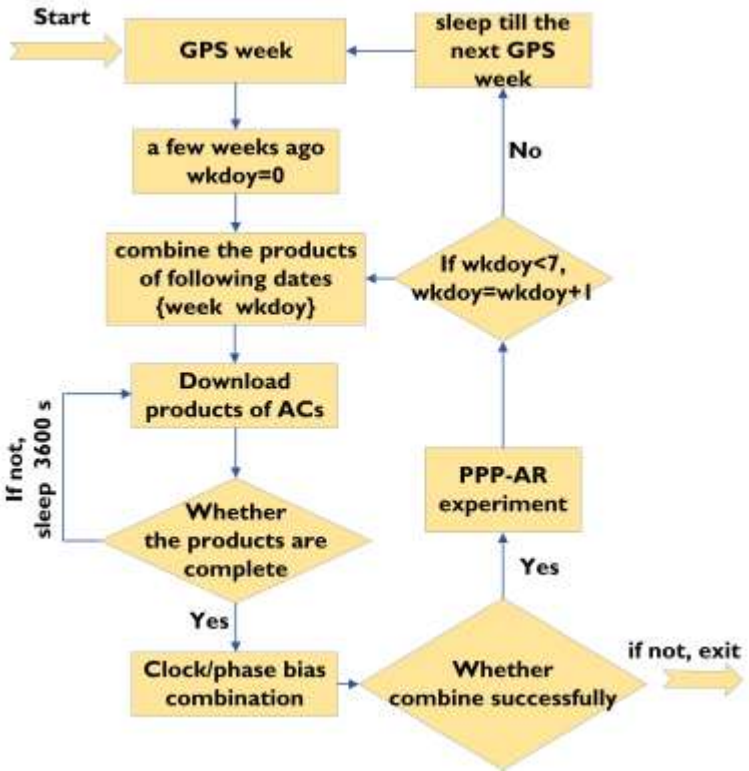
- Daily position RMS (mm) for GPS/Galileo from 2016 to 2020



mm	CMB	COD	TUG
East	1.53	1.68	1.59
North	1.71	1.89	1.74
Up	5.60	5.82	5.52

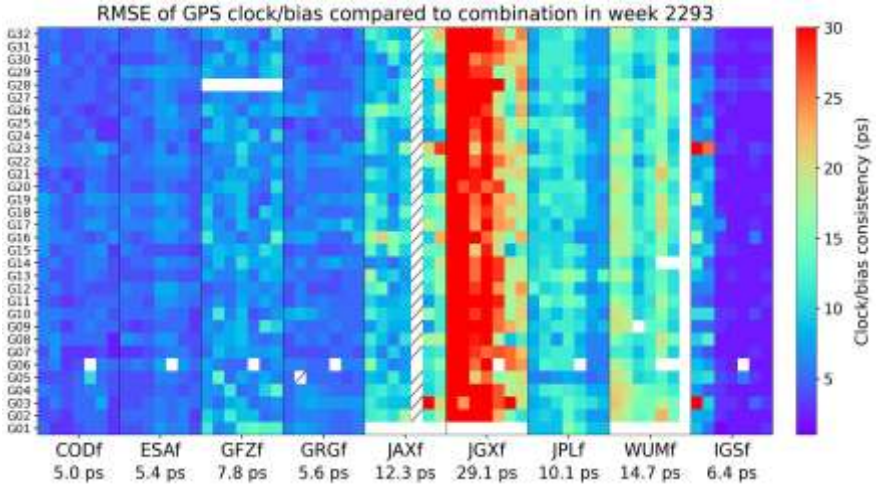
Routine combination efforts

- A brief summary of routine clock/bias combination
  - Rapid/final products
  - GPS/GLONASS/Galileo
  - Reference orbit combined by Wuhan
  - Reference attitudes create by GROOPS
  - Update on a weekly basis

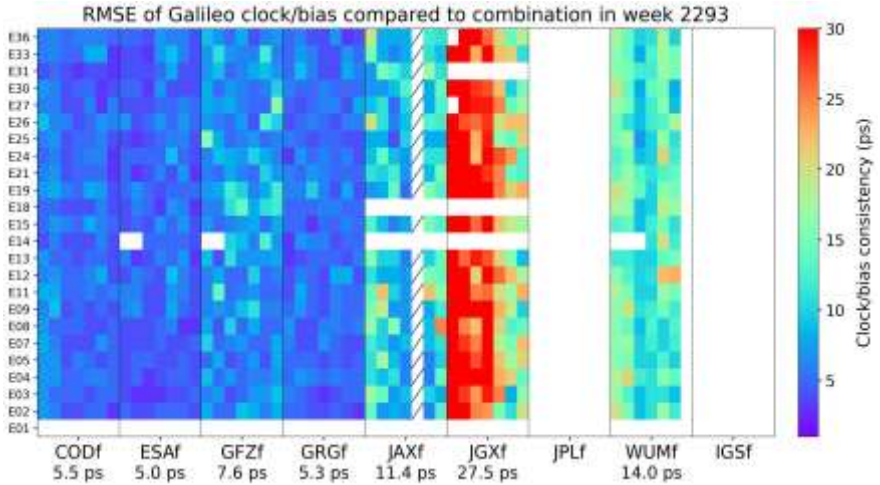


Routine combination efforts

- The weekly clock/bias RMSE
  - reflects the consistency between individual AC



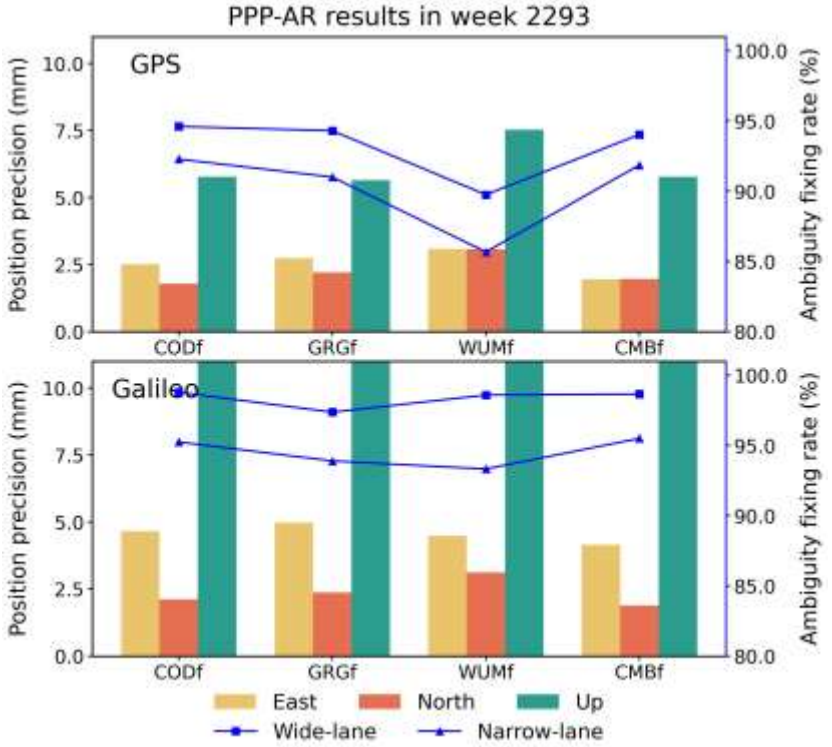
GPS



Galileo

Routine combination efforts

- PPP-AR validation
  - Software: PRIDE-PPPAR v2.2
  - Static daily solution
  - 10 stations
  - Results:
    i. Daily position RMS
    ii. Ambiguity fixing rates



Visualization of combination results on IGS websites

- IGS websites
  - Rapid products combination: https://igs.org/wg/ppp-ar/#rapid
  - Final products combination: https://igs.org/wg/ppp-ar/#final
- Upload the combined product
  - Upload to ftp://igs.gnsswhu.cn/pub/whu/phasebias/
  - Include (take final products as an example):
    i. Oribt: WMC0DEMFIN_YYYYDDD000_01D_05M_ORB.SP3
    ii. Attitude: WMC0DEMFIN_YYYYDDD000_01D_30S _ATT.OBX
    iii. Clock: WMC0DEMFIN_YYYYDDD000_01D_30S_CLK.CLK
    iv. Bias: Clock: WMC0DEMFIN_YYYYDDD000_01D_01D_OSB.BIA
    v. Summary file: WMC0DEMFIN_YYYYDDD000_01D_ 01D_CLS.SUM

Summary

- The various PPP-AR products can be converted into a uniform format to ensure interoperability
- PPP-AR products have achieved excellent consistency through the combination, and more robust and more precise solutions
- Wuhan University as one IGS AC has released routine combined phase clock/bias products to the public

Thank you!

Jianghui GENG

jgeng@whu.edu.cn