Developments within the IGS Real-Time Service towards PPP-AR

A. STÜRZE[1], A. RÜLKE[1], N. WANG[2], E. WIESENSARTER[1]

[1]Federal Agency for Cartography and Geodesy (BKG), Germany;

[2]Chinese Academy of Sciences (CAS), China

Federal Agency for Cartography and Geodesy

IGS 2026 WORKSHOP

SANTIAGO DE CHILE

33°26' S 70°39' O

INTRODUCTION

The IGS RTS provides real-time access to precise products such as orbits, clocks, biases and models of the ionosphere, which can be used as a substitute for ultra-rapid products in global real-time applications to support science and society.

Therefore, a number of about 10 Real-Time Analysis Centers (RTACs) currently estimate GNSS satellite orbit and clock corrections to broadcast ephemerides. And an increasing number of these RTACs also provide code and, in particular, phase biases.

- The RTACC generates multi-GNSS combined solutions and provides dedicated resources for solution monitoring.
- The consistency of individual and combined real-time products can be assessed by comparison with IGS rapid products.
- As a performance review from the user perspective, the IGS RTS products were applied in Precise Point Positioning (PPP)

Hence, the IGS RTS monitoring needs to include phase biases and PPP with ambiguity resolution (PPP-AR)

	Orbits and Clocks				Code Biases				Phase Biases				VTEC
	G	E	C	R	G	E	C	R	G	E	C	R	
APM	o	o	o	o									
BKG	o	o		o	o	o		o					
CAS	o	o	o		o	o	o		o	o	o		o
CHC	o	o	o	o	o	o	o	o	o	o	o		
CNE	o	o	o		o	o	o		o	o			o
GFZ	o	o		o	o	o		o					
GMV	o	o	o		o	o	o						
JPL	o			o									
NRC	o				o				o				o
SHA	o	o	o	o	o	o		o					
UPC													o
WHU	o	o	o	o	o	o	o	o	o	o	o		o

IGS RTS ORBIT AND CLOCK REFERENCE

IGS RTS Orbit Reference (IGS SSR Format Version 1.0 2020)

The satellite orbit corrections must refer to a Satellite Reference Point (SRP)

- Center of Mass (CoM)
- Antenna phase center (APC) of a selected reference frequency

GNSS	APC of Reference Frequency
G	L1
E	E1
C	B1-2
R	G1

IGS RTS Clock Reference

Definition of a "Satellite Bias Datum" which sets the bias of a certain linear combination (LC) of signals to zero / ignoring any code biases of these signals:

- ➢ The ionosphere-free (IF) linear combination of specific code observables serve as reference signal
- ➢ The code biases of these signals are absorbed in the satellite clock.

GNSS	IGS RTS Reference Signal
G	C1W/C2W
E	C1C/C5Q
C	C2I/C6I
R	C1P/C2P

RTAC ANALYSES STRATEGIES ENABLING PPP-AR

1. Ionosphere-free (IF) linear combinations & estimable parameters = phase biases — **Code Clock Definition**
   - Uncalibrated Phase Delays (UPDs) or Integer Clocks
2. Ionosphere-free linear combinations & estimable parameters = code biases — **Phase Clock Definition**
   - Phase Clocks
3. Uncombined observations & estimable parameters = phase biases or code biases — **Code or Phase Clock Definition**

- ➢ OSB definition varies as function of the processing strategy but all transformations respect the following condition:

$$c_{AC}^s - b_*^s = dt^s - \Delta t - b_*^s$$

- ➢ When satellite clocks c_{AC}^s and biases b_*^s are used together, the effective observable-specific biases are recovered.
- ➢ When the equation above is satisfied, the interoperability between corrections of different RTACs and the consistency with the IGS convention can be ensured (Banville et al. 2020).

IGS RTS CLOCK COMBINATION

Kalman Filter Clock Combination Approach

$$c_{AC}^s - dC_{AC}^s = c_{cmb}^s + o_{AC} + o_{AC}^s$$

- with pseudo-observations

c_{AC}^s .. the clock corrections for satellite S estimated by individual RTACs, referring to a common broadcast clock

dC_{AC}^s .. a priori corrections

- and unknowns, which differ in their stochastic properties

	Initial	White Noise
c_{cmb}^s	100.0 m	> 0 m
o_{AC}	1000.0 m	1000.0 m
o_{AC}^s	100.0 m	0 m

c_{cmb}^s .. the resulting combined clock correction for satellite S

o_{AC} .. the analysis center specific offset common for all satellites

o_{AC}^s .. the satellite and analysis center specific offset, absorbing differently modelled satellite specific errors

- ➢ Consideration of satellite code biases supplied by individual RTACs: $c_{AC\_corrected}^s = c_{AC}^s - dC_{AC}^s - (\alpha_{IF} CB_{AC,ref1}^s + \beta_{IF} CB_{AC,ref2}^s)$
  - – The combined satellite clocks are consistent to IGS clocks: Ionosphere-free clocks based on the defined reference signals
  - – This convention allows the ionosphere-free linear combination of the two Observable-Specific Signal Biases (OSBs) of the reference signals to be set to zero. All other OSBs can then be expressed in terms of Differential Code Biases.
  - – The satellite code biases for the combination solution are computed using the IGS bias product from CAS with satellite antenna phase center corrections (Wang et all. 2025).

IGS RTS ORBIT AND CLOCK VALIDATION

SP3-File Comparison

- SP3 reference file, for example the IGS rapid solution (e.g. Deng et all. 2017) and
- SP3 file generated using an IGS RTAC or product stream together with a broadcast ephemeris stream
- SSR correction can be 'combined' with broadcast ephemerides to generate orbit and clock results in SP3 format.
- Satellite code biases supplied by individual RTACs are taken into account.

Orbits: $\boldsymbol{X}_{CoM}^s = \boldsymbol{X}_{APC}^s - \boldsymbol{A}_{BodyFixed_{ECEF}}^s * \boldsymbol{PCO}_{ref_{freq}}^s$

Clocks: $c_{AC\_corrected}^s = c_{AC}^s - (\alpha_{IF} CB_{AC,ref1}^s + \beta_{IF} CB_{AC,ref2}^s)$

Orbits

- Computation of orbit differences dX, dY, dZ using common epochs from both files and conversion of the coordinate differences dX, dY, dZ into *along track*, *cross-track*, and *radial* components.

Clocks

- Computation of the clock differences Δc_A^S from common epochs of both files, correct them for the radial component of coordinate differences $dC\_radial_{AC}^s$ and using them in a least square adjustment $\Delta c_{AC}^S = o_{AC} + o_{AC}^S$ with the following unknowns:

o_A .. the analysis center specific offset common for all satellites — o_A^S .. the satellite and analysis center specific offset

IGS RTS VALIDATION RESULTS: ORBITS & CLOCKS

- The GFZ MGEX rapid products (Deng et all. 2017) are used as reference for monitoring and comparison. More specifically: the product chain with the same satellite clock reference observables as defined within the IGS RTS is used.
- Monitoring results are available at https://igs.org/rts/monitoring/

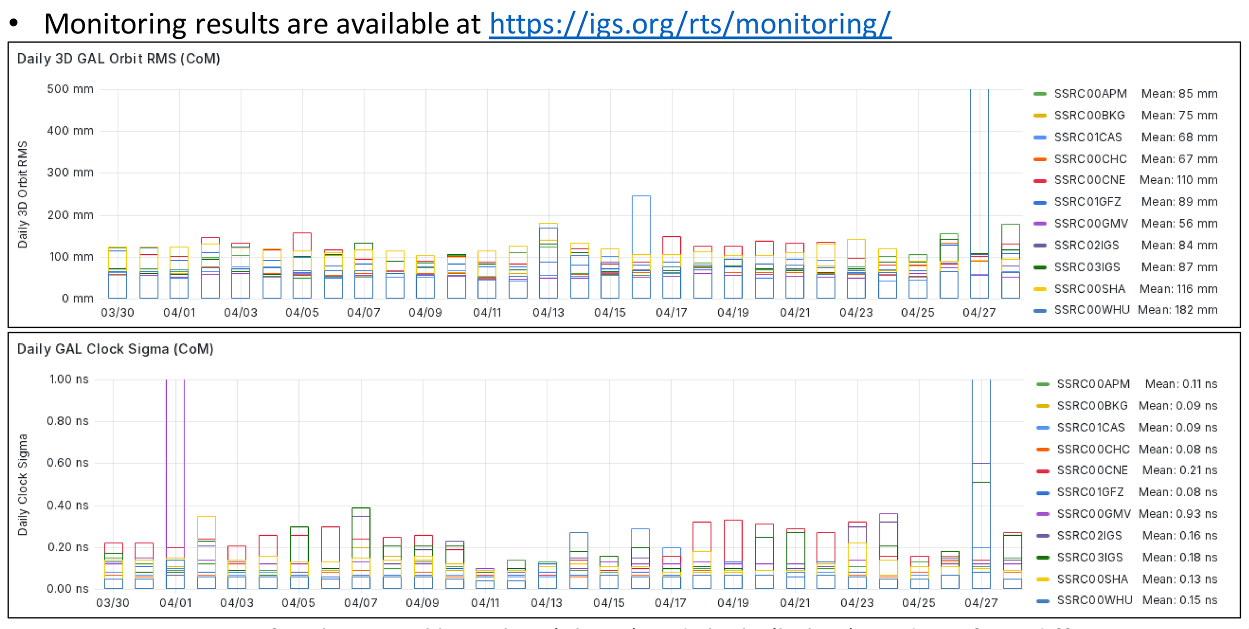

Figure 1: Agreement of real time Galileo orbits (above) and clocks (below) products from different RTACs with GFZ MGEX rapid product.

IGS RTS VALIDATION RESULTS: PPP-AR

- The Ambiguity Resolution (PPP with AR) is based on the ***Best Integer Equivalent*** algorithm (Teunissen 2005).
- PPP results for all IGS RTS ACs and IGS RTS products are available at: https://igs.bkg.bund.de/ntrip/ppp

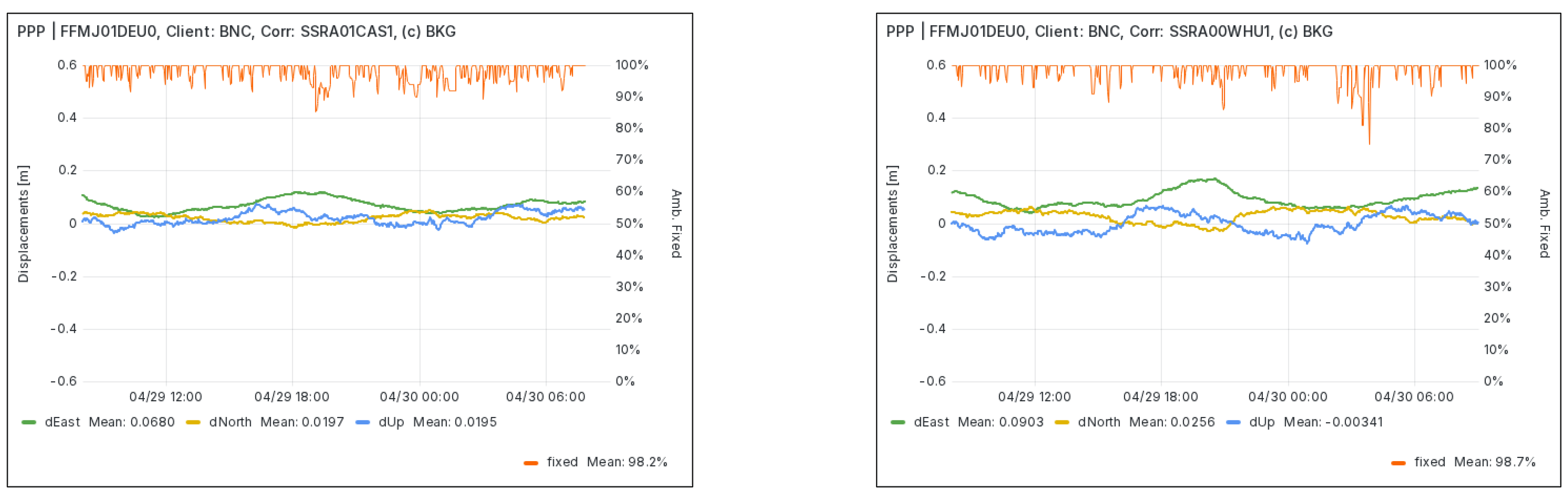

Figure 2: Real Time Positioning estimates of PPP-AR solutions using IGS RTS products SSRA01CAS1 (left) and SSRA00WHU1 together with OSBC00WHU1 (right). The PPP client Software BNC is used to estimate for positions of station FFMJ (Frankfurt, Germany) at April 29th and 30th 2026

OUTLOOK & TODO

Implementation: 5-step methodology to produce combined satellite clock corrections and OSBs valid for PPP-AR

1. Combination of Differential Code Bias Estimates DCB by differencing OSBs
2. Melbourne-Wuebbena linear combination of estimated biases
3. Ionosphere-free phase clocks: clock combination
4. Ionosphere-free code biases

$$\begin{bmatrix} c_{AC}^s \\ DCB_{C1W,C2W}^s \\ DCB_{C1W,C1C}^s \\ DCB_{C2W,C2C}^s \\ LIF = 0 \\ UPD_{WL} \\ b_{IF}^s \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & -\alpha_{IF} & -\beta_{IF} \\ 0 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \alpha_{IF} & \beta_{IF} \\ 0 & -\alpha_{NL} & -\beta_{NL} & 0 & 0 & \alpha_{WL} & \beta_{WL} \\ 0 & -\alpha_{IF} & -\beta_{IF} & 0 & 0 & \alpha_{IF} & \beta_{IF} \end{bmatrix} \begin{bmatrix} dt^s - \Delta t \\ CB_{C1W}^s \\ CB_{C2W}^s \\ CB_{C1C}^s \\ CB_{C2C}^s \\ PB_{L1W}^s \\ PB_{L2W}^s \end{bmatrix}$$

5. Transformation of the linear combinations of biases from step 1-4 to OSBs (Banville et al. 2020, Banville and Laurichesse 2017)

Minimization of differently modelled satellite specific errors

- The orbit information is extracted from one of the incoming RTAC solutions = Master
- A priori corrections $dC_{AC}^s = dC_{AC,frame}^s + dC_{AC,att}^s + dC_{AC,pco}^s$ are applied to the remaining RTAC clocks: $c_{AC\_corrected}^S = c_{AC}^S - dC_{AC}^s$ to compensate for inconsistencies between individual AC and Master using:

✓ Orbit difference $dC_{AC,frame}^s = \frac{(\boldsymbol{O}_{AC}^s - \boldsymbol{O}_{Master}^s - D_{AC})}{R^s} \cdot \boldsymbol{O}_{AC}^s$ — D_{AC} .. Geo-center offset vector (not part of SSR)

\+ Yaw angle (θ) difference: $dC_{AC,att}^s = (\theta_{AC}^s - \theta_{Master}^s) / (2\pi * \lambda_{IF}^s)$ — RTACs have to provide server side used values

\+ PCO differences: $dC_{AC,pco}^s = 0$ — RTACs should switch to `igs20_wwww.atx` exactly at the start of GPS week `wwww`

REFERENCES

Banville S., Geng J., Loyer S., Schaer S., Springer T., Strasser S. (2020) On the interoperability of IGS products for precise point positioning with ambiguity resolution. Journal of Geodesy. 94, 10 (2020). https://doi.org/10.1007/s00190-019-01335-w

IGS State Space Representation (SSR) Format, Version 1.00 International GNSS Service (IGS) (2020). https://files.igs.org/pub/data/format/igs_ssr_v1.pdf

Wang N., Li Y., Li Z., Liu A., Liu B. (2025) Determination of multi-GNSS differential code biases with satellite antenna phase center corrections. GPS Solutions 30, 22 (2026). https://doi.org/10.1007/s10291-025-01983-w

Banville S., Laurichesse D. (2017) A real-time clock combination supporting precise point positioning with ambiguity resolution. IGS Workshop, Paris, 2017

Deng Z., Nischan T., Bradke M. (2017): Multi-GNSS Rapid Orbit-, Clock- & EOP-Product Series. GFZ Data Services. https://doi.org/10.5880/GFZ.1.1.2017.002

ABSTRACT ID 6944