WROCŁAW UNIVERSITY
OF ENVIRONMENTAL
AND LIFE SCIENCES

# APPLICATIONS OF GALILEO HIGH ACCURACY SERVICE

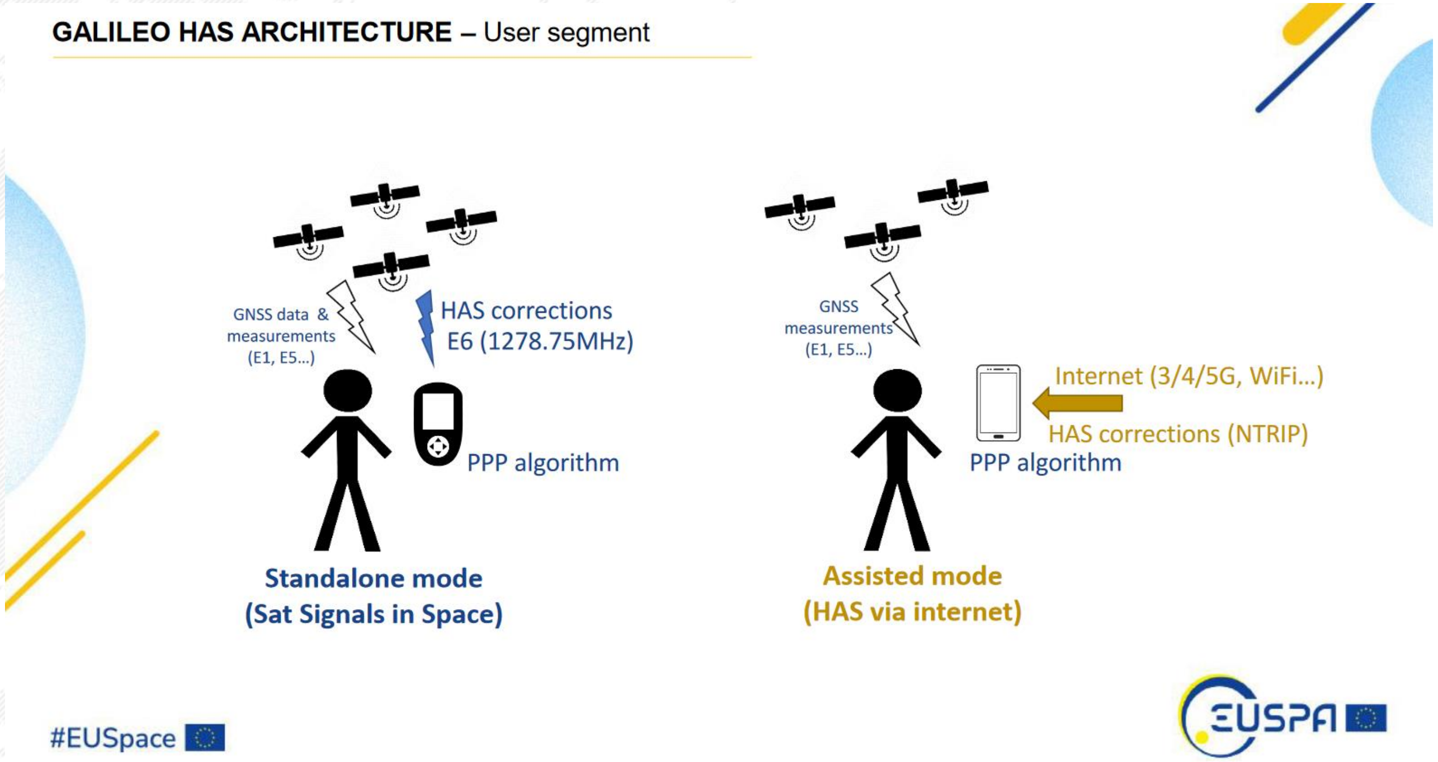
Kamil **Kazmierski**, Tomasz **Hadas**, Iwona **Kudłacik**,
Grzegorz **Marut**, Szymon **Madraszek**

FAKULTA
STAVEBNÍ
ústav geodézie

**KONFERENCE GNSS 2024**
26. ročník konference s mezinárodní účastí DRUŽICOVÉ METODY V TEORII A PRAXI

# Motivation

- ➔ Galileo HAS Initial Service available since the 24th of January 2023
- ➔ Wide availability of the service thanks to the transmission of corrections via satellite signal
- ➔ SSR00EUH0 stream publicly available
- ➔ How Galileo HAS performs in different applications?



https://www.euspa.europa.eu/

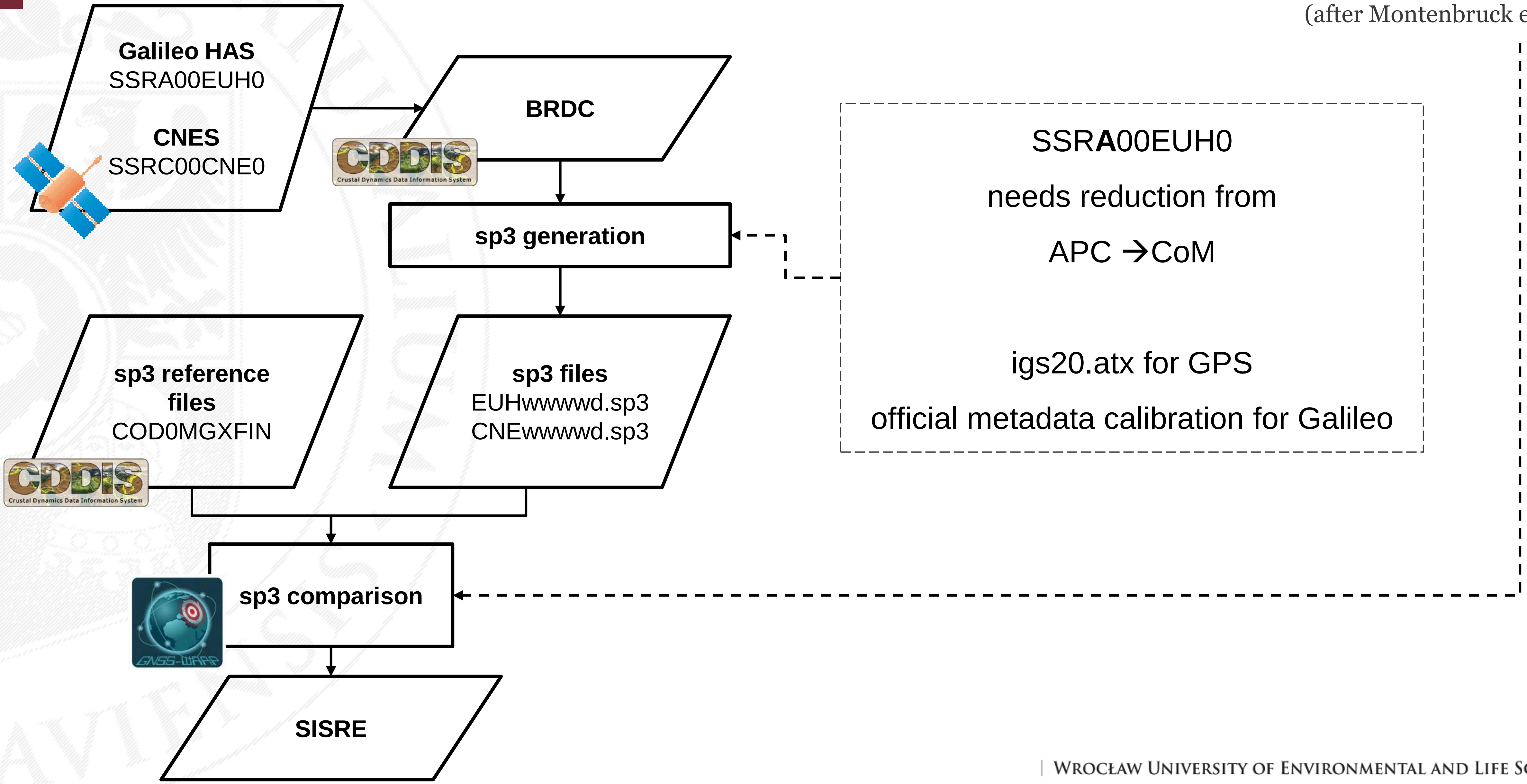
## Experiment design

1. Quality of Galileo HAS corrections
2. Positioning performance: static and kinematic
3. Timing
4. Troposphere monitoring
5. Coseismic vibrations monitoring

# Quality of Galileo HAS corrections

$$\mathrm{SISRE} = \sqrt{\left[\mathrm{RMS}\left(w_R \cdot \Delta r_R - \Delta cdt\right)\right]^2 + w_{A,C}^2 \cdot \left(A^2 + C^2\right)}$$

(after Montenbruck et al. 2015)



**Galileo HAS**
SSRA00EUH0

**CNES**
SSRC00CNE0

**BRDC**

**sp3 generation**

**sp3 files**
EUHwwwwd.sp3
CNEwwwwd.sp3

**sp3 reference files**
COD0MGXFIN

**sp3 comparison**

**SISRE**

SSR**A**00EUH0

needs reduction from

APC →CoM

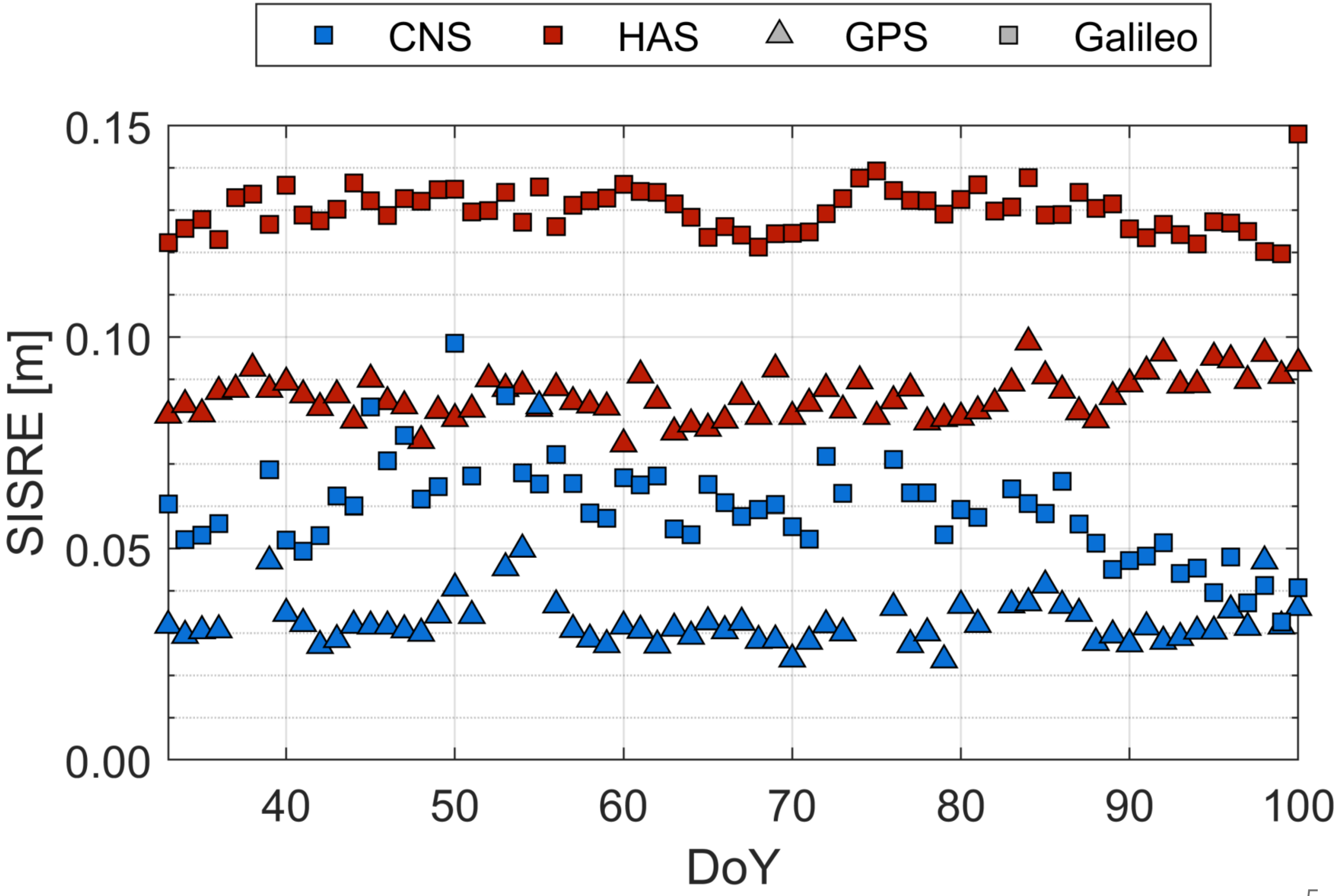
igs20.atx for GPS

official metadata calibration for Galileo

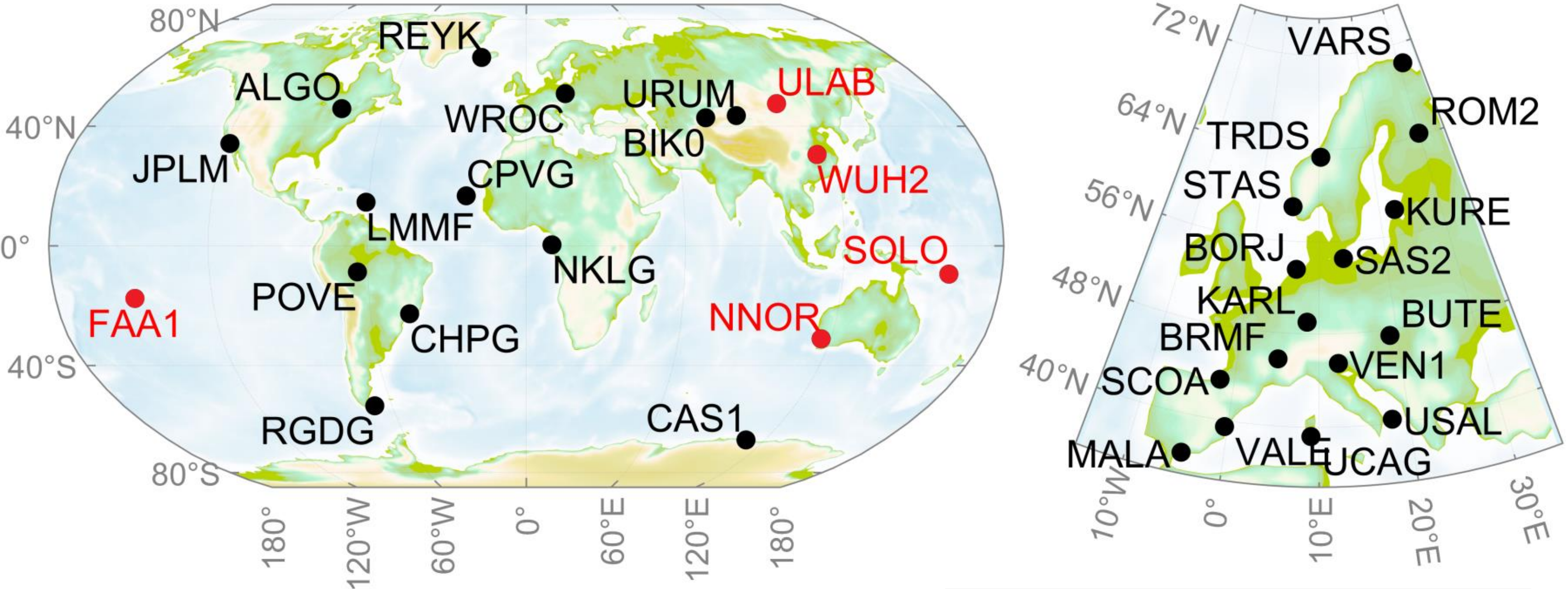
# Quality of Galileo HAS corrections

- ➔ GPS performs better
- ➔ HAS products have two times biger SISRE than CNS

| | Average SISRE [cm] | |
|---|---|---|
| **Stream** | **CNS** | **HAS** |
| **GPS** | **3.3** | **8.6** |
| **Galileo** | **5.9** | **13.0** |



# Positioning, timing, and troposphere monitoring experiment



- ➔ DoY 33-100, 2023
- ➔ 18 IGS + 16 EPN stations
- ➔ GPS (L1/L2) + Galileo (E1/E5a)
- ➔ RT streams:
  - ◆ CNES (orb, clk, CB, PB)
  - ◆ HAS (orb, clk, CB)
- ➔ reference:
  - ◆ CSRS-PPP (coord.)
  - ◆ EPN & IGS (ZTD)

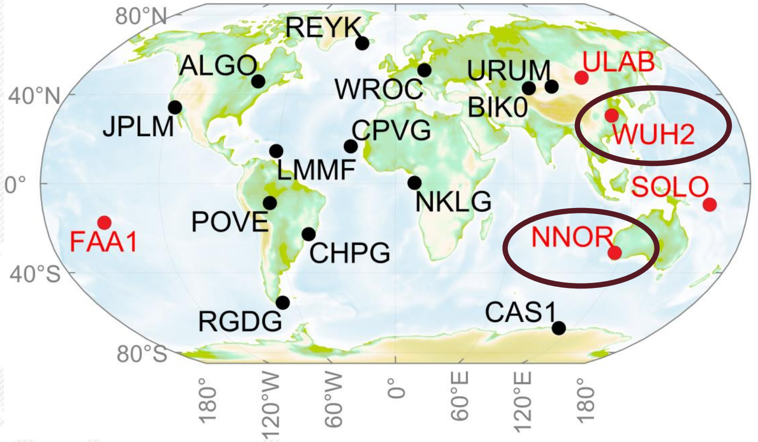
Processing strategy:

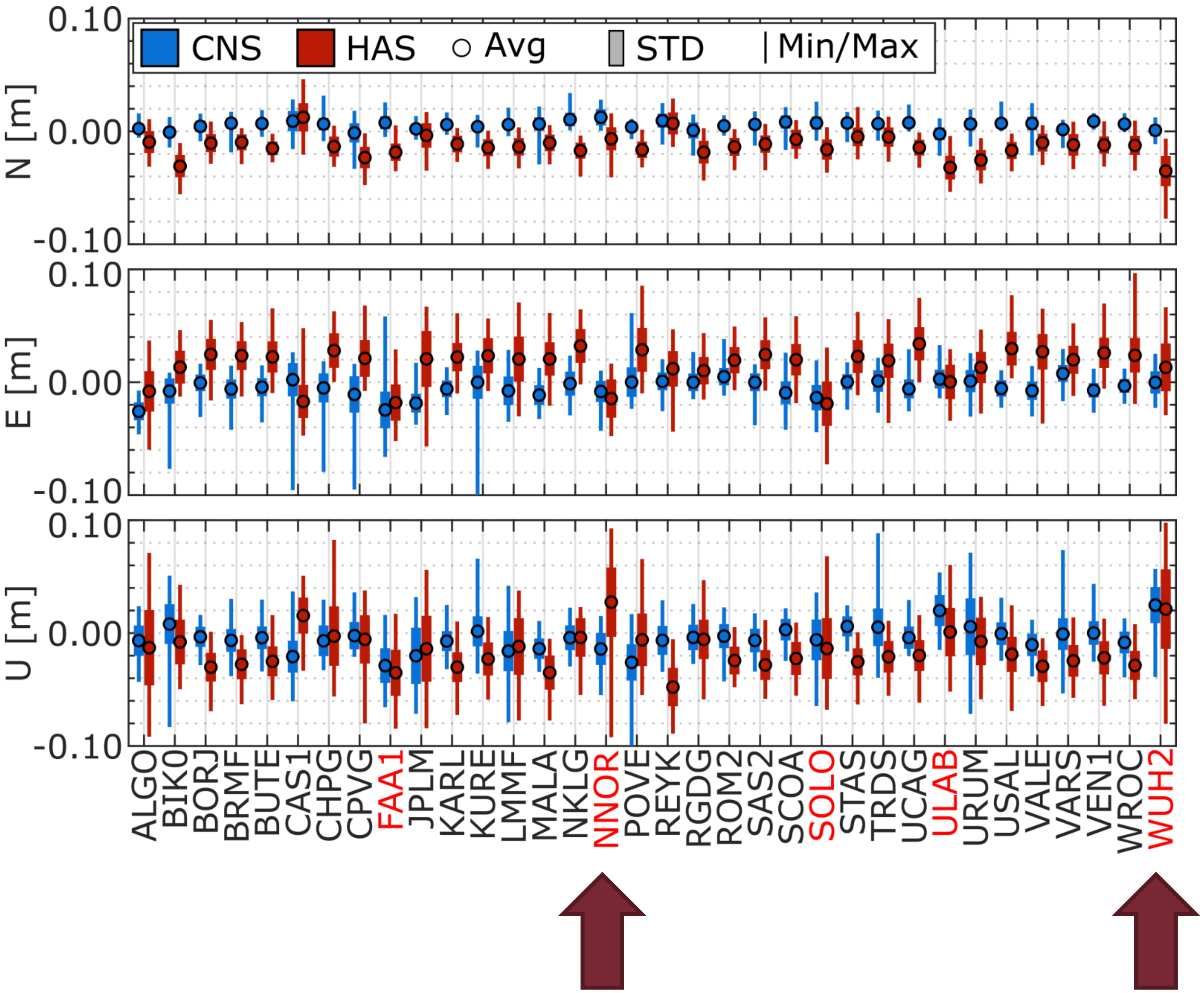
- ➔ undifferenced uncombined dual-frequency float PPP
  - daily static solution (positioning)
  - continuous static solution (troposphere)
- ➔ ITRF2020, IERS Convention 2010, GPT+GMF

# Daily Static PPP

➔ Positive bias for HAS solution
➔ 1.5 smaller StdDev for CNS

| | | mean | StdDev | RMS |
|---|---|---|---|---|
| **Hz** | **CNS** | **8** | **11** | **15** |
| | **HAS** | **21** | **18** | **31** |
| **V** | **CNS** | **-5** | **13** | **17** |
| | **HAS** | **-16** | **19** | **29** |





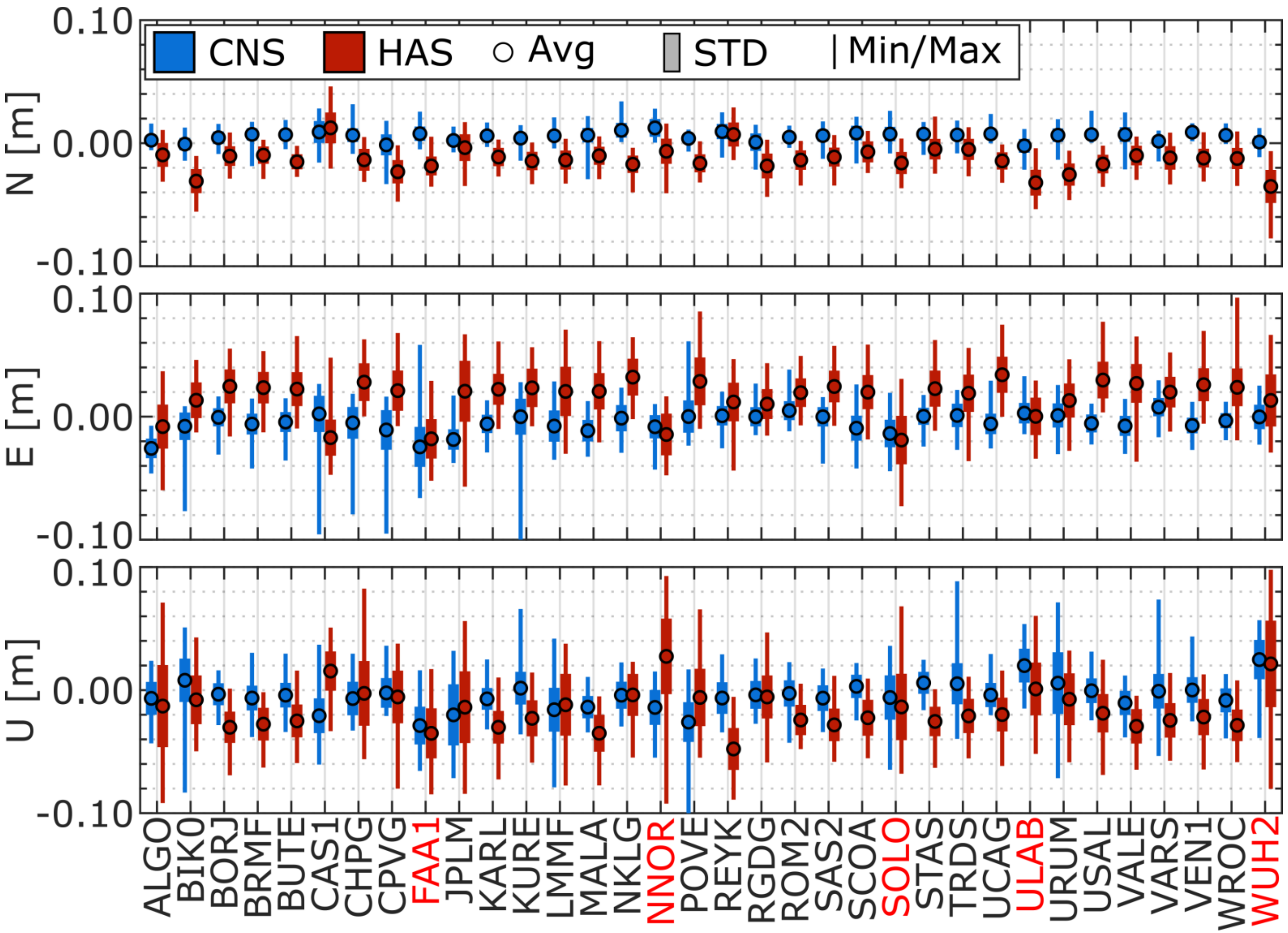
# Daily Static PPP

- ➔ Positive bias for HAS solution
- ➔ 1.5 smaller StdDev for CNS

| | | mean | StdDev | RMS |
|---|---|---|---|---|
| **Hz** | **CNS** | **8** | **11** | **15** |
| | **HAS** | **21** | **18** | **31** |
| **V** | **CNS** | **-5** | **13** | **17** |
| | **HAS** | **-16** | **19** | **29** |

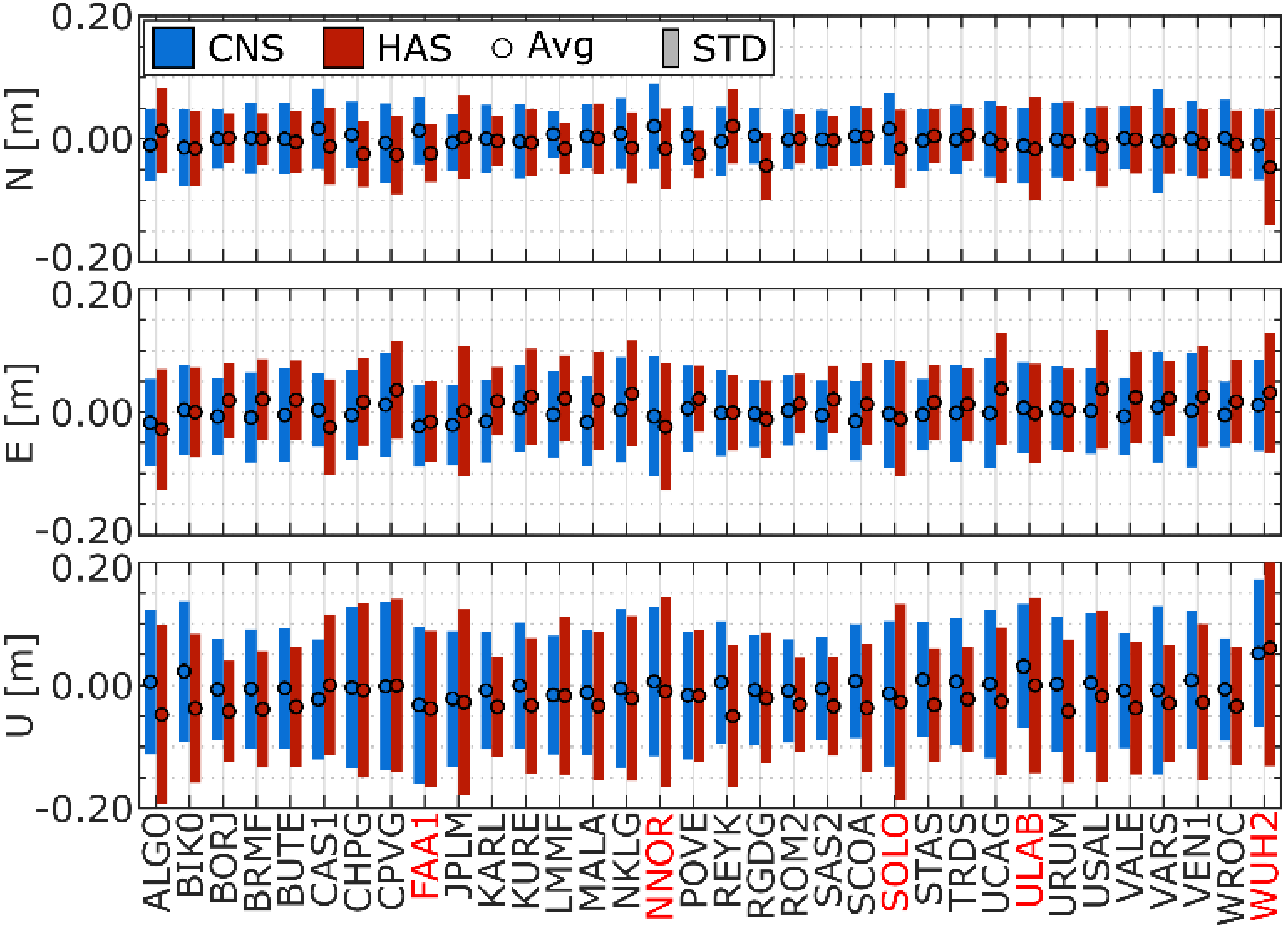
- ➔ Average CNES vs HAS convergence time rate

| | N | E | U |
|---|---|---|---|
| **5 cm** | **2.0** | **1.5** | **1.5** |
| **20 cm** | **2.1** | **1.8** | **1.8** |

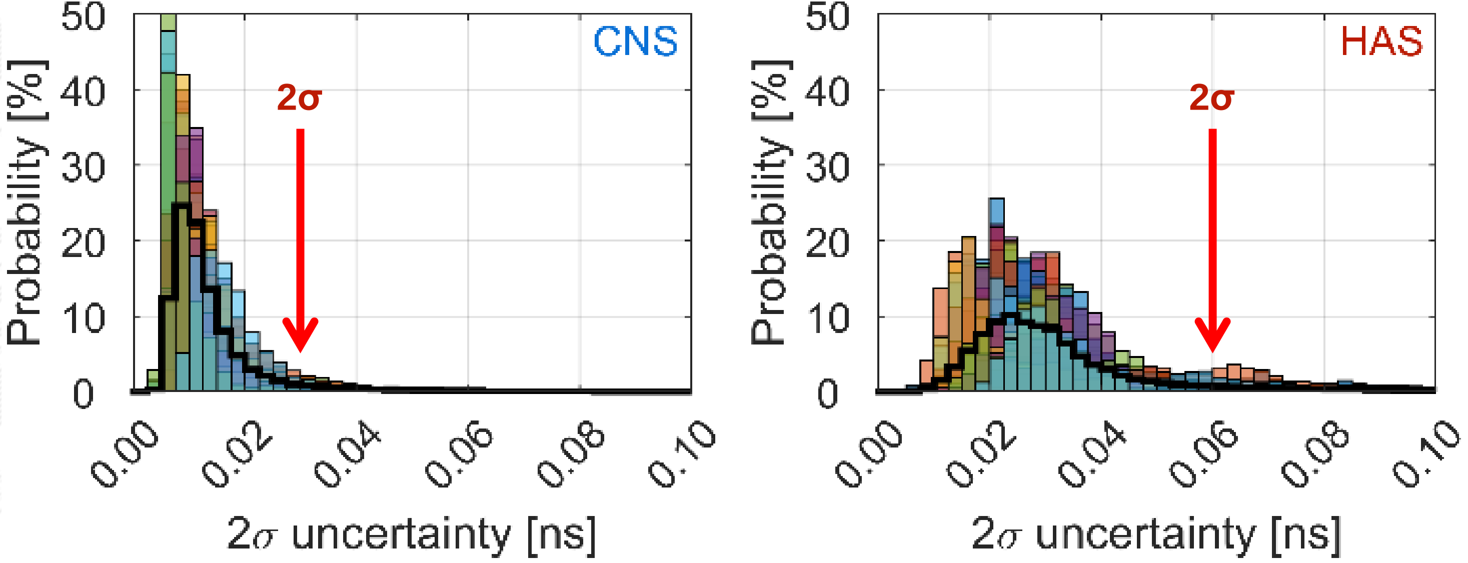


# Kinematic PPP

- ☐ A few centimeter station-specific offsets
- ☐ Similar precision
  Hz
  CNS: 91 mm
  HAS: 93 mm
  V
  CNS: 106 mm
  HAS: 118 mm
- ☐ Real-time corrections quality is not a main limiting factor in kinematic PPP



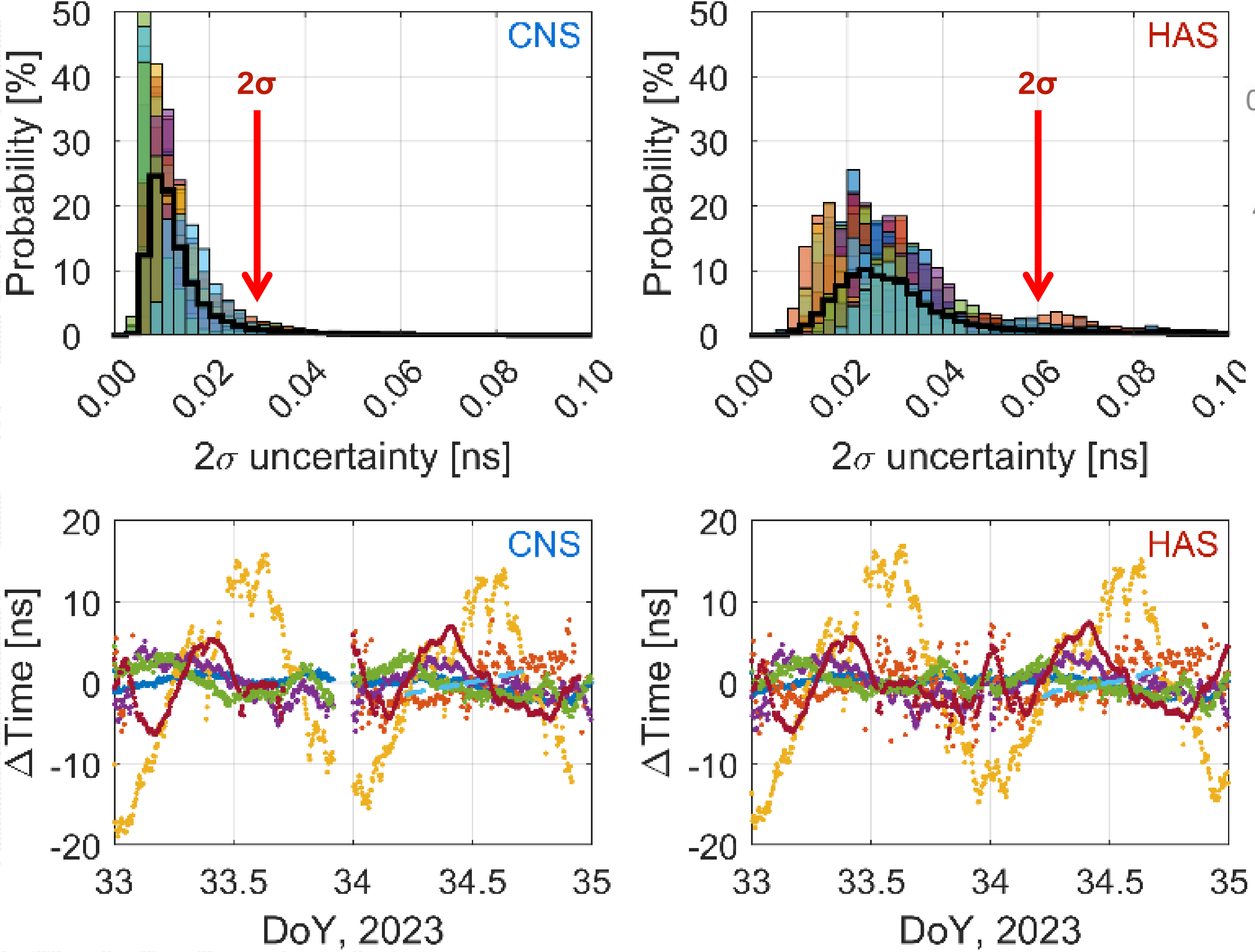
# Timing

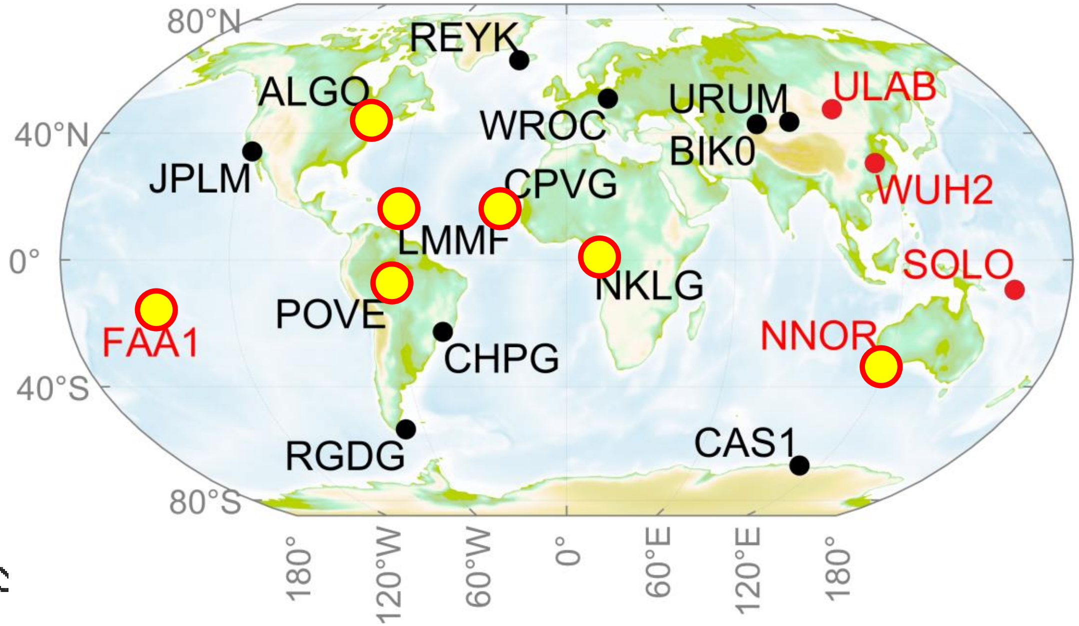


❑ Significantly lower receiver clock offsets estimated for CNS than for HAS

❑ 95% confidecnce level
CNS: 0.03 ns (max 0.08 ns)
HAS: 0.06 ns (max 0.10 ns)

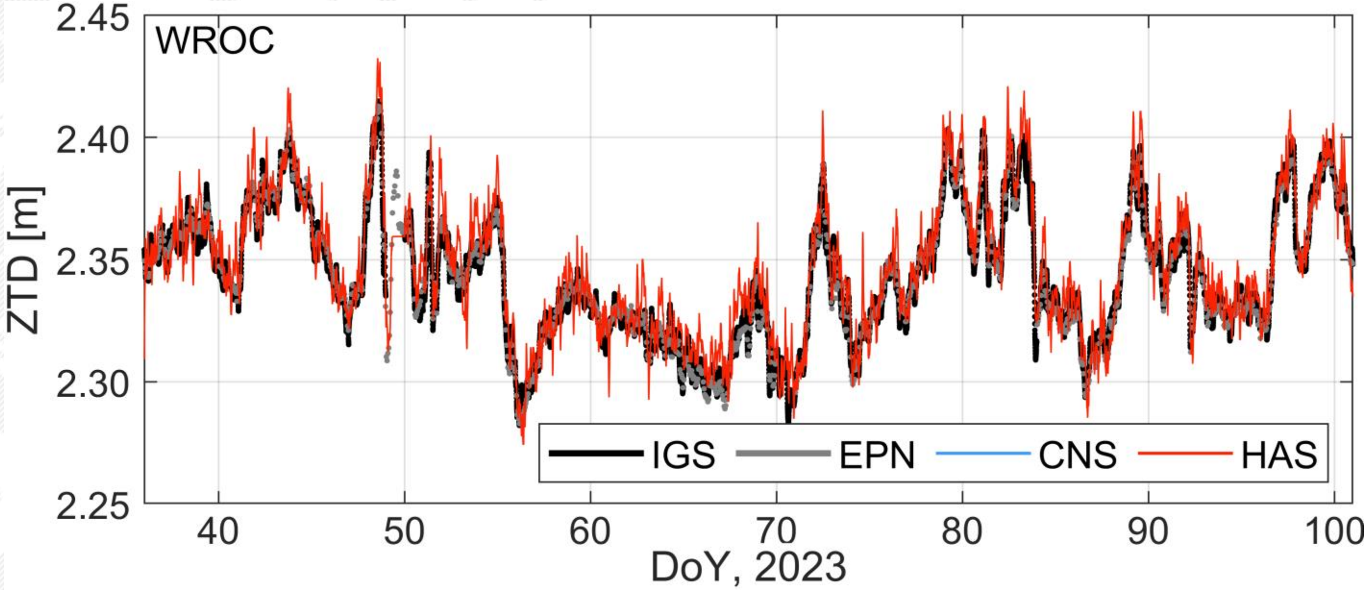
# Timing

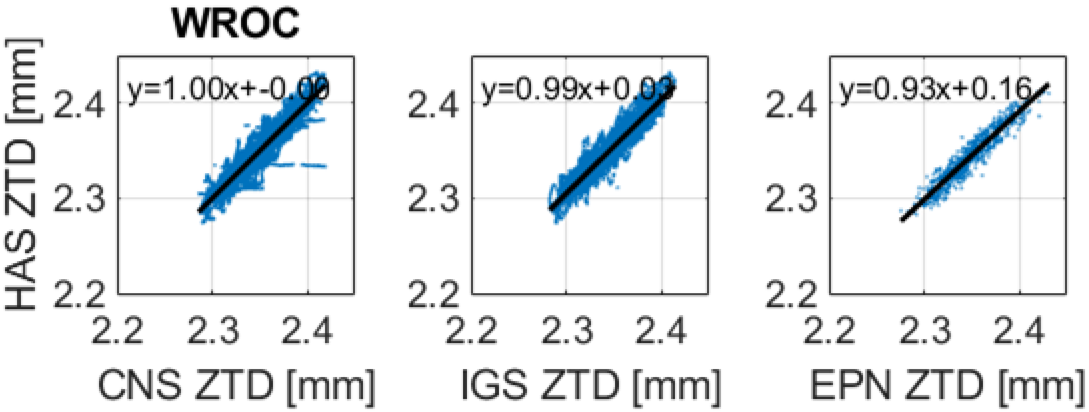


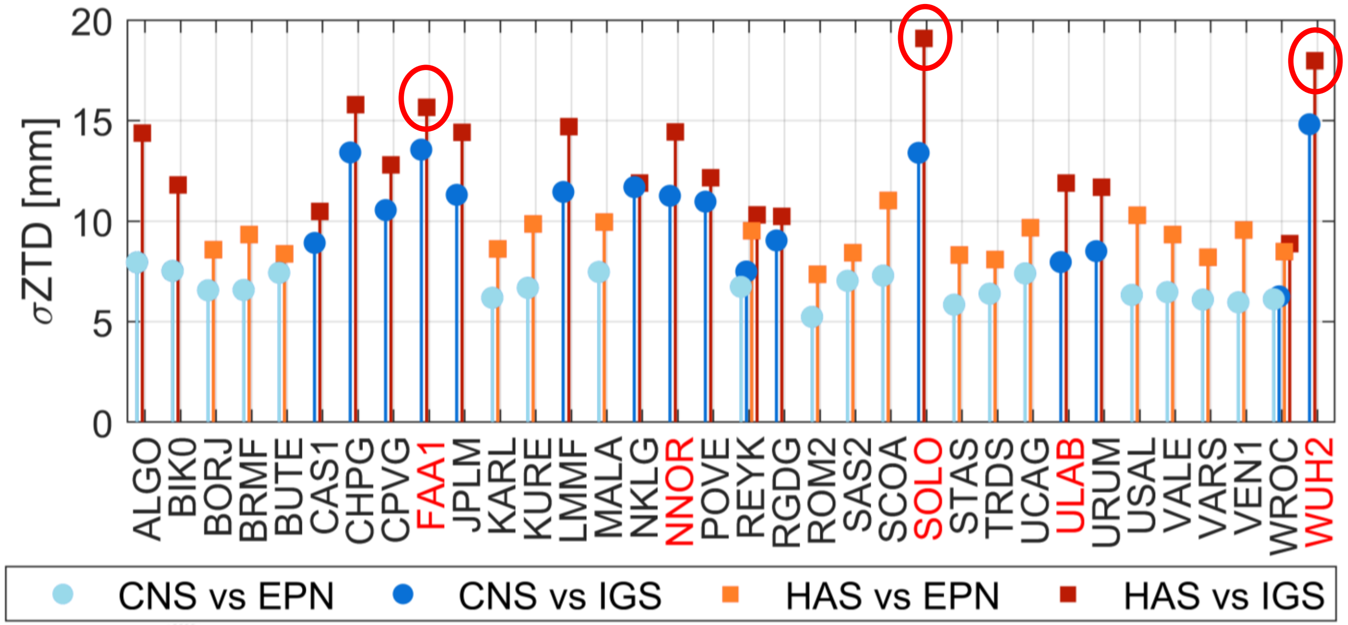


- Comparison with IGS Final clock product
- CNS bias smaller than for HAS by 0.5 to 1.5 ns
- StdDev
  - CNS: 0.9 to 3.3 ns
  - HAS: 0.8 to 3.3 ns
- Both streams agree to 0.3 ns and better for HAS data

# Troposphere estimation



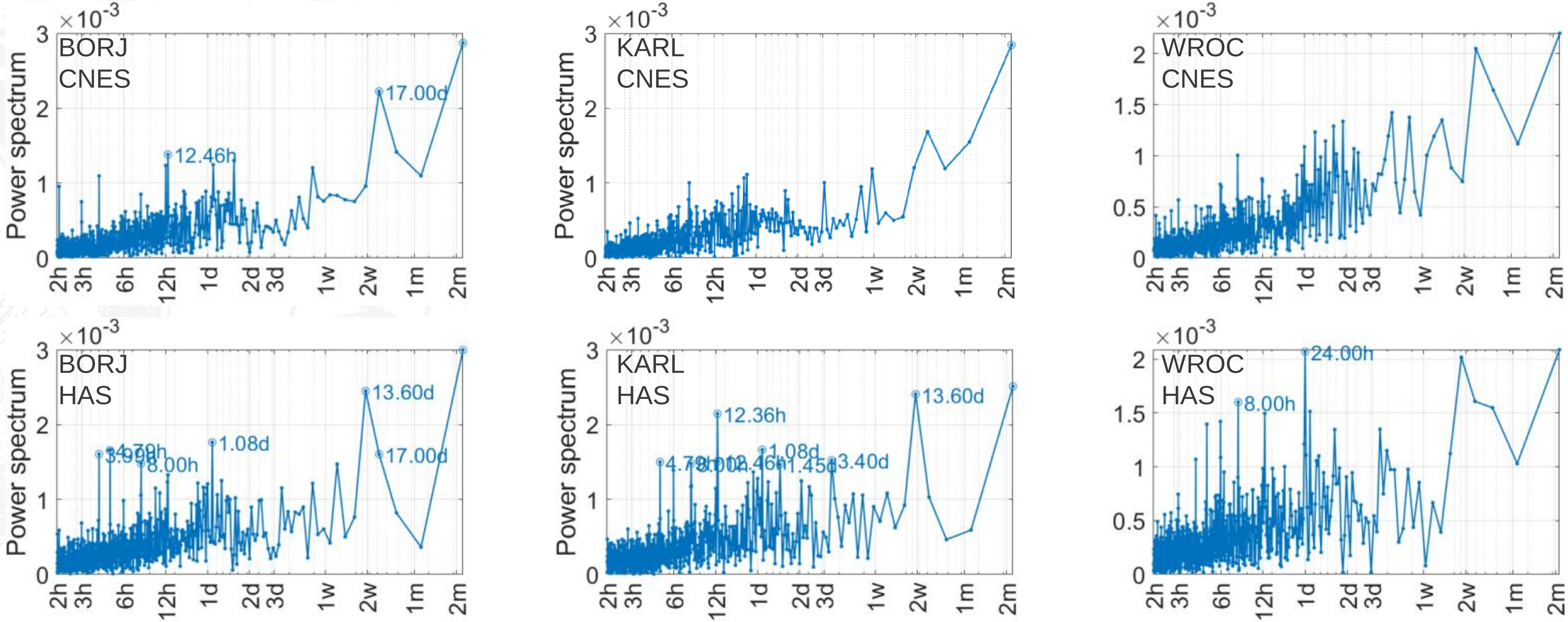




| [mm] | mean | StdDev | RMSE |
|---|---|---|---|
| CNS vs EPN | 3,7 | 6,5 | 7,7 |
| CNS vs IGS | 0,1 | 10,3 | 11,1 |
| HAS vs EPN | 3,0 | 9,1 | 9,6 |
| HAS vs IGS | 1,9 | 13,3 | 13,9 |

# **Troposphere determination**: orbital artifacts?

- GPS+Galileo (with CNES RT) suppresses artificial orbital effects in ZTD time-series [1];
- HAS -> some daily and sub-daily signals are amplified (further investigation required)



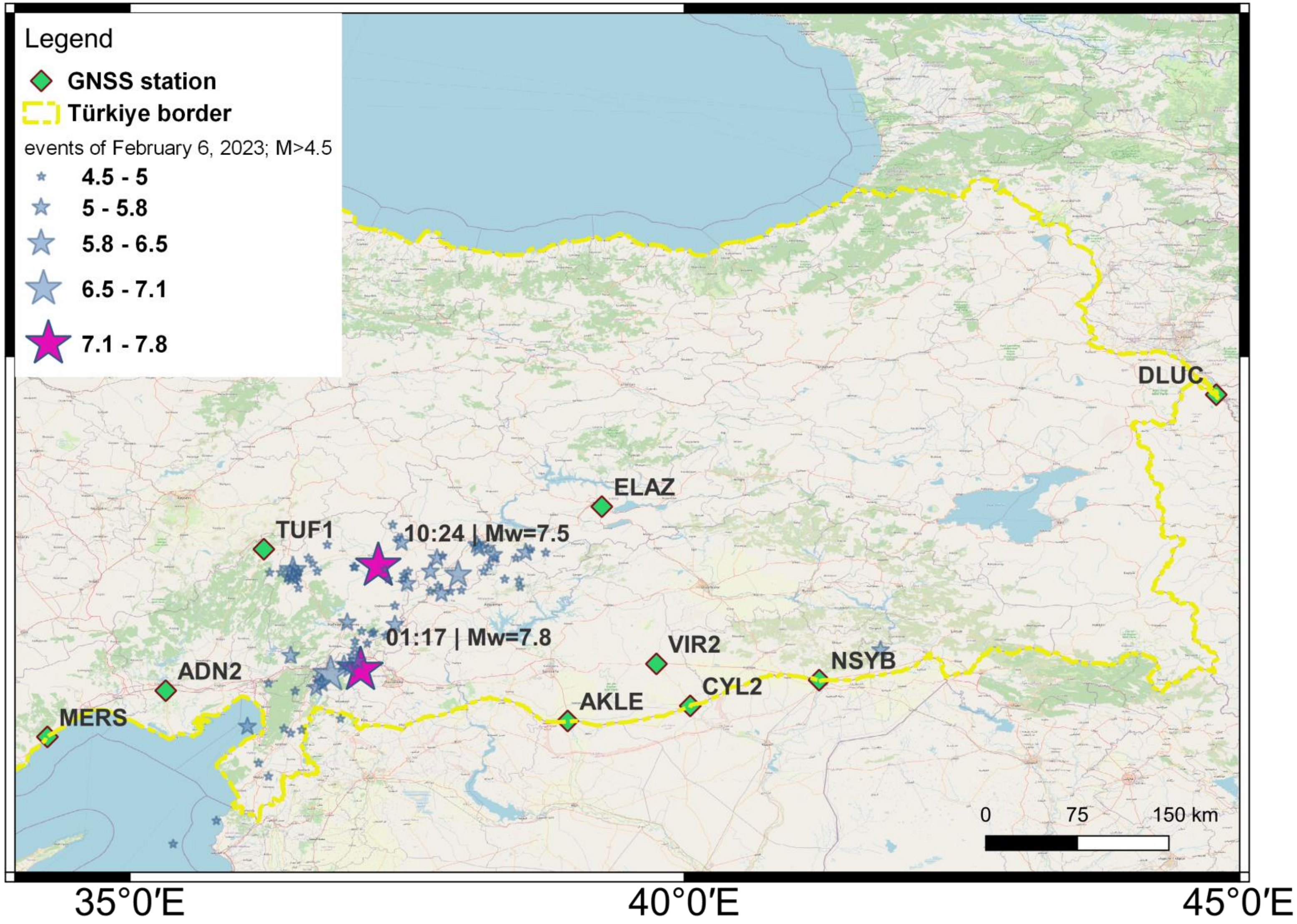
---

[1] T. Hadas and T. Hobiger, "Benefits of Using Galileo for Real-Time GNSS Meteorology," in *IEEE Geoscience and Remote Sensing Letters*, vol. 18, no. 10, pp. 1756-1760, Oct. 2021, doi: 10.1109/LGRS.2020.3007138.

# Coseismic vibrations experiment

- ➔ 2023 Turkey-Syria Earthquake
- ➔ Map shows events M >4.5
- ➔ 10 Hz positioning GPS+Galileo Galileo HAS
- ➔ Vibration detection with dedicated algorithm

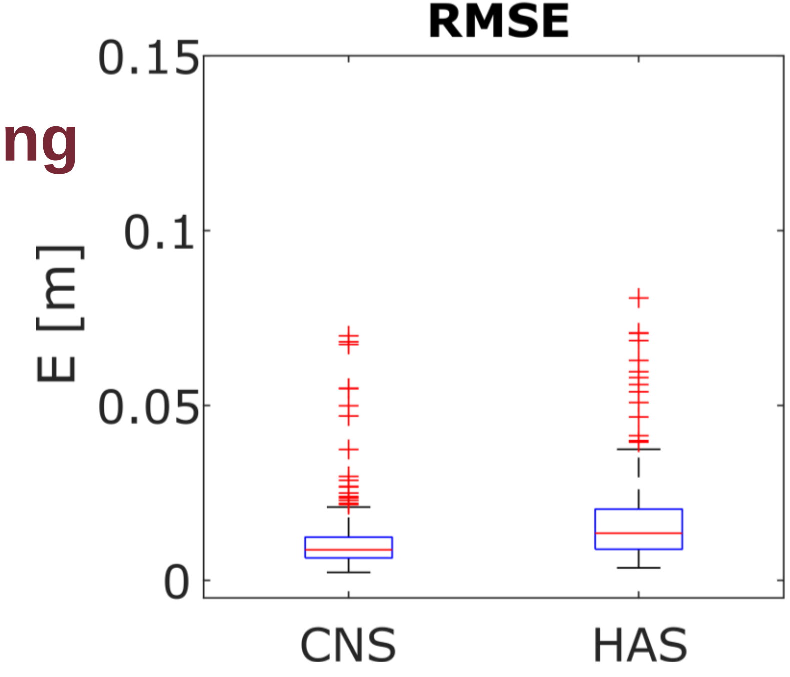
Kudłacik, I., Kapłon, J., Kazmierski, K. *et al.* First feasibility demonstration of GNSS-seismology for anthropogenic earthquakes detection. *Sci Rep* **13**, 20905 (2023). https://doi.org/10.1038/s41598-023-47964-2

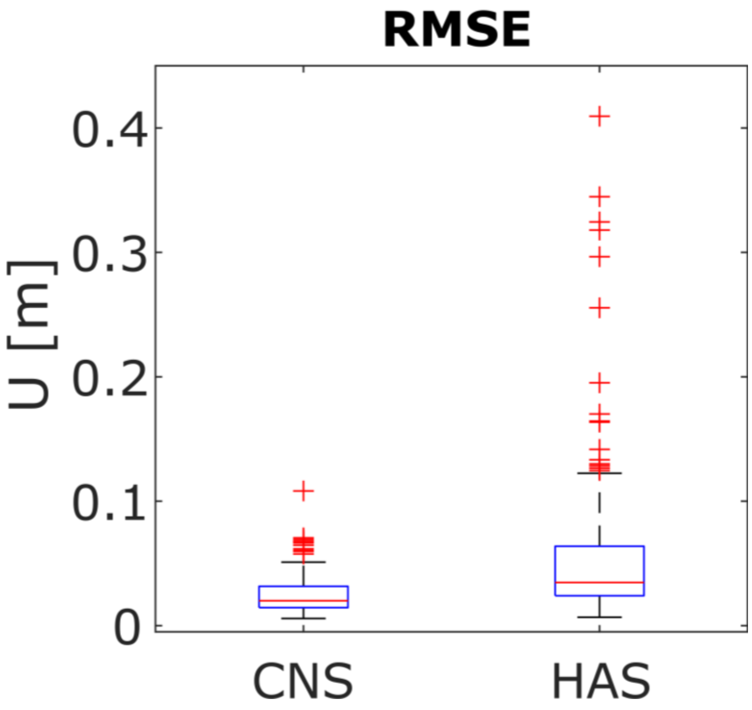


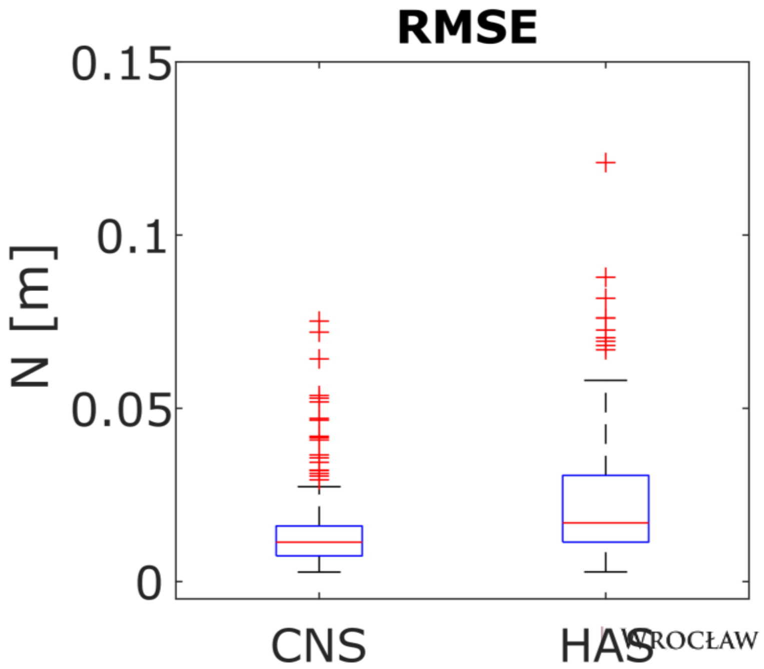
# Coseismic vibrations monitoring

❑ Accuracy

| | CNS | HAS |
|---|---|---|
| Hz | 12 mm | 20 mm |
| V | 25 mm | 46 mm |







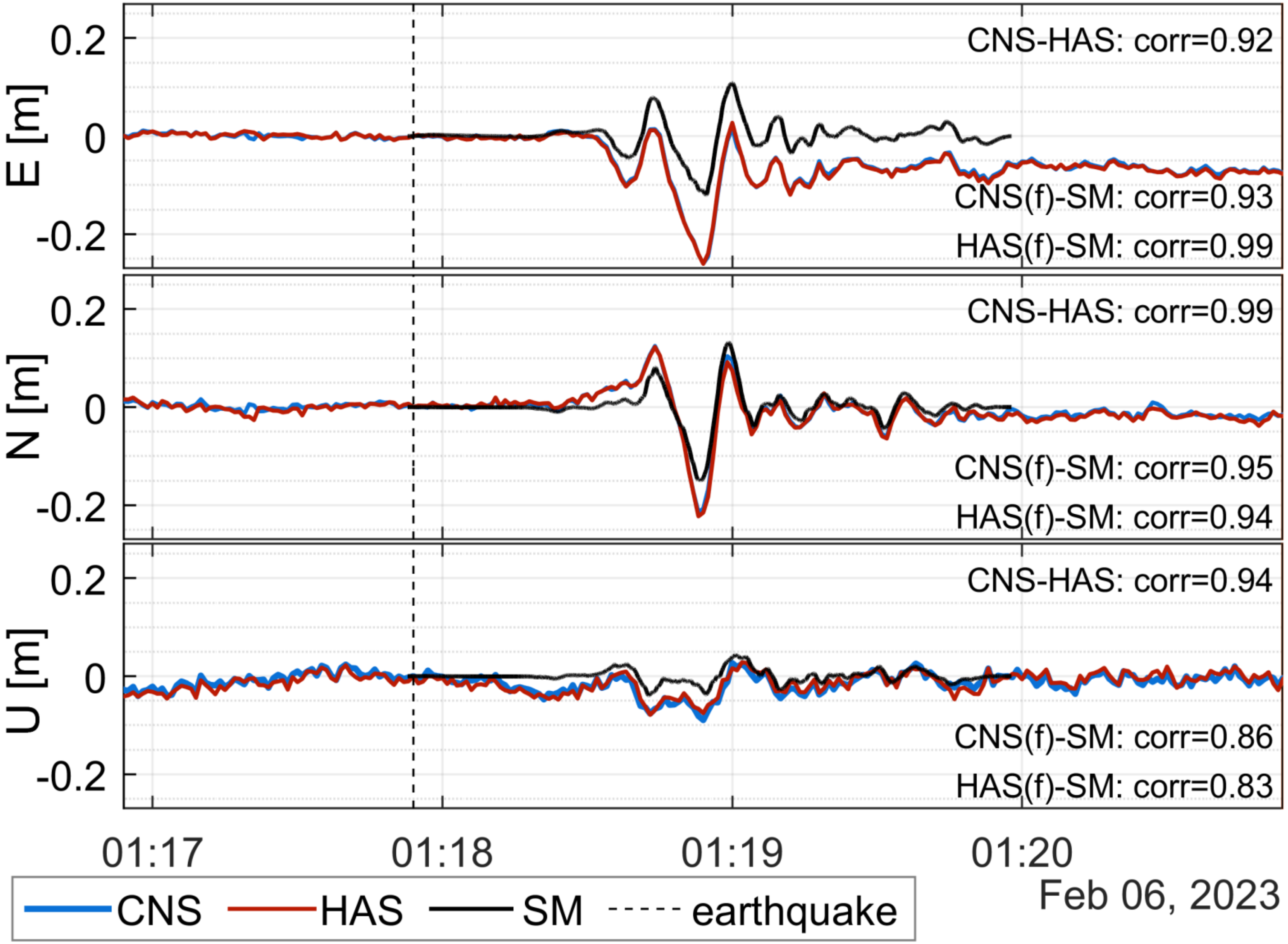
# Coseismic vibrations monitoring

- ☐ Accuracy

| | CNS | HAS |
|---|---|---|
| Hz | 12 mm | 20 mm |
| V | 25 mm | 46 mm |

- ☐ The median Pearson's correlation with seismograph almost identical for E and N
  - CNS: 0.85
  - HAS: 0.84

  for U component
  - CNS: 0.72
  - HAS: 0.60



Feb 06, 2023

# Conclusions: Performance with HAS

- ❑ **Positioning:**
  - ○ Galileo HAS perform better than nominally
  - ○ Only minor degradation outside operation area
- ❑ **Timing:**
  - ○ Significantly lower estimated receiver clock offsets for CNES than for HAS
  - ○ Good agreement between both streams (0.3 ns)
- ❑ **Troposphere:**
  - ○ ZTD precision of 10 mm (13 mm) compared to EPN (IGS) Final solutions;
  - ○ 30-45% of degradation compared to processing with real-time CNES products
- ❑ **Coseismic vibrations:**
  - ○ Galileo HAS has slightly smaller accuracy than CNES
  - ○ Good agreement between CNES and HAS results in terms of horizontal components

# For extanded description:

T. Hadas, K. Kazmierski, I. Kudłacik, G. Marut and S. Madraszek, "Galileo High Accuracy Service in real-time PNT, geoscience and monitoring applications," in *IEEE Geoscience and Remote Sensing Letters*, doi: 10.1109/LGRS.2024.3354293.

SCAN ME

This article has been accepted for publication in IEEE Geoscience and Remote Sensing Letters. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/LGRS.2024.3354293

## Galileo High Accuracy Service in real-time PNT, geoscience and monitoring applications

Hadas T., Kazmierski K., Kudlacik I., Marut G., Madraszek S.

***Abstract*— Satellite transmission of orbit and clock corrections is critical for real-time positioning, navigation and timing (PNT), geoscience applications, safety and liability critical services based on Global Navigation Satellite Systems (GNSS) precise positioning. In response to such a demand, Galileo has established a High Accuracy Service (HAS) of almost global coverage for GPS and Galileo. We validate the quality of HAS corrections and investigate service performance in a variety of applications. Decimeter-level accuracy of HAS corrections leads to static and kinematic positioning with precision of a few centimeters and sub-decimeter, respectively, and timing precision of a single nanosecond. Other GNSS-derived products meet the requirements of real-time GNSS meteorology and allow for monitoring coseismic vibrations. Although other Internet correction streams offer superior results, HAS provides better performance than nominal and nearly global coverage.**

***Index Terms*— Galileo, High Accuracy Service, Global Navigation Satellite Systems, GNSS, real-time, troposphere, remote sensing, earthquakes, PNT**

### I. INTRODUCTION

REAL-TIME precise positioning, navigation, and timing (PNT) with Global Navigation Satellite Systems (GNSS) for many years was limited to the Real-Time Kinematics (RTK) technique, which allows for achieving an accuracy of few centimeters but requires a nearby reference station to transmit corrections to observations via radio or internet connection [1]. Worldwide PNT coverage is offered by the Precise Point Positioning (PPP) technique, but the sub-decimeter accuracy requires at least dual-frequency observations and some time, typically minutes to hours, before the solution converges [2]. Real-time PPP has been available since 2013, when the International GNSS Service (IGS) launched the IGS Real-Time Service (RTS, https://igs.org/rts/) with satellite orbit and clock corrections for GPS and GLONASS streamed over the Internet. Several IGS analysis centers that contribute to RTS currently support all four GNSS; some of them additionally provide code and phase biases, the latter being a prerequisite for PPP with ambiguity resolution [3].

Although the accuracy of PPP depends, among others, on satellite visibility, length of observation, and receiver dynamics, the accuracy of satellite orbits and clocks directly affects the PPP results. The combined IGS RTS orbits are accurate to 50 mm for GPS and 130 mm for GLONASS. The corresponding values for clocks are 0.3 ns and 0.8 ns [4]. Over the last decade, together with the major evolution of GNSS, like the development of Galileo and BeiDou constellations, the accuracy of real-time products has been improved. Nevertheless, their quality is heterogeneous across different systems and satellite types. The Signal in Space Range Error (SISRE) [5] varies from 16 mm for Galileo, through 23 mm for GPS, and exceeds 50 mm for GLONASS and BeiDou [6].

A variety of geoscience applications exploiting real-time PPP has been demonstrated. The technique supports robust and accurate navigation for unmanned aerial vehicles [7]. It has proved to be useful for highly dynamic airplane flights, providing accuracy at the level of 0.20-0.30 m [8], whereas a sub-decimeter accuracy is achievable for in-land autonomous driving in the urban environment [9] and vessel navigation [10]. PPP is demanded in precision agriculture applications, in which centimeter-level precision is demonstrated under open-sky conditions [11]. The technique is also used as an all-weather tool for water vapor monitoring, providing performance that legitimates the assimilation of troposphere products from GNSS into numerical weather models [12]. Due to its low cost and no reference station required, PPP is directly applicable to a large area and slow-variable landslide monitoring [13]. Sub-cm land deformations in the mining areas are detectable [14]. Coseismic displacement waveforms are retrieved with horizontal and vertical accuracy of 1.2 cm and 2.4 cm, respectively [15]. Time transfer uncertainty with real-time PPP is better than 0.3 ns [16].

Despite the great potential of the real-time PPP technique, temporal unavailability of real-time corrections, i.e. due to Internet disconnections, prevents from providing continuous results. Therefore, real-time PPP has not been operationally implemented in safety or liability critical systems such as natural hazard monitoring, aviation, or time transfer. To overcome this limitation, orbit and clock corrections need to be

Manuscript received 23 October 2023; revised 28 December, accepted 1 January 2024. Date of publication 11 February 2024; date of current version 3 February 2024. Project funded by the National Centre for Research and Development under the LEADER XIII Programme. Contract No. LIDER13/0075/2022. (Corresponding author: Tomasz Hadas).

The authors are with the Wroclaw University of Environmental and Life Sciences, 50357 Wroclaw, Poland (e-mail: tomasz.hadas@upwr.edu.pl, kamil.kazmierski@upwr.edu.pl, iwona.kudlacik@upwr.edu.pl, grzegorz.marut@upwr.edu.pl, szymon.madraszek@upwr.edu.pl).

Color versions of one or more of the figures in this article are available online at http://ieeexplore.ieee.org

Digital Object Identifier XXXXXXXXXXXXXXX

# Thank you for your attention!

## APPLICATIONS OF GALILEO HIGH ACCURACY SERVICE

kamil.kazmierski@upwr.edu.pl
www.up.wroc.pl