Report of Transnational Access Projects

(Note: the information here will be publicly disclosed in the Geo-INQUIRE website, do not include sensitive information)

Project ID: *C2_TA3-88-2_1*

Principal investigator:

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Project title: *Low-cost HR-GNSS with external receiver clock corrections*

Project acronym: *LC-HERC[2]*

Hosting installation: *Corinth Rift Laboratory – GNSS [ID TA3-88-2]*

Hosting team:

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Period of access: *18-22.01.2026*

Report of activities:

The project was conducted in accordance with the structured work plan, with particular attention paid to the deployment and evaluation of the high rate GNSS (HR-GNSS) technology. The main objective was to determine whether the sensitivity of low-cost GNSS receivers may be improved by an external time reference.

High-rate GNSS is reported as a complementary tool to classical seismic sensors (SM). Its sensitivity is lower than that of SM, but it does not suffer from drift or clipping and can record both long-term and short-term motion of the GNSS antenna at sampling frequencies of 1 Hz and above (typically 10 Hz, and up to 100-200 Hz). The development of novel low-cost GNSS technology makes it possible to reduce equipment costs without

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a significant loss of precision. However, low-cost GNSS receivers are often equipped with a weaker internal clock, which may introduce fluctuations in the resulting position time-series. Nevertheless, some low-cost GNSS receivers (such as Septentrio mosaic-X5) allow connecting an external clock input (i.e. atomic clock).

In this experiment we aim to investigate, over both short-term (single days) and long-term (several-month) periods, whether supplementing the low-cost GNSS receiver with an external clock improves its reliability and brings its positioning performance closer to that of a co-located geodetic-grade GNSS receiver.

During the visit, the UPWr team installed Septentrio mosaic-X5 receivers at CRL – in the seismic laboratory in Patras (working name: UPT1) and in the primary school (working name: UPT2) located in the Rio-Patra Fault Zone. The Septentrio receivers were connected to the GNSS antennas via a signal splitter, allowing simultaneous reception of the same satellite signals by the low-cost GNSS receivers and the existing professional-grade geodetic receivers.

At the UPT1 site the Septentrio receivers are supplied with an external time reference via the rubidium clock, whereas at the UPT2 site the receivers are supplied with an internal clock. The GNSS receivers are configured to record the GNSS observations with the sampling rate of 1 Hz.

To effectively integrate HR-GNSS into seismological workflows, it is necessary to ensure real-time transmission and processing of HR-GNSS data. This capability was tested during the period when the low-cost GNSS receivers were installed.

Data is collected in two parallel ways: (1) stored locally on the receivers and periodically downloaded manually to the UPWr server, and (2) transmitted via the Internet using the NTRIP to the Linux HPC computational server in Wrocław. This dual-path workflow enables continuous remote monitoring and increases the robustness and reliability of data recording and processing.

The data streamed to the UPWr computational server are processed in real time using the BNC (BKG NTRIP Client v. 2.13.4) software, allowing ongoing assessment of receiver performance.

RINEX observation files stored locally

The database contains RINEX observation files from two low-cost Septentrio mosaic-X5 receivers (UPT1 & UPT2). For each receiver, 68 daily multi-GNSS RINEX files sampled at 1 Hz are included, covering DOY 21–88 (22 January–29 March 2026). All files are Hatanaka-compressed and subsequently archived using gZip. Each day of observations is packaged into a separate ZIP archive, and all daily archives are then consolidated into a single dataset. Decompression of files is possible using the open-source CRX2RNX software (https://terras.gsi.go.jp/ja/crx2rnx.html).

Real-Time Precise Point Positioning Results with BKG Ntrip Client (BNC 2.13.4 software)

In parallel with GNSS data storing, described in the previous chapter, the Precise Point Positioning (PPP) with ambiguity resolution was performed using the BNC 2.13.4 software under the Linux environment. Both stations were processed simultaneously, and the resulting dataset were included in the dataset published in Zenodo (doi: 10.5281/zenodo.19237676) as PPP_Results.zip. This computation test was performed for checking whether the software can operate in real-time mode for seismological applications.

In these files, receiver UPT1 corresponds to UPAT1, and UPT2 corresponds to UPAT2. The database includes the PPP processing results covering DOY 25-88 (26.01-29.03.2026).

The BKG Ntrip Client 2.13.4 (BNC) PPP processing resulted in creating the following folders and file types:

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- PPP_Results.zip
  - LOG.zip
    - Patras_YYMMDD.
  - NMEA.zip
    - UPAT1_GRE_YYYYDDDHHMM_01D_01S.nmea
    - UPAT2_GRE_YYYYDDDHHMM_01D_01S.nmea
  - PPP_log.zip
    - UPAT1_GRE_YYYYDDDHHMM_01D_01S.ppp.gz
    - UPAT1_GRE_YYYYDDDHHMM_01D_01S.ppp.gz
  - TRO.zip
    - IGIGPATSAAST2_GRE__YYYYDDDHHMM_01H_05M_UPAT1_GRE_TRO.TRO
    - IGIGPATSAAST2_GRE__YYYYDDDHHMM_01H_05M_UPAT2_GRE_TRO.TRO

Figure 1 BNC 2.13.4 PPP processing results structure

The folder LOG (here LOG.zip) contains the PPP processing results as well as the estimated coordinates in cartesian ECEF coordinate system (here IGS20 aligned to ITRF2020 reference frame). The example is presented in Figure 2.

```
26-03-30 00:00:03 2026-03-29_23:59:43.000 UPAT2_GREC X = 4652935.0365 Y = 1862616.8485 Z = 3931816.1136 NEU:  -0.0959  +0.2299  +1.1759 TRP:  +2.3569  +0.0299
26-03-30 00:00:03 2026-03-29_23:59:44.000 UPAT2_GREC X = 4652935.0404 Y = 1862616.8485 Z = 3931816.1130 NEU:  -0.0986  +0.2285  +1.1784 TRP:  +2.3569  +0.0299
26-03-30 00:00:03 2026-03-29_23:59:45.000 UPAT2_GREC X = 4652935.0419 Y = 1862616.8501 Z = 3931816.1139 NEU:  -0.0991  +0.2294  +1.1806 TRP:  +2.3569  +0.0299
26-03-30 00:00:03 2026-03-29_23:59:46.000 UPAT2_GREC X = 4652935.0407 Y = 1862616.8524 Z = 3931816.1144 NEU:  -0.0986  +0.2320  +1.1806 TRP:  +2.3569  +0.0298
26-03-30 00:00:03 2026-03-29_23:59:43.000 UPAT1_GREC X = 4655046.0646 Y = 1860588.7811 Z = 3930243.6093 NEU:  -0.0663  +0.2184  -0.1269 TRP:  +2.3663  +0.0120
26-03-30 00:00:03 2026-03-29_23:59:47.000 UPAT2_GREC X = 4652935.0420 Y = 1862616.8523 Z = 3931816.1139 NEU:  -0.0997  +0.2314  +1.1813 TRP:  +2.3569  +0.0298
26-03-30 00:00:03 2026-03-29_23:59:44.000 UPAT1_GREC X = 4655046.0655 Y = 1860588.7810 Z = 3930243.6082 NEU:  -0.0677  +0.2180  -0.1270 TRP:  +2.3663  +0.0120
26-03-30 00:00:03 2026-03-29_23:59:45.000 UPAT1_GREC X = 4655046.0687 Y = 1860588.7819 Z = 3930243.6086 NEU:  -0.0694  +0.2176  -0.1241 TRP:  +2.3663  +0.0120
26-03-30 00:00:03 2026-03-29_23:59:46.000 UPAT1_GREC X = 4655046.0682 Y = 1860588.7831 Z = 3930243.6076 NEU:  -0.0702  +0.2189  -0.1248 TRP:  +2.3663  +0.0120
26-03-30 00:00:03 2026-03-29_23:59:47.000 UPAT1_GREC X = 4655046.0688 Y = 1860588.7853 Z = 3930243.6063 NEU:  -0.0721  +0.2207  -0.1245 TRP:  +2.3663  +0.0120
```

Figure 2 Example of BNC software processing log file with PPP results (Patras_YYMMDD).

The NMEA folder (NMEA.zip) contains the PPP processing results in NMEA format (https://www.nmea.org/nmea-0183.html). Each of the processed stations has a separate file (Figure 3).

```
$GPRMC,235942.000,A,3818.0648,N,02149.0034,E,,,290326,,*05
$GPGGA,235942.00,3818.0648416,N,02149.0034479,E,1,35,0.5,147.148,M,0.0,M,,*53
$GPRMC,235943.000,A,3818.0648,N,02149.0034,E,,,290326,,*04
$GPGGA,235943.00,3818.0648424,N,02149.0034482,E,1,35,0.5,147.147,M,0.0,M,,*58
$GPRMC,235944.000,A,3818.0648,N,02149.0034,E,,,290326,,*03
$GPGGA,235944.00,3818.0648415,N,02149.0034484,E,1,35,0.5,147.145,M,0.0,M,,*59
$GPRMC,235945.000,A,3818.0648,N,02149.0034,E,,,290326,,*02
$GPGGA,235945.00,3818.0648414,N,02149.0034480,E,1,35,0.5,147.137,M,0.0,M,,*58
$GPRMC,235946.000,A,3818.0648,N,02149.0034,E,,,290326,,*01
$GPGGA,235946.00,3818.0648425,N,02149.0034486,E,1,35,0.5,147.141,M,0.0,M,,*5e
$GPRMC,235947.000,A,3818.0648,N,02149.0034,E,,,290326,,*00
$GPGGA,235947.00,3818.0648413,N,02149.0034478,E,1,35,0.5,147.147,M,0.0,M,,*5d
$GPRMC,235948.000,A,3818.0648,N,02149.0034,E,,,290326,,*0f
$GPGGA,235948.00,3818.0648408,N,02149.0034481,E,1,35,0.5,147.146,M,0.0,M,,*5f
$GPRMC,235949.000,A,3818.0648,N,02149.0034,E,,,290326,,*0e
```

Figure 3 Example of BNC software NMEA output from PPP processing for one station (here UPAT2_GRE_20260890000_01D_01S.nmea).

The PPP_log (PPP_log.zip) folder contains the PPP processing results, separately for each of the processed stations (Figure 4) including the cartesian coordinates and processing GNSS code and phase residuals for detailed PPP processing inspection.

```
PPP of Epoch 2026-03-30_00:00:00.000
---------------------------------------------------------------
2026-03-30_00:00:00.000 BANCROFT:    4652941.574    1862615.994    3931820.888      63112.348

2026-03-30_00:00:00.000 SATNUM G  9
2026-03-30_00:00:00.000 RES c1  G05   0.1118
2026-03-30_00:00:00.000 RES c1  G07   0.1514
2026-03-30_00:00:00.000 RES c1  G09  -0.2298
2026-03-30_00:00:00.000 RES c1  G11   0.7423
2026-03-30_00:00:00.000 RES c1  G13   0.3536
2026-03-30_00:00:00.000 RES c1  G14   0.0449
2026-03-30_00:00:00.000 RES c1  G21   0.0318
2026-03-30_00:00:00.000 RES c1  G22  -0.1911
2026-03-30_00:00:00.000 RES c1  G30  -0.0363
2026-03-30_00:00:00.000 RES c2  G05  -0.1215
2026-03-30_00:00:00.000 RES c2  G07  -0.0228
2026-03-30_00:00:00.000 RES c2  G09   0.5474
2026-03-30_00:00:00.000 RES c2  G11   0.4208
2026-03-30_00:00:00.000 RES c2  G13  -0.0853
2026-03-30_00:00:00.000 RES c2  G14   0.0246
2026-03-30_00:00:00.000 RES c2  G21  -0.1526
2026-03-30_00:00:00.000 RES c2  G22   0.0417
2026-03-30_00:00:00.000 RES c2  G30   0.0134
2026-03-30_00:00:00.000 RES l1  G05  -0.0007
2026-03-30_00:00:00.000 RES l1  G07   0.0005
2026-03-30_00:00:00.000 RES l1  G09   0.0007
2026-03-30_00:00:00.000 RES l1  G11   0.0087
2026-03-30_00:00:00.000 RES l1  G13  -0.0035
2026-03-30_00:00:00.000 RES l1  G14  -0.0002
2026-03-30_00:00:00.000 RES l1  G21   0.0005
2026-03-30_00:00:00.000 RES l1  G22  -0.0034
2026-03-30_00:00:00.000 RES l1  G30   0.0001
2026-03-30_00:00:00.000 RES l2  G05   0.0004
2026-03-30_00:00:00.000 RES l2  G07  -0.0003
2026-03-30_00:00:00.000 RES l2  G09  -0.0004
2026-03-30_00:00:00.000 RES l2  G11  -0.0053
2026-03-30_00:00:00.000 RES l2  G13   0.0021
2026-03-30_00:00:00.000 RES l2  G14   0.0001
2026-03-30_00:00:00.000 RES l2  G21  -0.0003
2026-03-30_00:00:00.000 RES l2  G22   0.0020
2026-03-30_00:00:00.000 RES l2  G30  -0.0001
```

Figure 4. Example of PPP processing results hourly file content for one epoch at one station (here UPAT2_GRE_20260890000_01D_01S.ppp) including the ECEF XYZ coordinates and.GNSS code and phase observables' residuals.

The TRO (TRO.zip) folder contains the troposphere SINEX formatted (https://files.igs.org/pub/data/format/sinex_tropo.txt) files including the zenith total troposphere delays in 5 minute intervals.

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```
+TROP/SOLUTION
*STATION__ ____EPOCH_____ TROTOT STDDEV
 UPAT2_GRE 2026:089:43200 2548.3    3.9
 UPAT2_GRE 2026:089:43500 2481.3    2.7
 UPAT2_GRE 2026:089:43800 2472.1    1.7
 UPAT2_GRE 2026:089:44100 2456.2    1.4
 UPAT2_GRE 2026:089:44400 2436.9    1.2
 UPAT2_GRE 2026:089:44700 2420.8    1.0
 UPAT2_GRE 2026:089:45300 2523.0    9.0
 UPAT2_GRE 2026:089:45600 2466.9    3.3
 UPAT2_GRE 2026:089:45900 2436.6    1.9
 UPAT2_GRE 2026:089:46200 2422.2    1.3
 UPAT2_GRE 2026:089:46500 2414.7    1.0
-TROP/SOLUTION
```

Figure 5 Example of the BNC software PPP processing output for troposphere results: total zenith delay in [mm] (TROTOT) and its standard deviation (STDDEV). Taken from IGIGPATSAAST2_GRE__20260891200_01H_05M_UPAT2_GRE_TRO.TRO.

A representative example of the real-time PPP coordinate time series obtained from the BNC 2.13.4 processing is shown in Figure 6. This real-time processing experiment purpose was to test the availability of the signal from the receivers as well as the external streams of satellite orbits, clocks, ionosphere parameters and SSR (State-Space-Representation) corrections. The plot illustrates the real-time PPP position time series for both stations (UPT1), including periods of stable coordinate estimation as well as short data gaps characteristic of real-time streaming. These timeseries provide an essential first-stage assessment of the applicability of low-cost HR-GNSS receivers for real-time seismological workflows, demonstrating both the continuity of the real-time solution and the presence of artefacts relevant for further analysis. The daily completeness of calculated epochs is presented in Figure 7 - on most days over 90% of epochs were calculated in real-time, but there are some days with missing solutions. The evaluation of the positioning quality requires more advanced software than BNC (e.g. gNUT, Bernese GNSS Software, GipsyX, groops or GNSS WARP) to perform phase ambiguity fixed PPP solution allowing the external clock information to be included. This will be performed using the resultant project's dataset in simulated real-time conditions.

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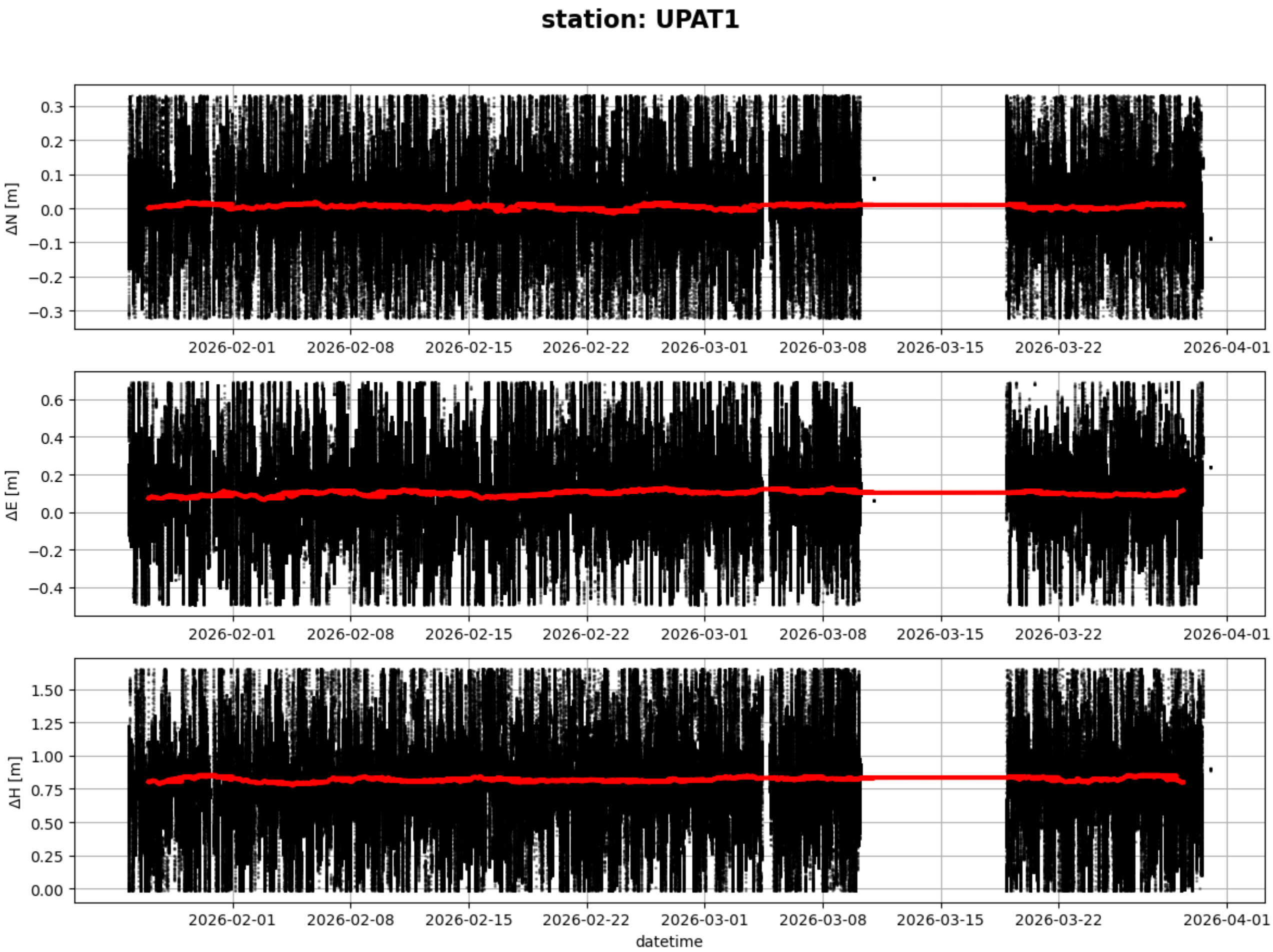

Figure 6 Example of real-time PPP coordinate time series for stations UPT1 (external clock) after outlier removal with marked trend calculated as moving median (red). The plot illustrates gaps, noise levels, and short-term instability visible in the real-time PPP solution.

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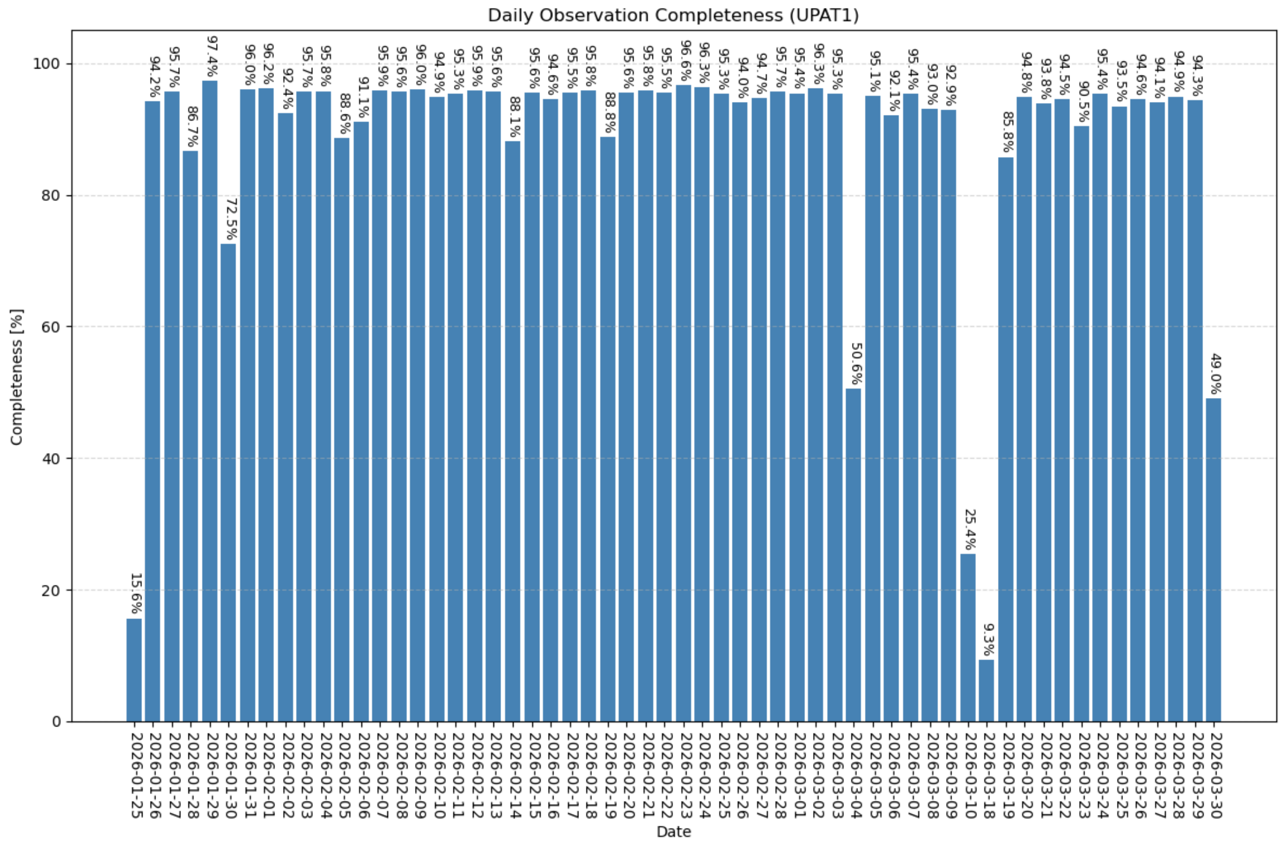

Figure 7 Example of real-time PPP coordinate time series for stations UPT1 (external clock). The plot illustrates gaps, noise levels, and short-term instability visible in the real-time PPP solution. Values for UPT2 are similar.

These results provide an essential first-stage assessment of the applicability of low-cost HR-GNSS receivers for real-time seismological workflows, demonstrating both the continuity of the real-time solution and the presence of artefacts relevant for further analysis. The observed gaps and instabilities indicate that real-time HR-GNSS integration is feasible, but also highlight specific technical challenges that must be addressed in subsequent project stages to fully achieve the scientific objectives.

Project outcomes:

Zenodo database: 10.5281/zenodo.19237676

Signed by /
Podpisano przez:

Jan Andrzej Kapłon

Date / Data: 2026-06-01 07:52

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