DANGO
Danish National Galileo Overlay

Final Presentation

Magdalena Golofit
Research Assistant
DTU Space

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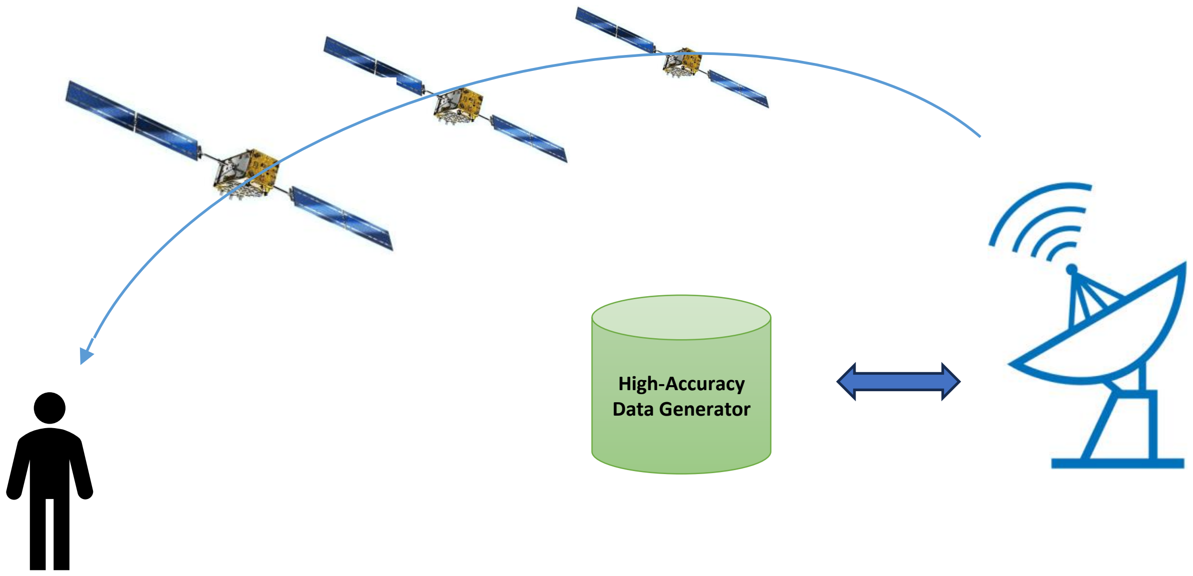
Image credit: https://www.esa.int/ESA_Multimedia/Images/2015/09/Denmark_from_the_ISS

Introduction - Danish National Galileo Overlay

The Galileo Overlay

- Galileo High Accuracy Service (Galileo HAS)
- Novel PPP service
- Interest to utilize the Galileo HAS in Denmark



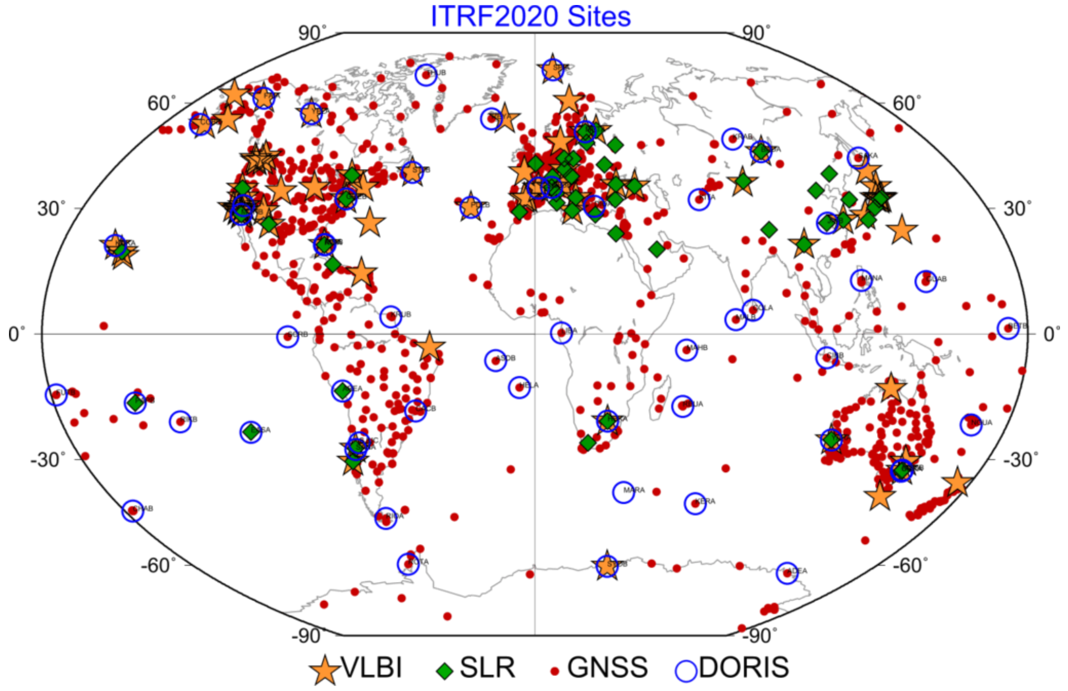
The challenge: HAS PPP corrections come in Galileo Terrestrial Reference System (GTRS).

GTRS is equivalent to International Terrestrial Reference System (ITRS).

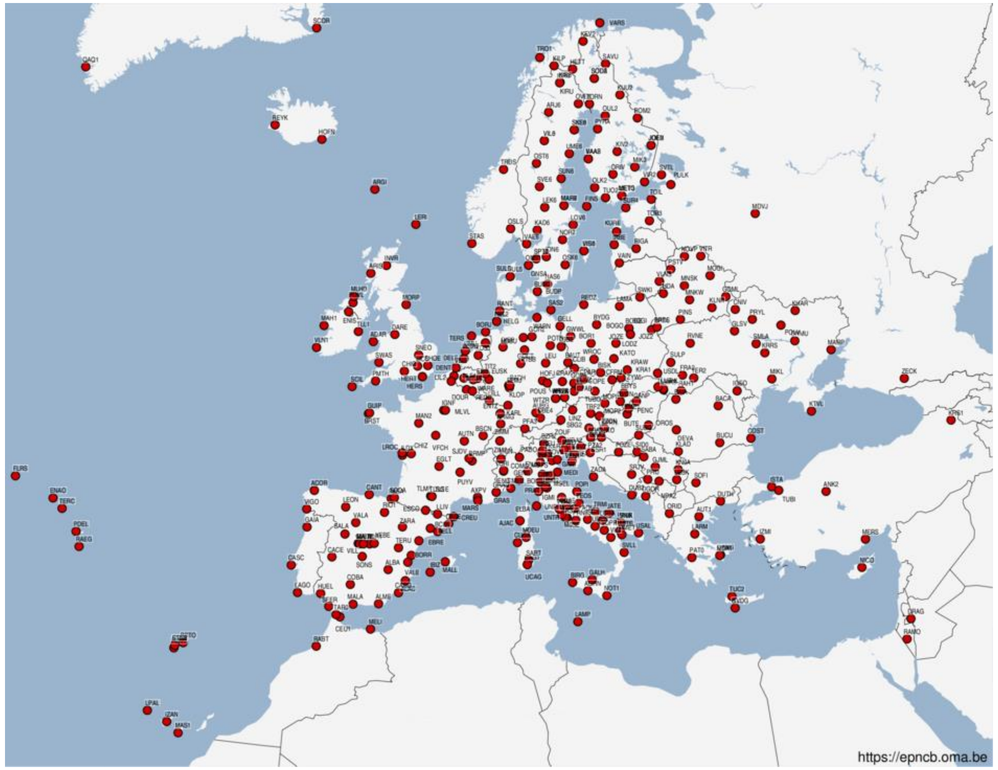
GTRS = ITRS

Reference frame transformations

ITRS ↷ ETRS89DK

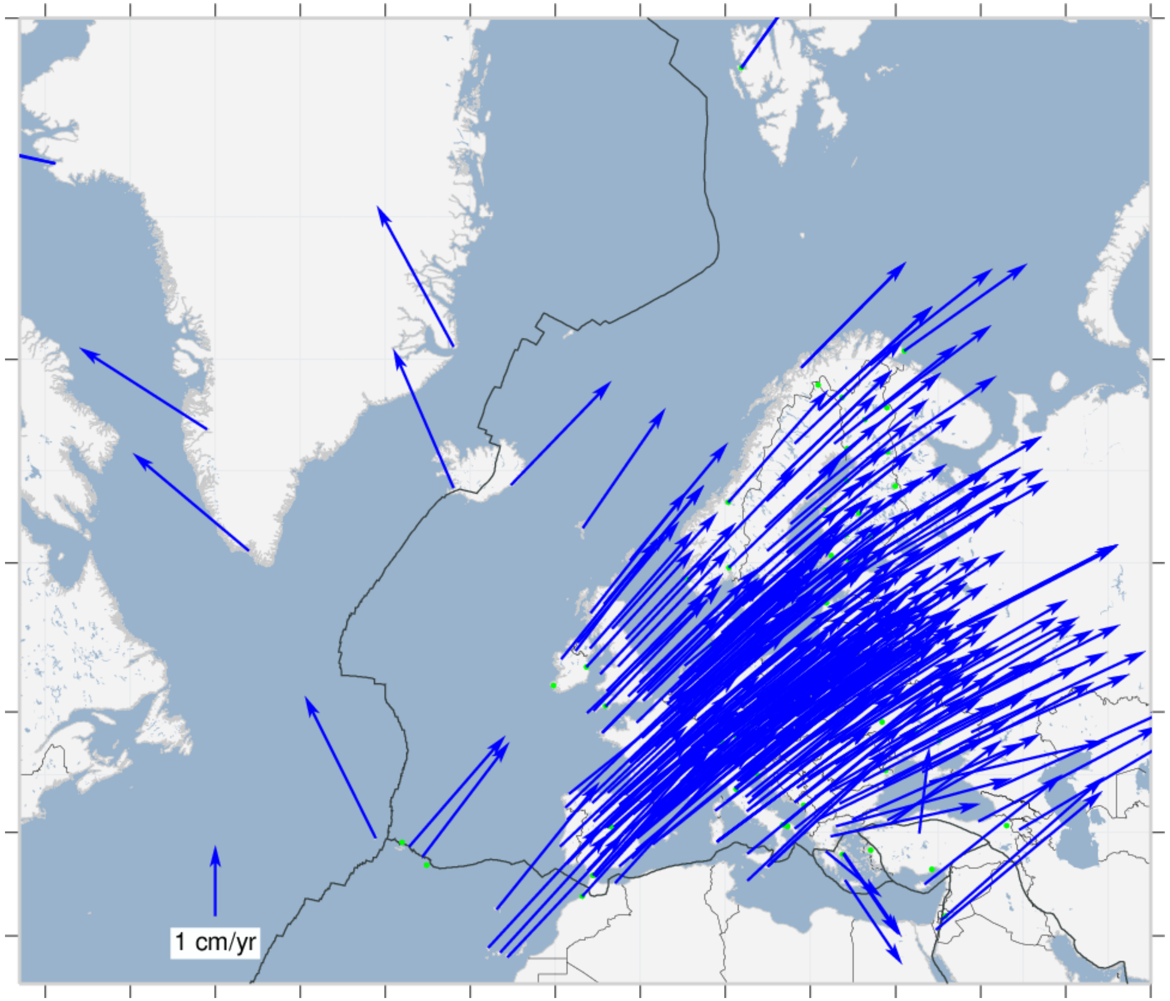


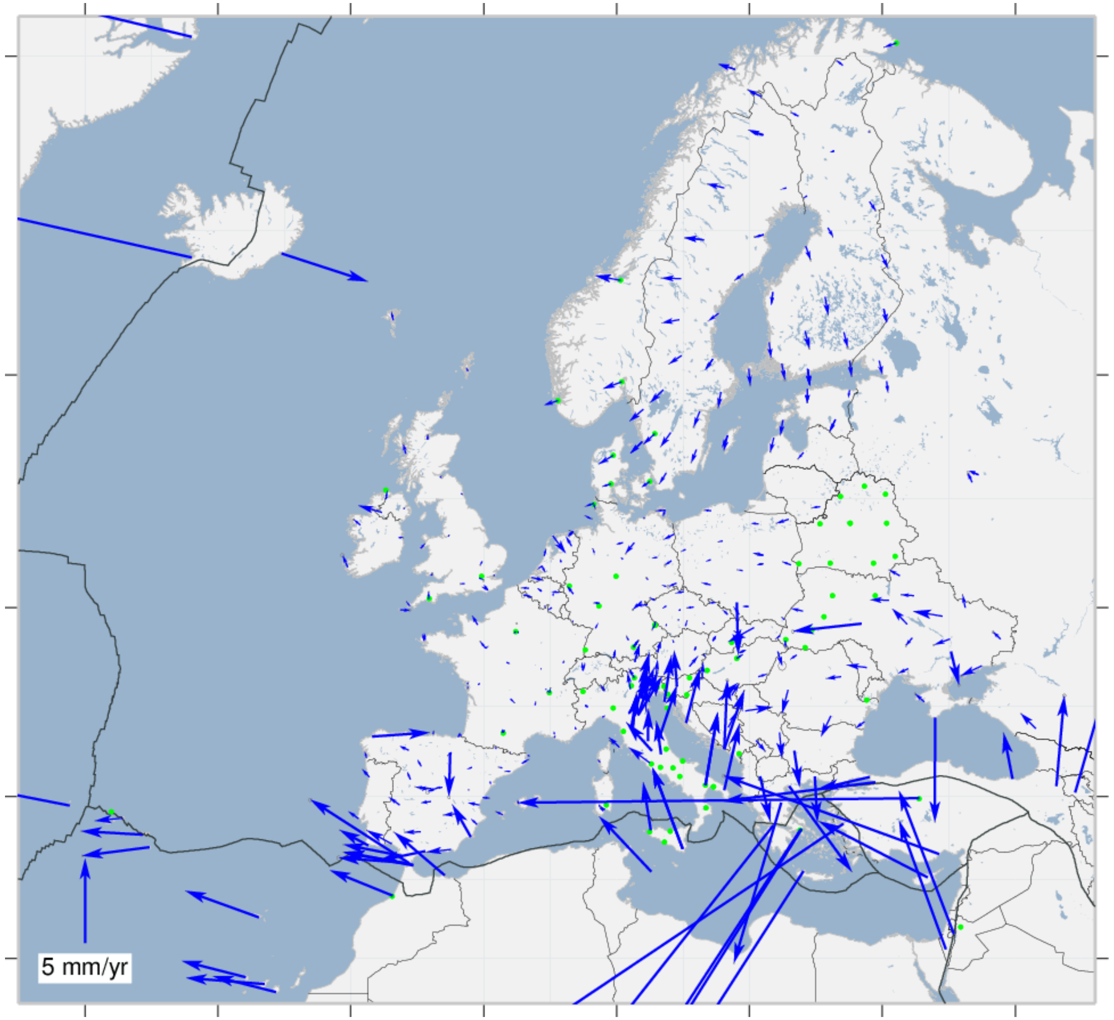
ITRS stations - https://itrf.ign.fr/en/homepage



EUREF Permanent GNSS Network: https://www.epncb.oma.be/index.php

Intraplate motion





https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016JB013098

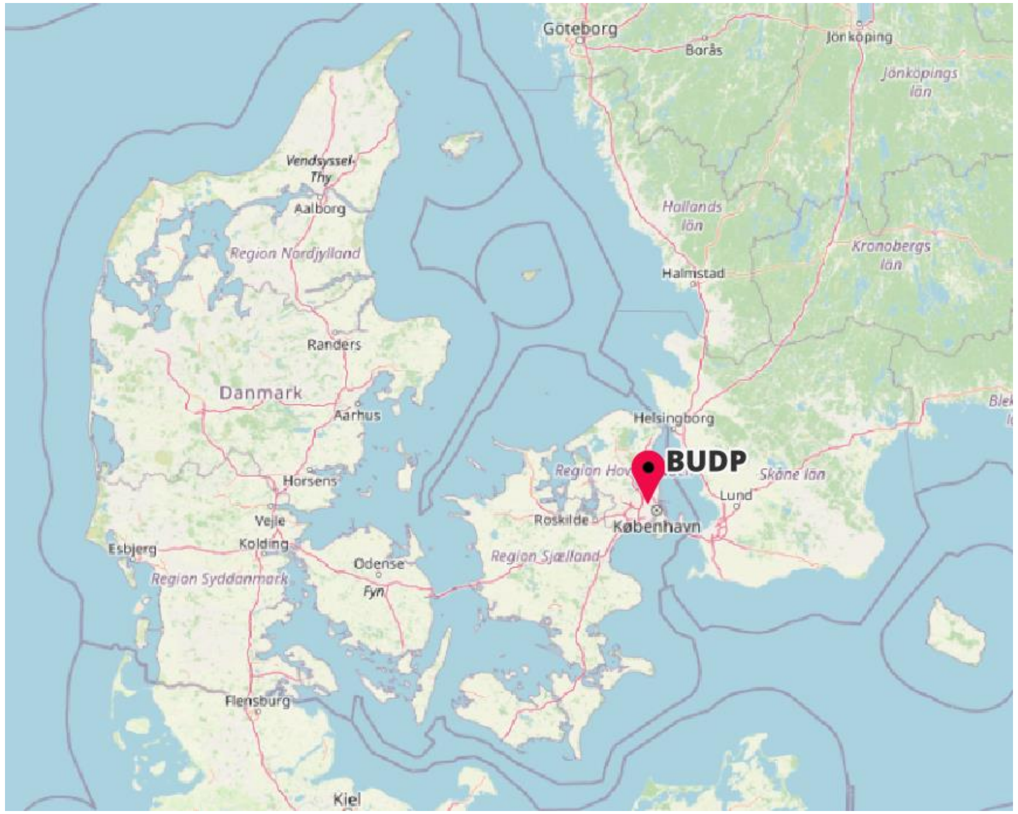
http://www.epncb.oma.be/_productsservices/coordinates/posvel_map.php

Example: Change in position of a Danish reference station

The two reference systems are not equivalent, and have a position bias of approximately 70 cm.

Positions between ITRS and ETRS89DK diverge at a speed of ~2.5 cm per year.

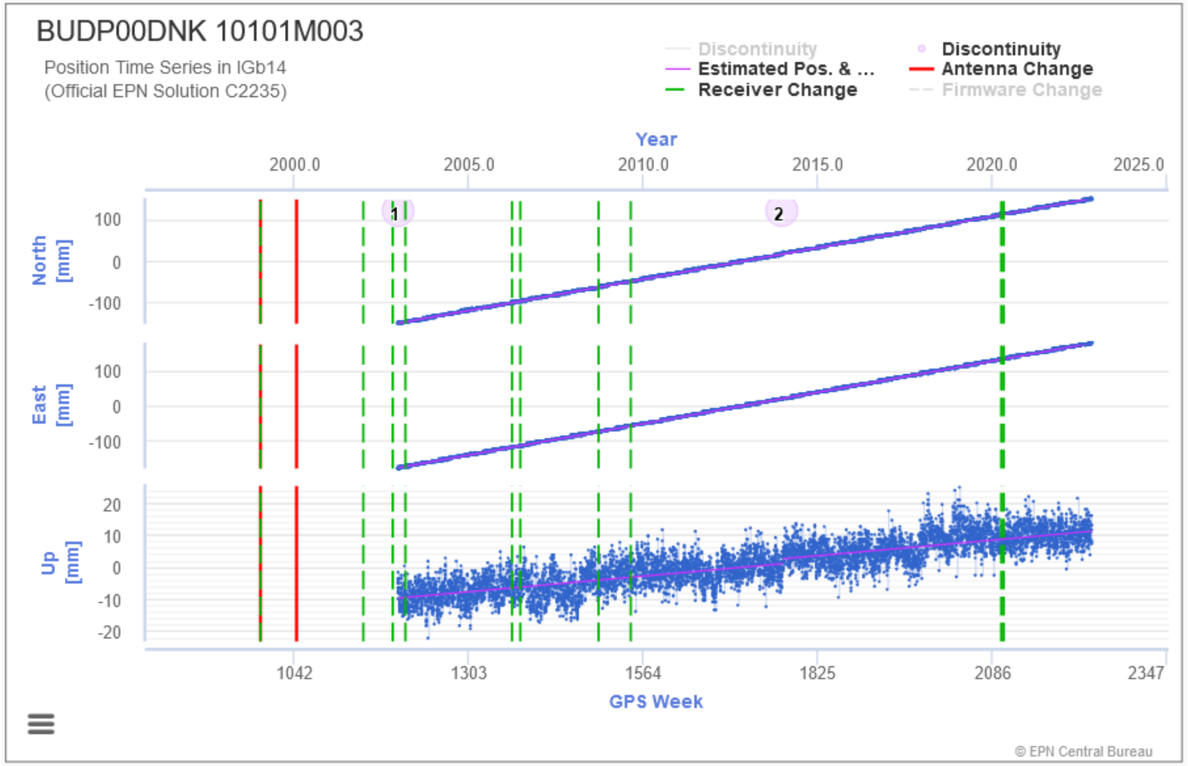
Example: Change in positioning of a continuously operating reference station **BUDP** in Copenhagen.



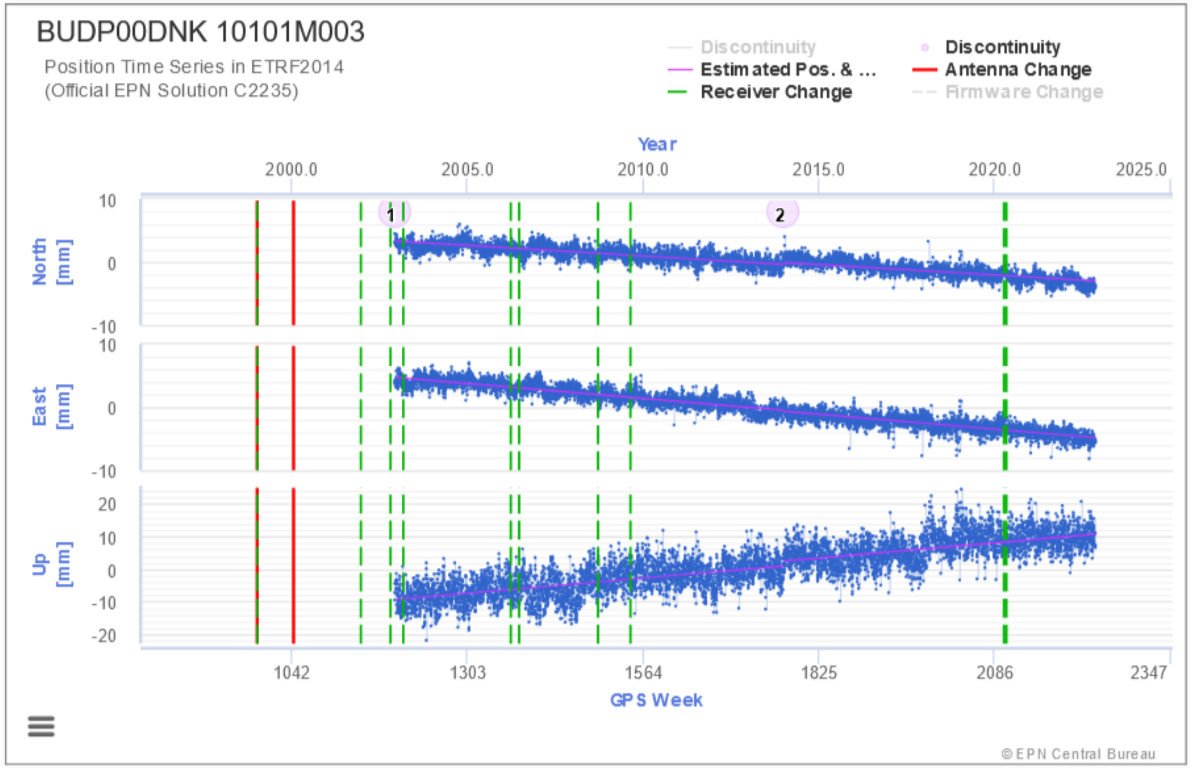
ITRS vs ETRS89DK

Multi-year Position Time Series of Buddinge reference station in Copenhagen – comparison in 2 datums:

- ITRS



- ETRS89



http://www.epncb.oma.be/_productsservices/timeseries/index.php?station=BUDP00DNK&type=ETRS89

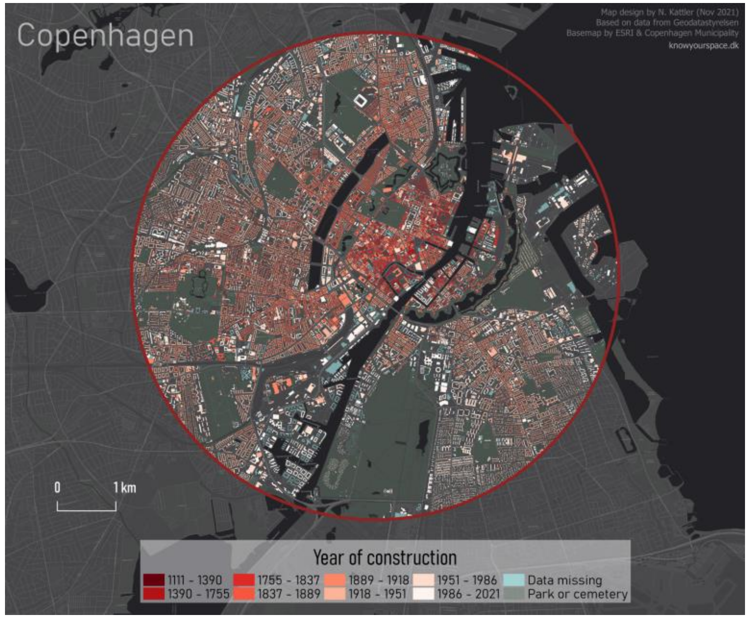
DANGO Transformations from ITRS to ETRS89DK

- DANGO provides 7 parameters.
- One direct transformation from ITRS to ETRS89DK.
- Parameters can be simply applied using the Helmert transformation formula:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{2015.829}^{ETRF92} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{2024.192}^{ITRFyy} + \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} + D \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{2024.192}^{ITRFyy} + \begin{bmatrix} 0 & -R_3 & R_2 \\ R_3 & 0 & -R_1 \\ -R_2 & R_1 & 0 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{2024.192}^{ITRFyy}$$

DANGO Applications

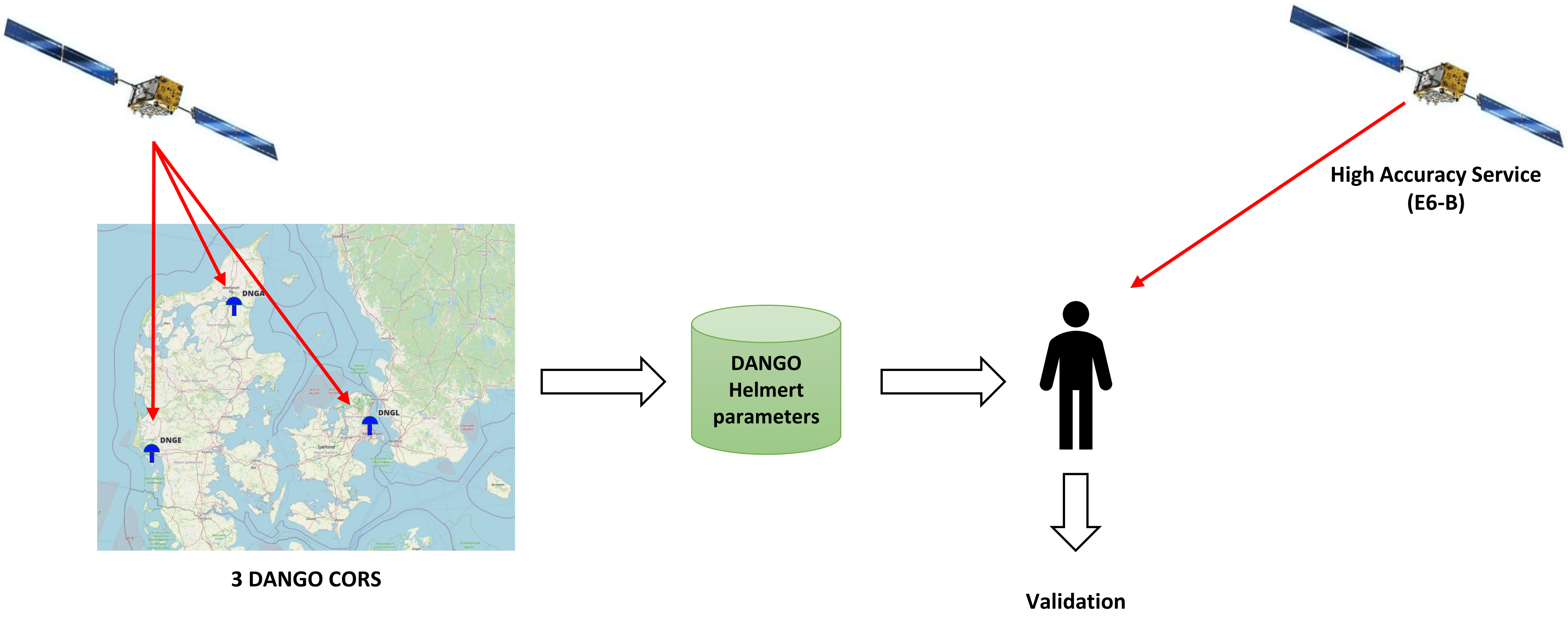
- ➢ Why do we want to correct the decimeter-level difference?



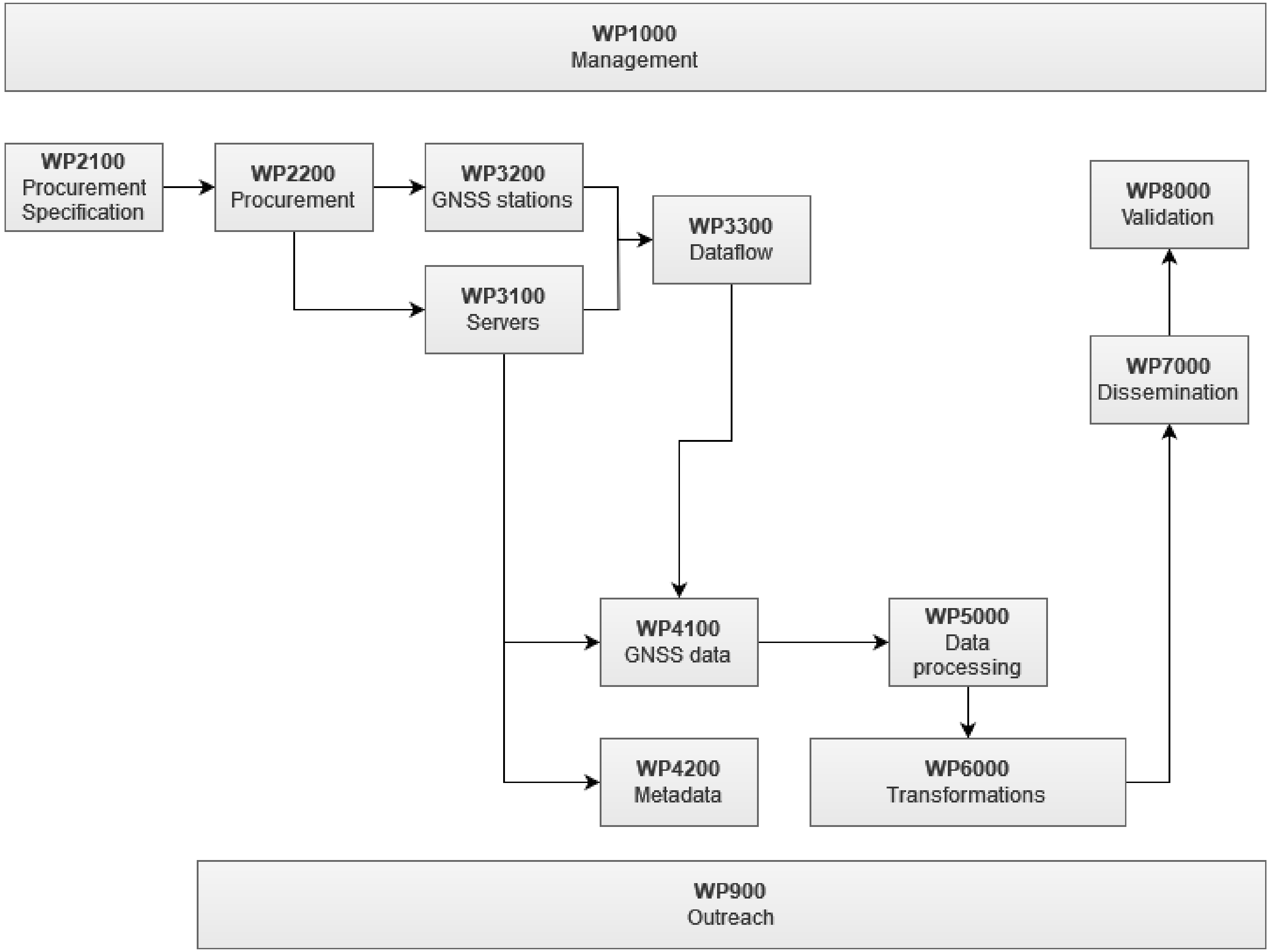
https://www.space.dtu.dk/english/research-divisions/geomagnetism-and-geospace/research-areas/autonomous-infrastructure
http://www.epncb.oma.be/_networkdata/siteinfo4onestation.php?station=BUDD00DNK
https://knowyourspace.dk/2021/11/01/visualising-the-age-of-buildings-copenhagen-qgis/
https://geomatas.com/sistemas-g-n-s-s/

Overview of the project structure

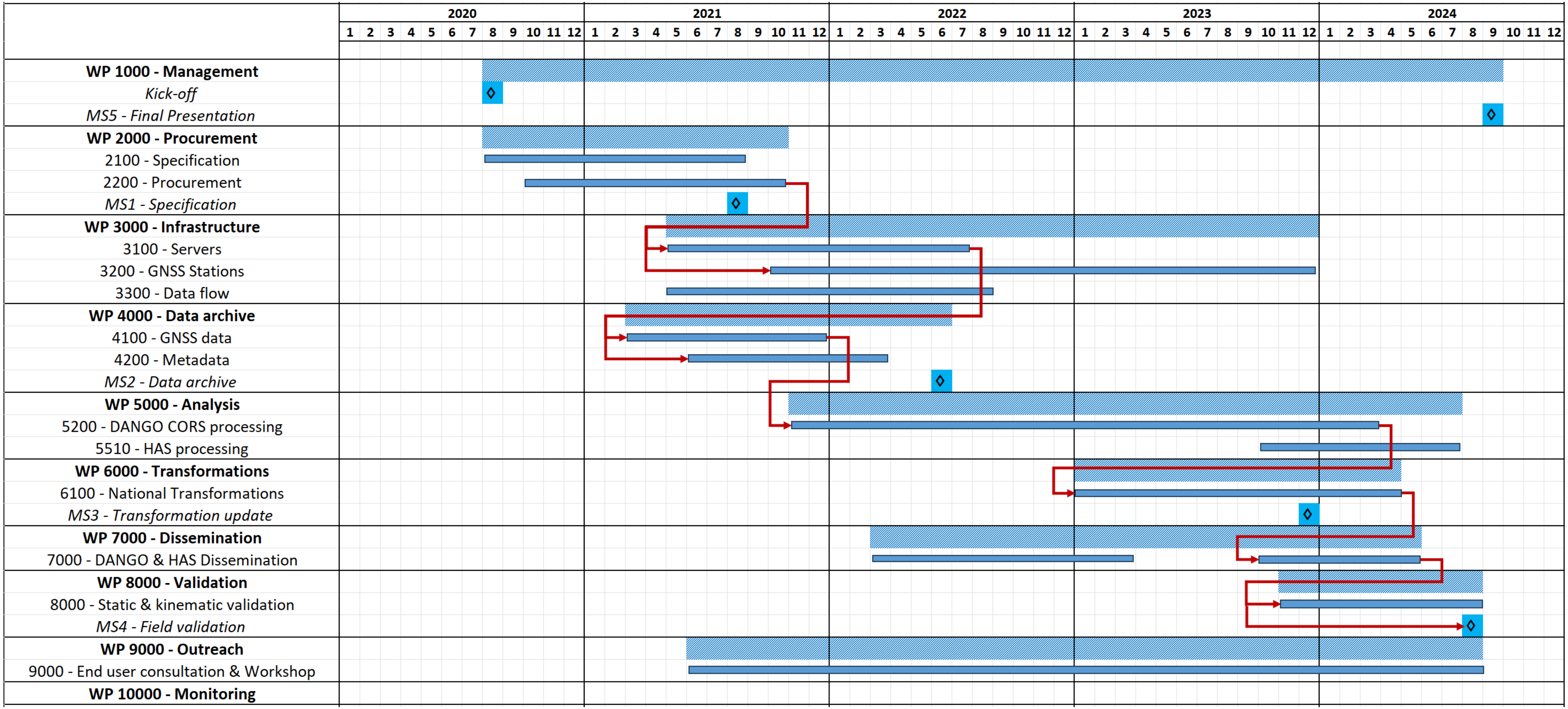
Project work logic



Project work logic



Gantt chart


2020
2021
2022
2023
2024
1 2 3 4 5 6 7 8 9 10 11 12
WP 1000 - Management
Kick-off
MS5 - Final Presentation
WP 2000 - Procurement
2100 - Specification
2200 - Procurement
MS1 - Specification
WP 3000 - Infrastructure
3100 - Servers
3200 - GNSS Stations
3300 - Data flow
WP 4000 - Data archive
4100 - GNSS data
4200 - Metadata
MS2 - Data archive
WP 5000 - Analysis
5200 - DANGO CORS processing
5510 - HAS processing
WP 6000 - Transformations
6100 - National Transformations
MS3 - Transformation update
WP 7000 - Dissemination
7000 - DANGO & HAS Dissemination
WP 8000 - Validation
8000 - Static & kinematic validation
MS4 - Field validation
WP 9000 - Outreach
9000 - End user consultation & Workshop
WP 10000 - Monitoring

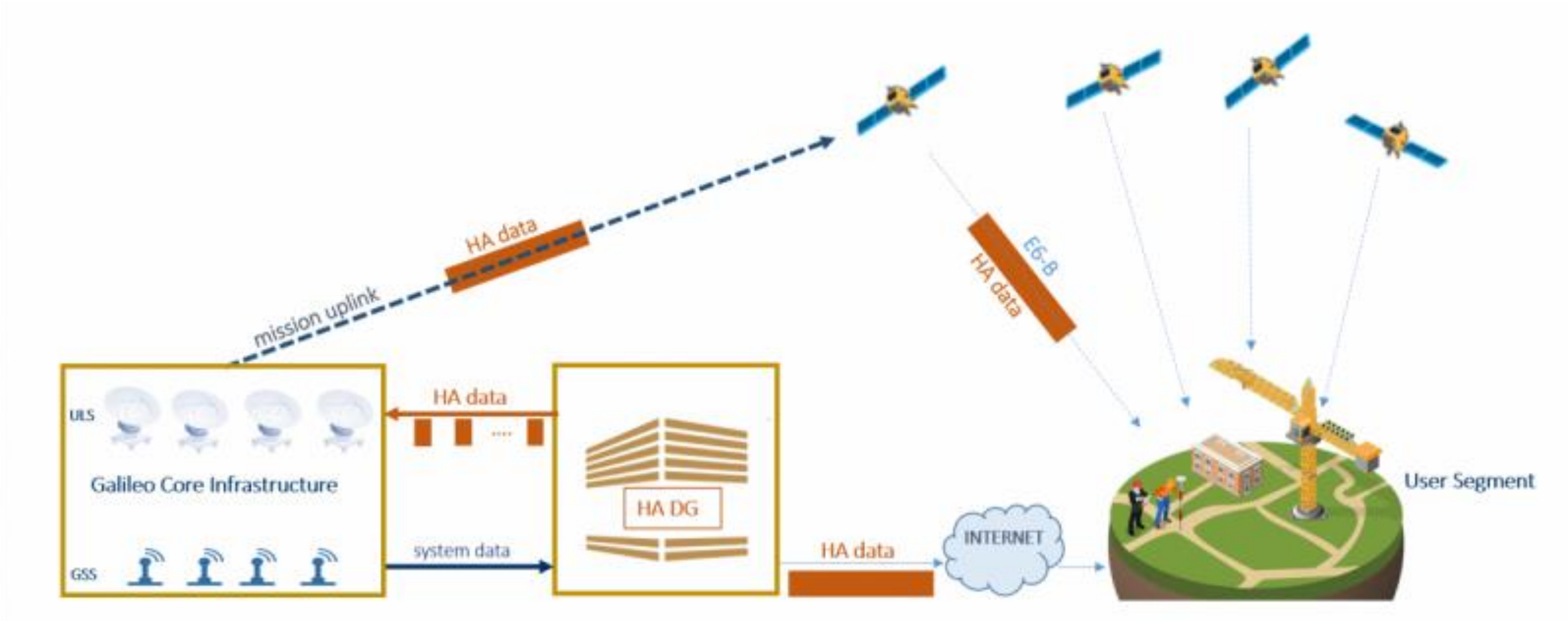
Methods

Galileo High Accuracy Service

- Free high accuracy PPP corrections (decimeter level).
- Provided through the Galileo signal E6-B (Signal-In-Space) or through terrestrial means (Internet Data Distribution).
- Galileo HAS corrections must be transformed into ETRS89DK to be used in Denmark.

	Service Level 1 (SL1)	Service Level 2 (SL2)
Coverage	Global	European Coverage Area (ECA)
Corrections	Orbit, clock, biases (code and phase)	Orbit, clock, biases (code and phase) + atmospheric corrections
Horizontal Accuracy (95%)	<20cm	<20cm
Vertical Accuracy (95%)	<40cm	<40cm
Converge Time	<300s	<100s
Availability	99%	99%
User HelpDesk	24/7	24/7

Target performances for Galileo HAS Service Level 1 (SL1) and Service Level 2 (SL2).



Galileo system elements involved in the generation, provision and exploitation of Galileo HAS.

Galileo HAS: https://www.euspa.europa.eu/european-space/galileo/services/galileo-high-accuracy-service-has

Reference frame transformations

- Conventional approach of transforming positions is:
  - 4-step chain of transformations (as used in e.g. PRØJ *).
  - Using publically available transformation parameters from EUREF.
  - Including the intraplate motion.

GTRS = ITRF2014 (2024.192) ↷ ETRF2014 (2024.192) ↷ ETRF2014 (2000.0) ↷ ETRF92 (2000.0) ↷ ETRF92 (2015.829) = ETRS89DK

- DANGO approach is:
  - One direct transformation using DANGO transformation parameters.
  - Intraplate motion not included.

GTRS = ITRF2020 (2024.192) ↷ ETRF92 (2015.829) = ETRS89DK

* PRØJ: https://proj.org/en/9.5/

Conventional approach

Method described in NKG paper and applied in PRØJ can be summarised in 4 steps:

- ITRF2014 @ t_0 ↷ ETRF2014 @ t_0

$$\begin{bmatrix}X\\Y\\Z\end{bmatrix}^{ETRF2014} = \begin{bmatrix}X\\Y\\Z\end{bmatrix}^{ITRF2014}_{t_0} + \begin{bmatrix}T_1\\T_2\\T_3\end{bmatrix} + \begin{bmatrix}0 & -\dot{R}_3 & \dot{R}_2\\ \dot{R}_3 & 0 & -\dot{R}_1\\ -\dot{R}_2 & \dot{R}_1 & 0\end{bmatrix}\begin{bmatrix}X\\Y\\Z\end{bmatrix}^{ITRF2014}_{t_0} \cdot (t_0 - 1989.0)$$

- ETRF2014 @ t_0 ↷ ETRF2014 @ 2000.0

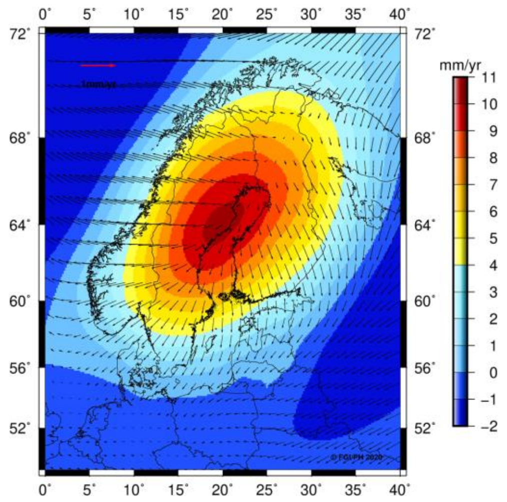
$$\begin{bmatrix}X\\Y\\Z\end{bmatrix}^{ETRF2014}_{2000.0} = \begin{bmatrix}X\\Y\\Z\end{bmatrix}^{ETRF2014}_{t_0} + (2000.0 - t_0)\cdot\begin{bmatrix}V_{X,intra}\\V_{Y,intra}\\V_{Z,intra}\end{bmatrix}^{ETRF2014}_{NKG\_RF17vel}$$

- ETRF2014 @ 2000.0 ↷ ETRF92 @ 2000.0

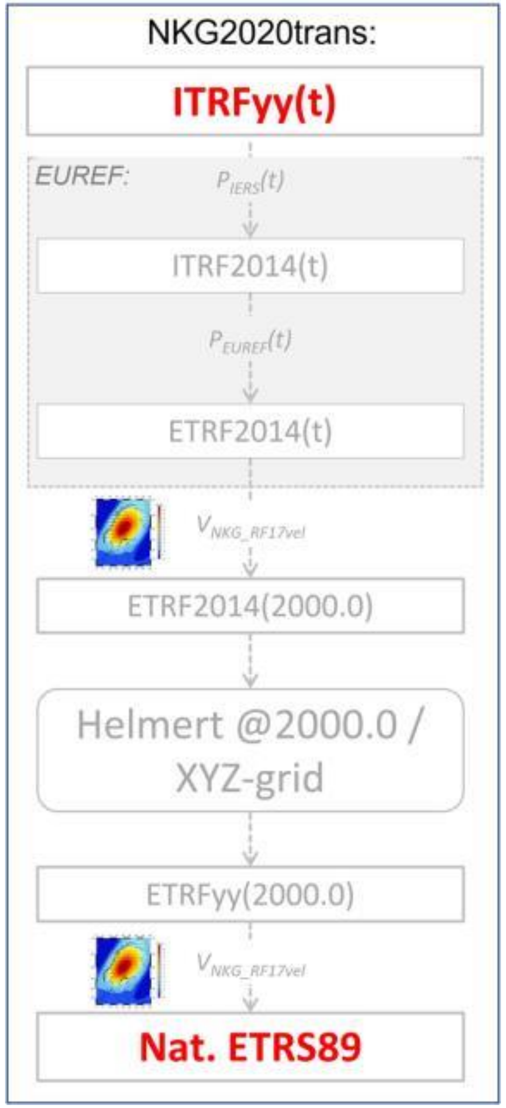
$$\begin{bmatrix}X\\Y\\Z\end{bmatrix}^{ETRF92}_{2000.0} = \begin{bmatrix}X\\Y\\Z\end{bmatrix}^{ETRF2014}_{2000.0} + \begin{bmatrix}T_1\\T_2\\T_3\end{bmatrix} + D\cdot\begin{bmatrix}X\\Y\\Z\end{bmatrix}^{ETRF2014}_{2000.0} + \begin{bmatrix}0 & -R_3 & R_2\\ R_3 & 0 & -R_1\\ -R_2 & R_1 & 0\end{bmatrix}\begin{bmatrix}X\\Y\\Z\end{bmatrix}^{ETRF2014}_{2000.0}$$

- ETRF92 @ 2000.0 ↷ ETRF92 @ 2015.829

$$\begin{bmatrix}X\\Y\\Z\end{bmatrix}^{ETRF92}_{t_c} = \begin{bmatrix}X\\Y\\Z\end{bmatrix}^{ETRF92}_{2000.0} + (t_c - 2000.0)\cdot\begin{bmatrix}V_{X,intra}\\V_{Y,intra}\\V_{Z,intra}\end{bmatrix}^{ETRF2014}_{NKG\_RF17vel}$$



NKG_RF17vel model intraplate velocities.



NKG2020 transformation method and the associated steps.

Source: NKG2020 transformation: An updated transformation between dynamic and static reference frames in the Nordic and Baltic countries. https://doi.org/10.1515/jogs-2022-0155

Transformation parameters

- Example transformation parameters from EUREF Technical Note:

Table 3: Transformation parameters from ITRF_{yy} to ETRF2014 **at epoch 2015.0** and their rates/year

ITRF Solution	T1 mm	T2 mm	T3 mm	D 10^{-9}	R1 mas	R2 mas	R3 mas
ITRF2020	-1.4	-0.9	1.4	-0.42	2.210	13.806	-20.020
rates	0.0	-0.1	0.2	0.00	0.085	0.531	-0.770
ITRF2014	0.0	0.0	0.0	0.00	2.210	13.806	-20.020
rates	0.0	0.0	0.0	0.00	0.085	0.531	-0.770
ITRF2008	-1.6	-1.9	-1.9	-0.13	2.210	13.806	-20.020
rates	0.0	0.0	0.1	-0.03	0.085	0.531	-0.770
ITRF2005	-4.1	-1.0	2.8	-1.07	2.210	13.806	-20.020
rates	-0.3	0.0	0.1	-0.03	0.085	0.531	-0.770
ITRF2000	-1.2	-1.7	35.6	-2.67	2.210	13.806	-20.020
rates	-0.1	-0.1	1.9	-0.11	0.085	0.531	-0.770
ITRF97	-7.9	3.0	79.3	-4.40	2.210	13.806	-20.380
rates	-0.1	0.5	3.3	-0.12	0.085	0.531	-0.790
ITRF96	-7.9	3.0	79.3	-4.40	2.210	13.806	-20.380
rates	-0.1	0.5	3.3	-0.12	0.085	0.531	-0.790
ITRF94	-7.9	3.0	79.3	-4.40	2.210	13.806	-20.380
rates	-0.1	0.5	3.3	-0.12	0.085	0.531	-0.790
ITRF93	64.4	-2.8	72.7	-4.89	5.570	18.136	-20.770
rates	2.8	0.1	2.5	-0.12	0.195	0.721	-0.840
ITRF92	-15.9	1.0	87.3	-3.69	2.210	13.806	-20.380
rates	-0.1	0.5	3.3	-0.12	0.085	0.531	-0.790
ITRF91	-27.9	-13.0	93.3	-5.09	2.210	13.806	-20.380
rates	-0.1	0.5	3.3	-0.12	0.085	0.531	-0.790
ITRF90	-25.9	-9.0	109.3	-5.39	2.210	13.806	-20.380
rates	-0.1	0.5	3.3	-0.12	0.085	0.531	-0.790
ITRF89	-30.9	-33.0	147.3	-8.79	2.210	13.806	-20.380
rates	-0.1	0.5	3.3	-0.12	0.085	0.531	-0.790

Altamimi et al. 2024, EUREF Technical Note 1: Relationship and Transformation between the International and the European Terrestrial Reference Systems. http://etrs89.ensg.ign.fr/pub/EUREF-TN-1-Mar-04-2024.pdf

DANGO Transformations from ITRS to ETRS89DK

- DANGO provides 7 parameters.
- One direct transformation from ITRS to ETRS89DK.
- Parameters can be simply applied using the Helmert transformation formula:

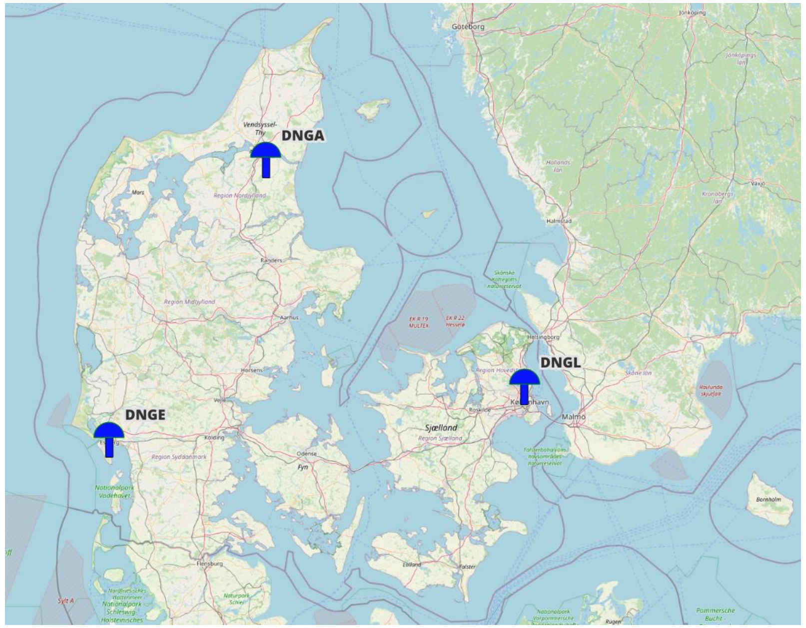
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{2015.829}^{ETRF92} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{2024.192}^{ITRFyy} + \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} + D \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{2024.192}^{ITRFyy} + \begin{bmatrix} 0 & -R_3 & R_2 \\ R_3 & 0 & -R_1 \\ -R_2 & R_1 & 0 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{2024.192}^{ITRFyy}$$

DANGO CORS

In order to obtain 7 parameters, data from at least three reference stations is required.

As part of DANGO, three permanent CORS were established in:

- Lyngby (DNGL)
- Esbjerg (DNGE)
- Aalborg (DNGA)



Equipment:

- Septentrio PolaRx5s GNSS receiver
- Leica LEIAR20 LEIM antenna

The data is accessible through the SFTP data infrastructure.

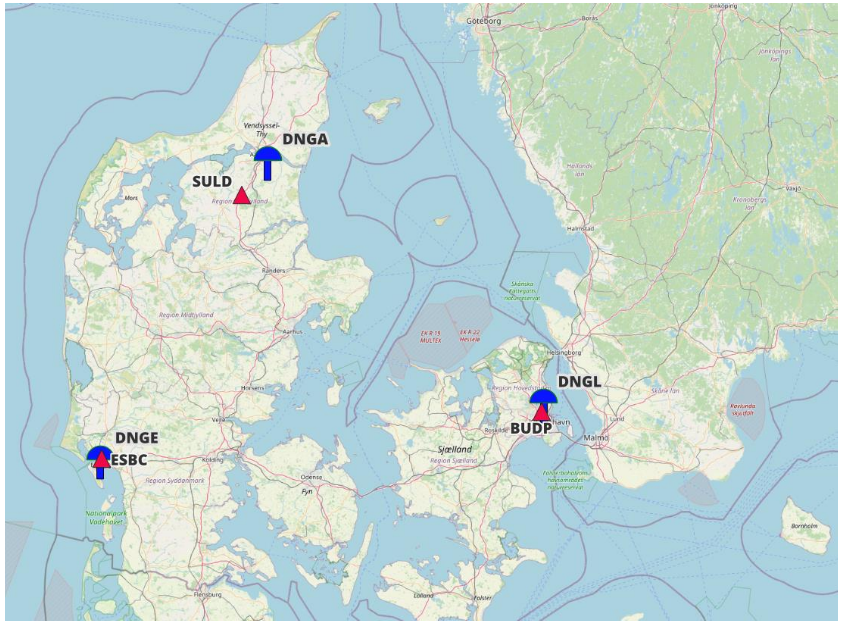
The stations will continue operating and will be maintained by the universities.

DANGO CORS positioning

- Obtaining precise positions of the 3 DANGO stations
- Positions have to be in **both ITRS and ETRS89DK**
- Method: **Post Processing Kinematic (PPK)**
  - Data from the DANGO stations
  - Data from Danish CORS with the shortest baselines.
  - Novatel Inertial Explorer
  - 24h 1Hz timeseries
  - Double-frequency mixed observation RINEX3 files.

Stations were paired as following (shortest baselines):

- DNGL + BUDP
- DNGE + ESBC
- DNGA + SULD



DANGO Transformation parameters

- 7 Helmert parameters.
- Derived using least squares adjustment*.

	ITRS -> ETRS89DK
T_x [mm]	876.599
T_y [mm]	-76.52
T_z [mm]	-626.228
D [10^{-9}]	2.197
R_x [mas]	2.878
R_y [mas]	-14.102
R_z [mas]	-20.630

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}^{ETRF92}_{2015.829} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}^{ITRFyy}_{2024.192} + \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} + D \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}^{ITRFyy}_{2024.192} + \begin{bmatrix} 0 & -R_3 & R_2 \\ R_3 & 0 & -R_1 \\ -R_2 & R_1 & 0 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}^{ITRFyy}_{2024.192}$$

* As described in: Altamimi, Z., Sillard, P., Boucher, C., (2002) ITRF2000: A new release of the International Terrestrial Reference Frame for earth science applications. https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2001JB000561

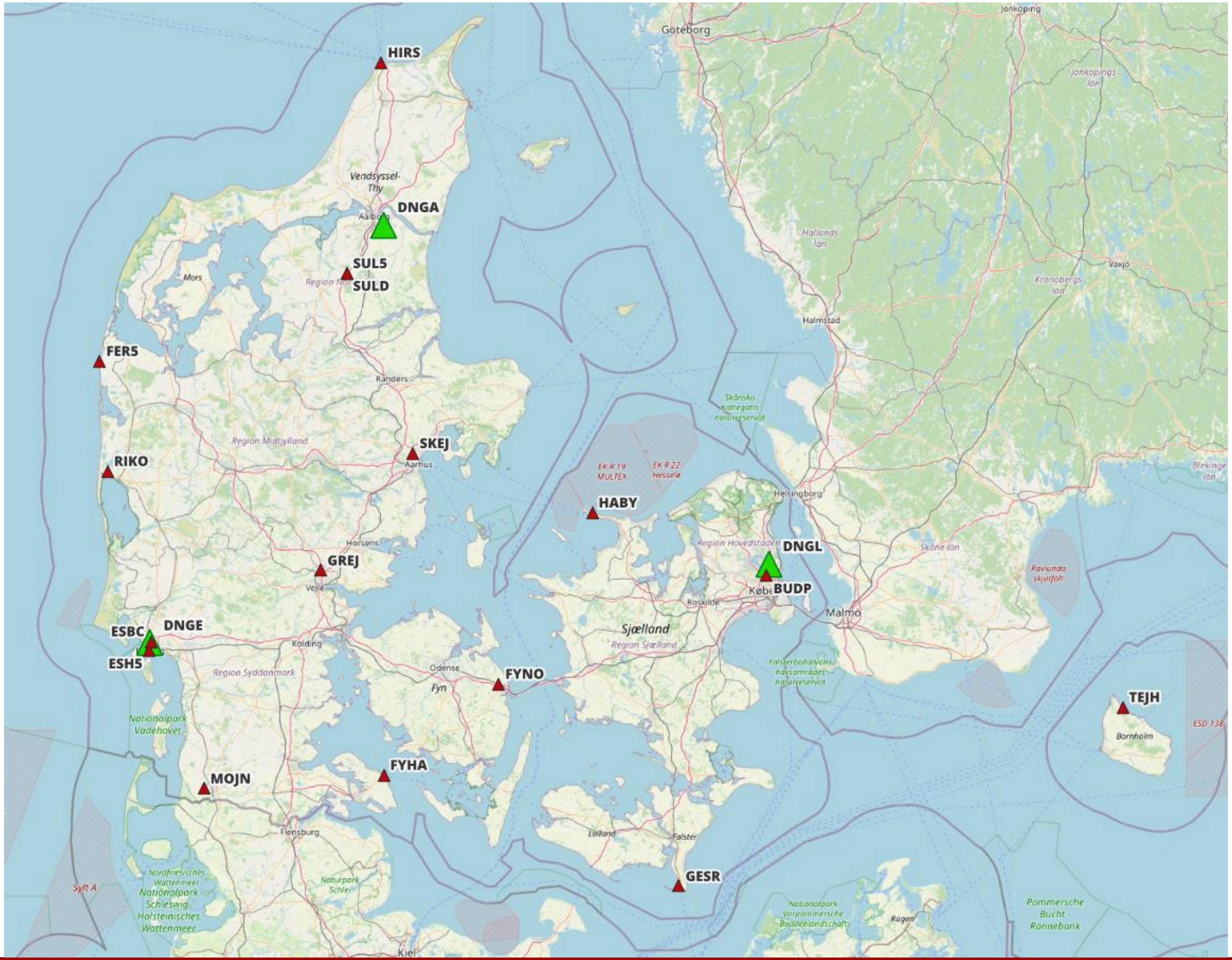
Validation of DANGO parameters

DANGO Validation

- Using known positions of the National CORS network of 16 stations.
- Using known positions of the TAPAS network.

- Evaluation is based on residuals between the known station coordinates in ETRS89DK and the coordinates transformed from ITRS into ETRS89DK.

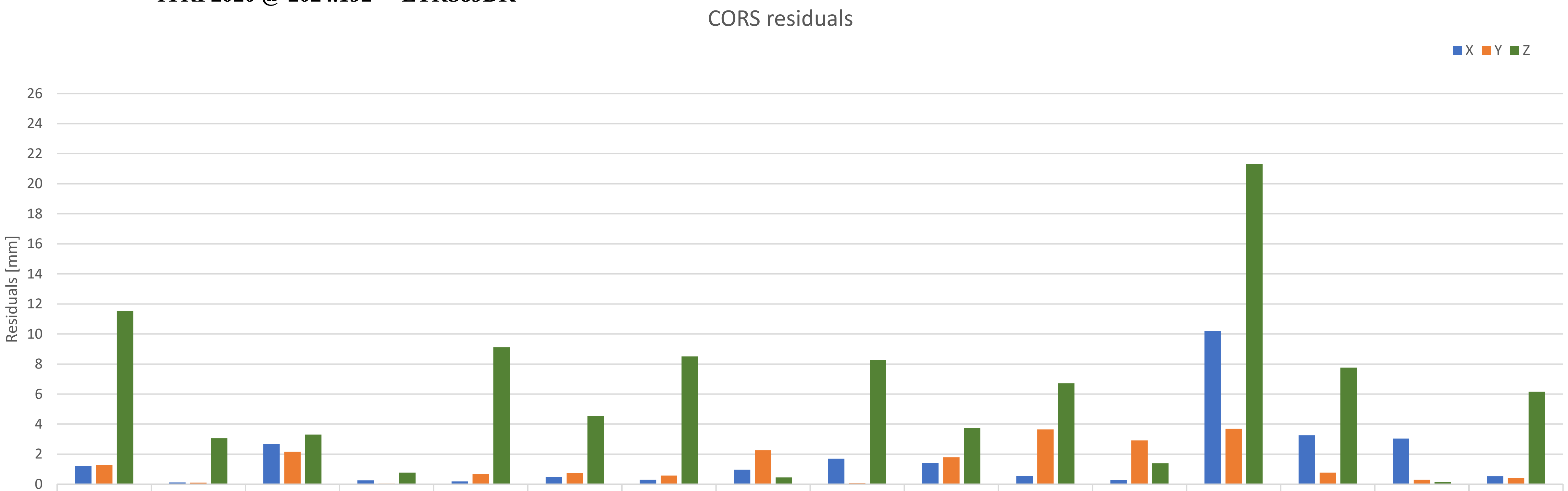
Danish National CORS and DANGO CORS



Validation using Danish National CORS

➢Based on known coordinates of 16 Danish National CORS in **ITRS** and **ETRS89DK**.

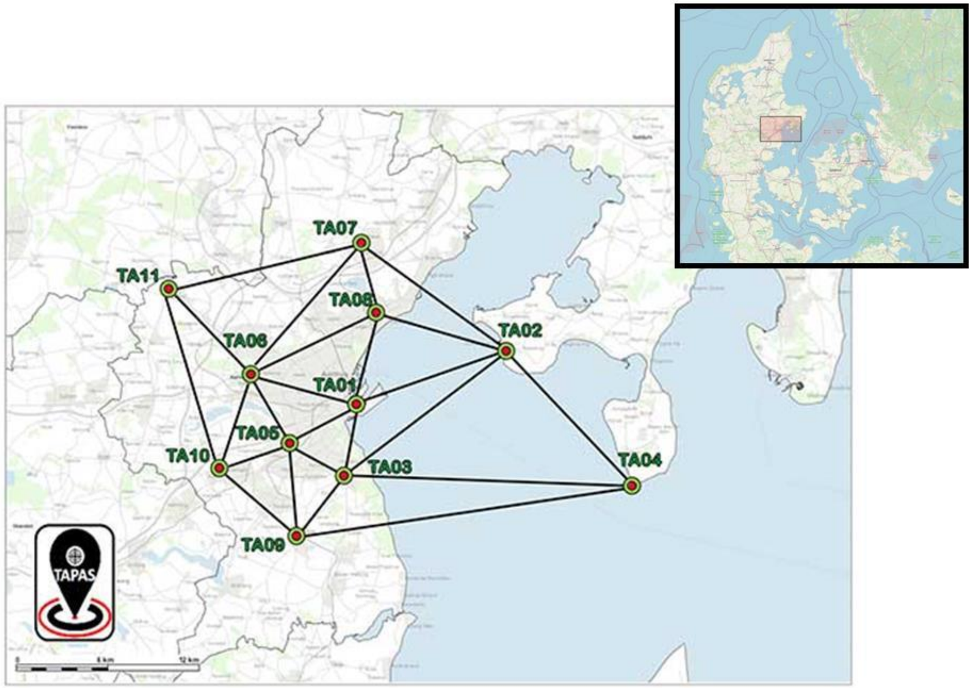
ITRF2020 @ 2024.192 ↷ ETRS89DK

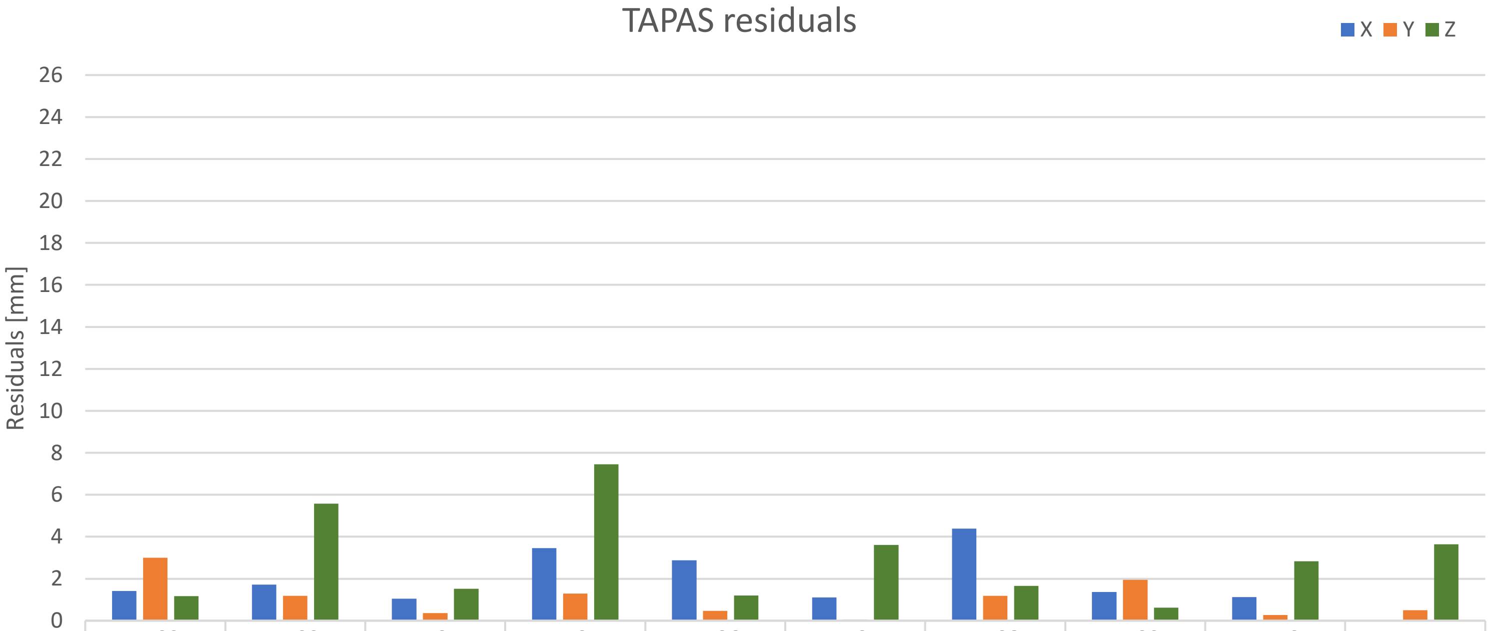


	ESH5	BUDP	SULD	ESBC	RIKO	GREJ	MOJN	SKEJ	SUL5	FYNO	FER5	FYHA	GESR	HABY	TEJH	HIRS
X	1.209459	0.11854	2.668621	0.25687	0.184975	0.488137	0.292602	0.95542	1.690926	1.420272	0.5443	0.266502	10.203477	3.251362	3.04291	0.533456
Y	1.281124	0.096395	2.169408	0.043461	0.673077	0.757574	0.578476	2.263319	0.059928	1.794865	3.640175	2.915101	3.681506	0.768893	0.298649	0.422494
Z	11.538843	3.047576	3.306017	0.769539	9.117797	4.536989	8.50261	0.441005	8.281027	3.72739	6.719286	1.387081	21.31044	7.759191	0.137932	6.145279

Validation using TAPAS stations

- TAPAS positions in ETRS89DK were given at an epoch 2020.19.
- Transformations use ETRF92@2015.829

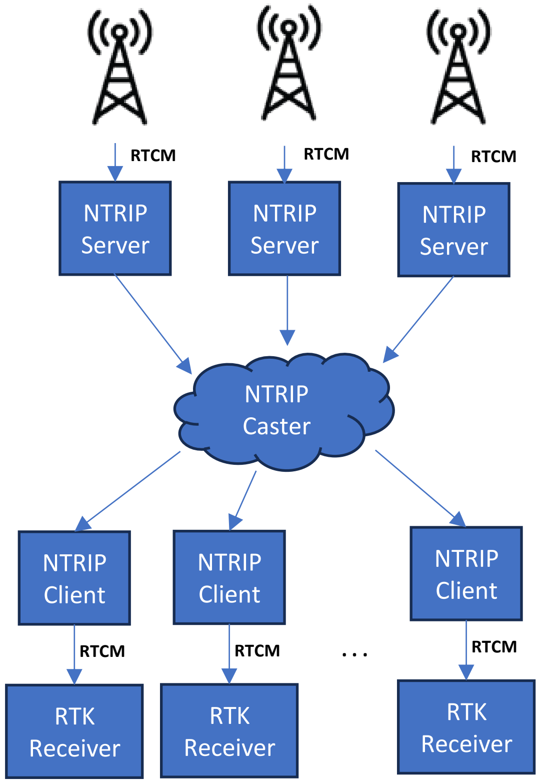




	TA02	TA03	TA04	TA05	TA06	TA07	TA08	TA09	TA10	TA11
X	1.408215	1.726998	1.051675	3.463187	2.884177	1.102661	4.391517	1.364594	1.1176	0.031467
Y	2.998806	1.181542	0.366826	1.292856	0.463798	0.064552	1.190466	1.949878	0.276823	0.498382
Z	1.170633	5.579798	1.518031	7.451673	1.196953	3.606479	1.660987	0.625469	2.826485	3.634648

Result dissemination

Data dissemination - Utilizing NTRIP with RTCM



Originally, open standards like NTRIP and RTCM were planned to be used for dissemination of the Helmert transformation parameters.

The following RTCM were chosen:

- 1021 – Helmert Transformation Parameters
- 1023 – Residuals, Ellipsoidal Grid Representation

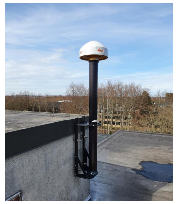
However, these are not found in actual use and they are not implemented for receivers.

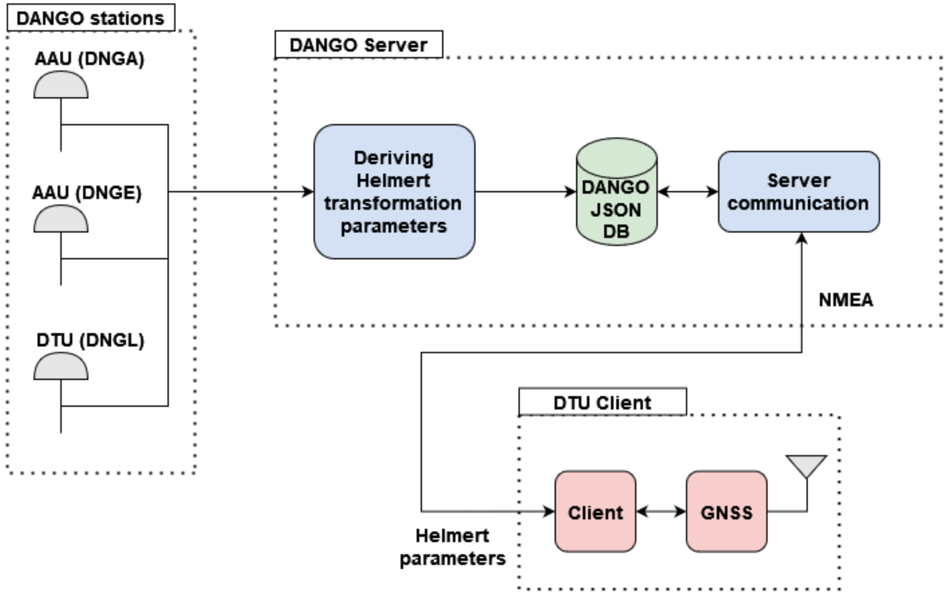
- Could implement RTCM encoder/decoder as replacement,

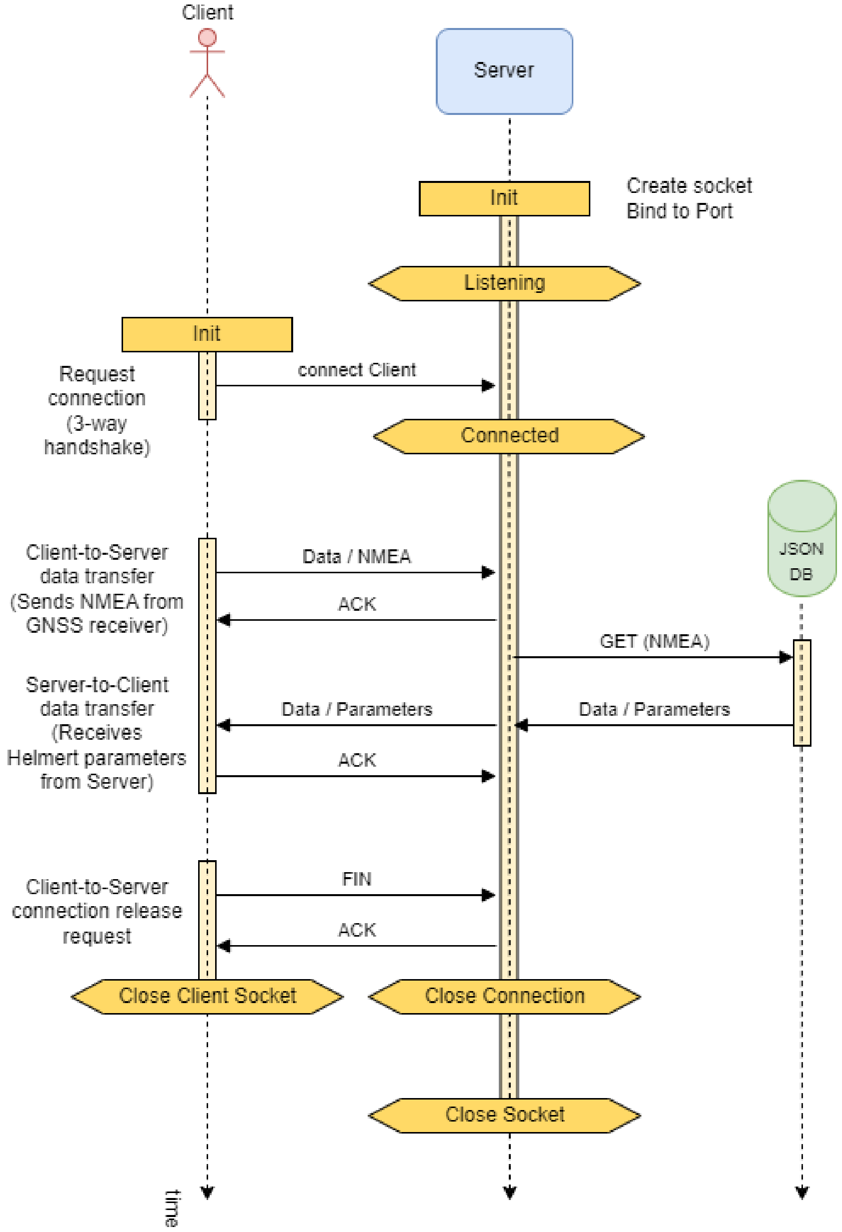
but this was outside of the scope of DANGO.

DANGO dissemination

- TCP/IP Client-Server structure.
- 7 Helmert parameters saved in a JSON file.
- JSON stored on the Server side.
- Client requests the parameters from the Server.
- Client can use the parameters to carry out transformations in real-time.







Demo example – TCP/IP System

Client

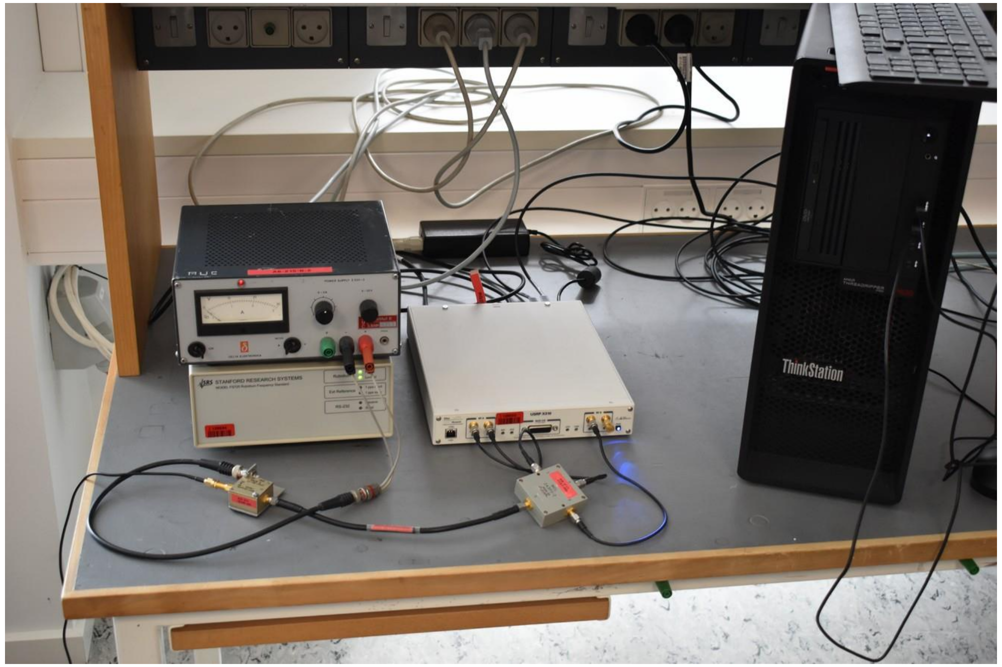
Server

HAS signals and DANGO

Utilizing the HAS signals with DANGO

- HAS messages were extracted using Software Defined Receiver (SDR) data stream.

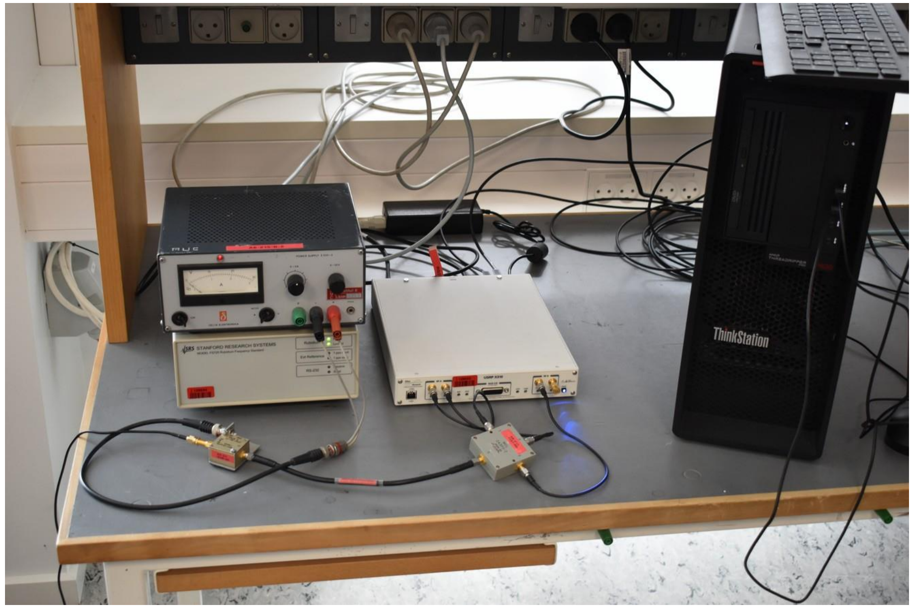
- HAS was utilized with the new HAS-capable GNSS receiver: EOS Arrow Gold+



System for capturing data stream with SDR

Hardware:

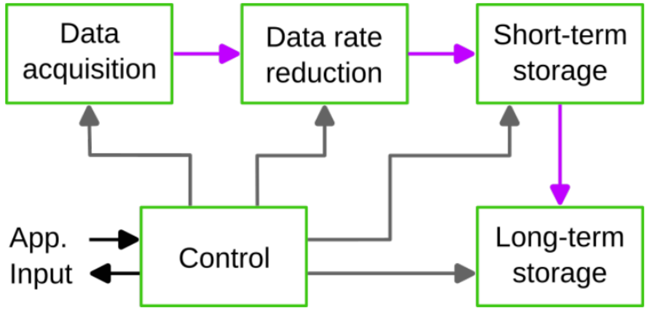
- Ettus Research X310 Software-Defined Radio (SDR)
  - Receives GNSS signals via antenna
  - Performs down-conversion from RF frequency range to baseband
  - Samples the baseband signal, I/Q data
  - Transfers data to host computer.



Hardware setup

Software for capture and storage consists of modules:

- Data acquisition
- Data rate reduction
- Short-term storage (FIFO)
- Long-term storage
- Control



Module structure

HAS message decoding

Status of the HAS decoding:

- Installed, configured, tested on the SDR platform.
- HAS messages successfully extracted.

Next steps:

- Output HAS messages as RTCM messages.
- Use SDR platform for channel sounding/sensing.

In-situ tests with EOS Arrow Gold+

Various tests were carried out with the EOS Arrow Gold+ GNSS receiver to test its performance.

Comparison of performance in different conditions:

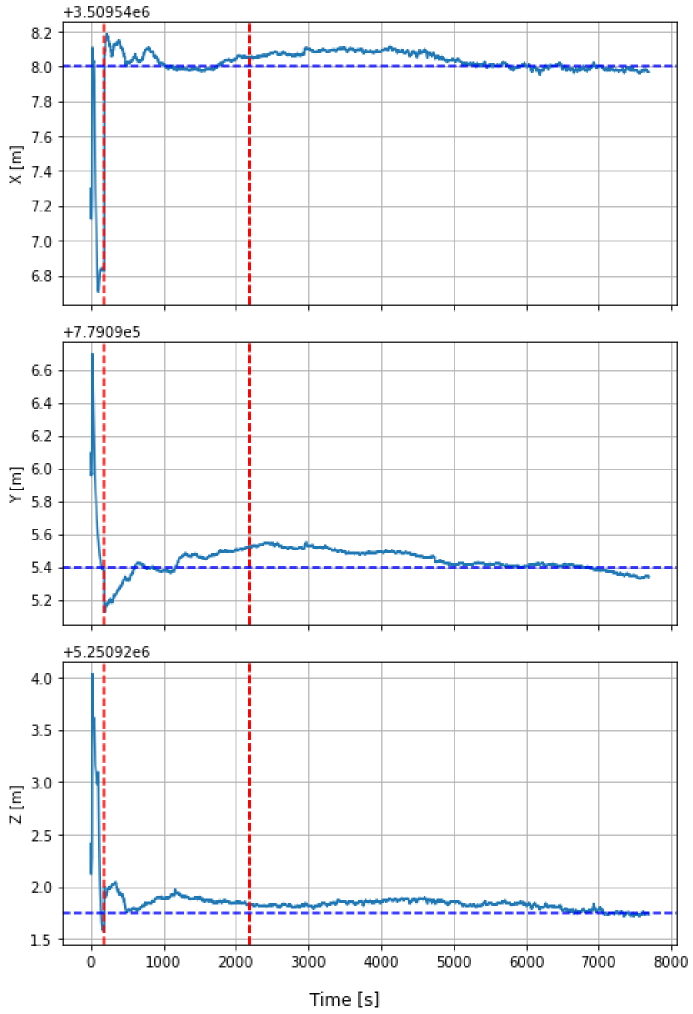
- A - Rooftop LEIAR20 LEIM antenna (ideal conditions)
- B - Urban conditions (EOS antenna)
- C - Semi-urban conditions (EOS antenna)
- D - Kinematic test (EOS antenna)

Aerial image of DTU and locations of 4 in-situ tests.

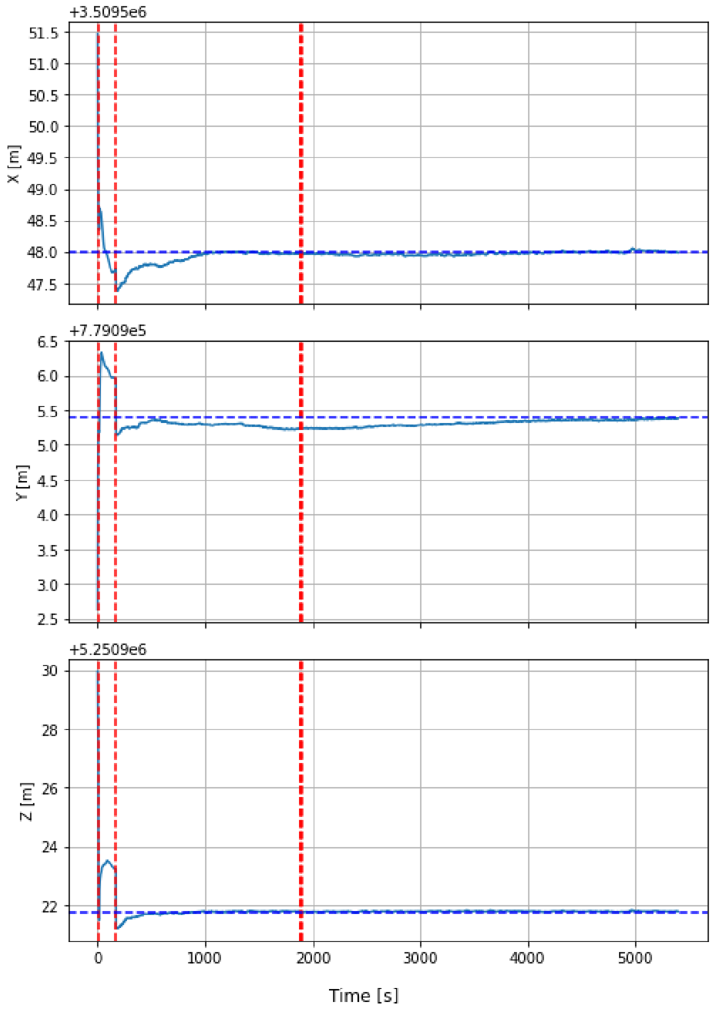
Rooftop tests

- Location A (Building 348, same location as DNGL)
- Connected Arrow to the DNGL antenna with a splitter.
- Unobstructed view of the sky from high location with no obstacles.
- 3 tests were carried out during different times of day.
- Since the precise position of DNGL is known, it can be used to verify accuracy of the static tests with Arrow.

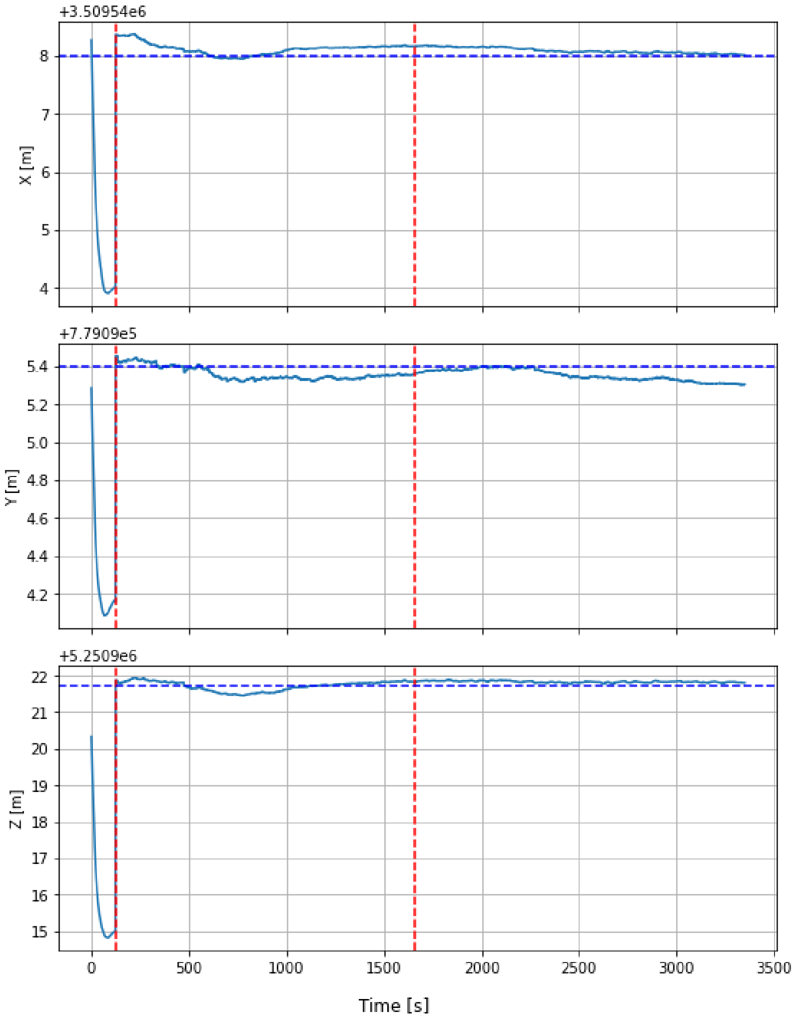
Rooftop tests



GALHAS FIX achieved after: 36.6 minutes



GALHAS FIX achieved after: 31.67 minutes

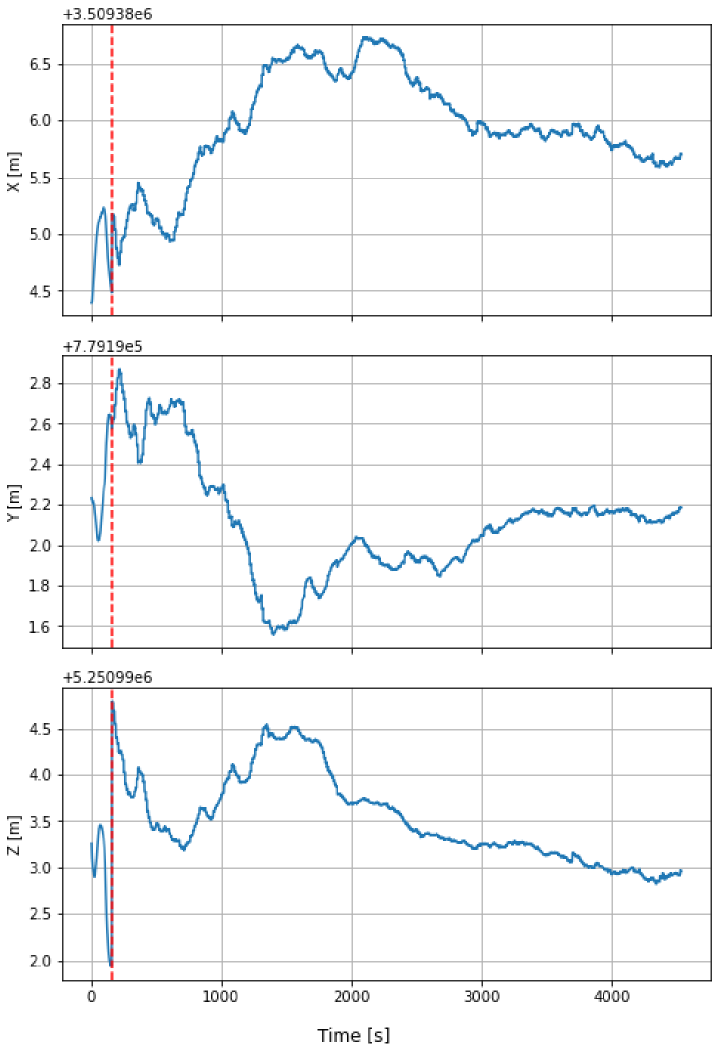


GALHAS FIX achieved after: 27.57 minutes

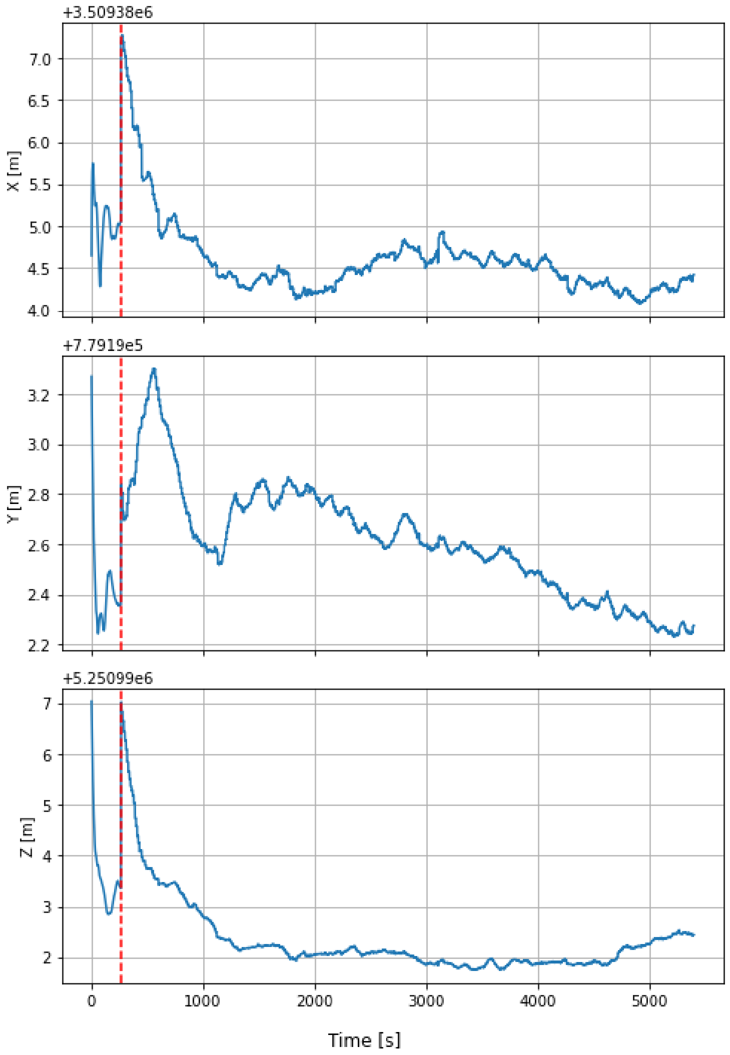
Urban conditions

- Location B (Urban location with trees and tall buildings nearby).
- Connected Arrow to the EOS antenna placed on a tripod.
- Very limited view of the sky from a ground location.
- 2 tests were carried out during different times of day.
- Tests were carried out to see if Galileo HAS Float/Fixed status can be achieved in difficult conditions.

Urban conditions



GALHAS FLT achieved after: 2.63 minutes

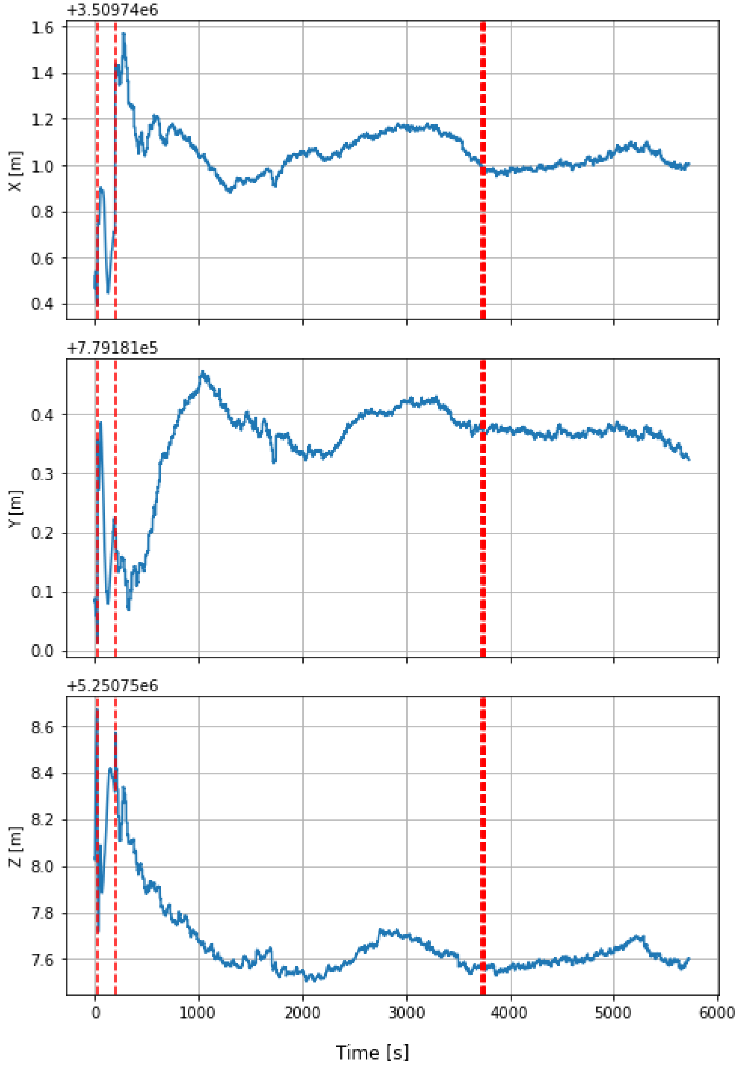


GALHAS FLT achieved after: 4.43 minutes

Semi-urban conditions

- Location C (Open field with few trees and tall buildings nearby).
- Connected Arrow to the EOS antenna placed on a tripod.
- Partial view of the sky from a ground location.
- 1 test was carried out.
- Testing possibility of Galileo HAS Float/Fixed on ground location with more ideal conditions.

Semi-urban conditions



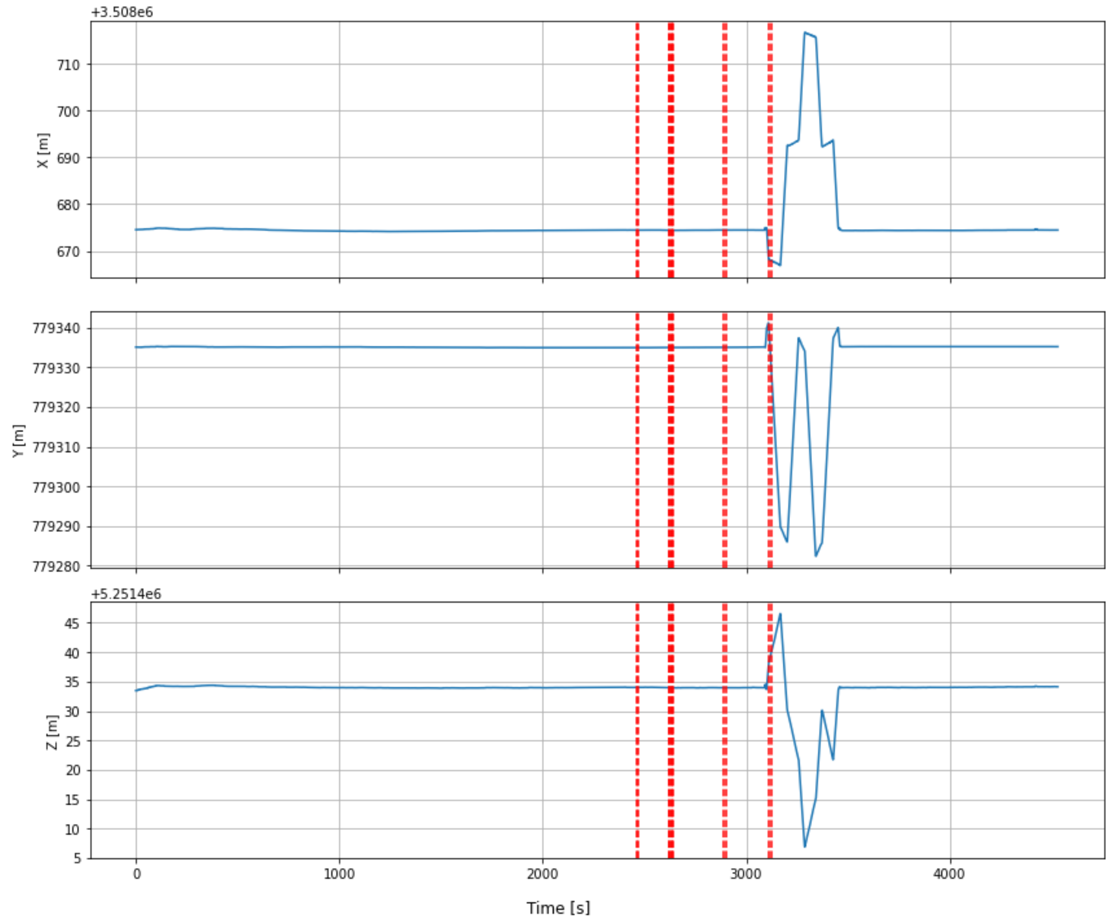
GALHAS FIX achieved after: 62.77 minutes

Kinematic test

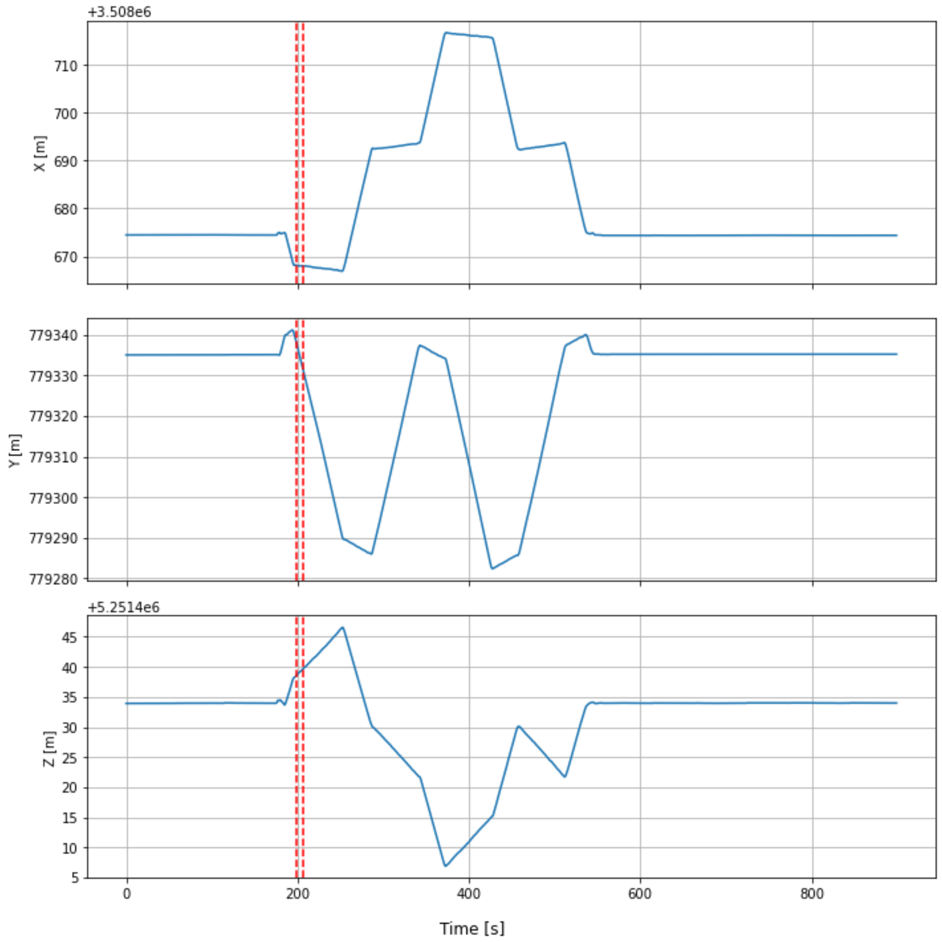
- Location D (Football field with open sky conditions).
- Connected Arrow to the EOS antenna placed on a tripod.
- Good sky view from the ground.
- 2 tests were carried out.
- Testing possibility of Galileo HAS Float/Fixed on the ground and the signal quality while performing a kinematic test.

Kinematic test 1

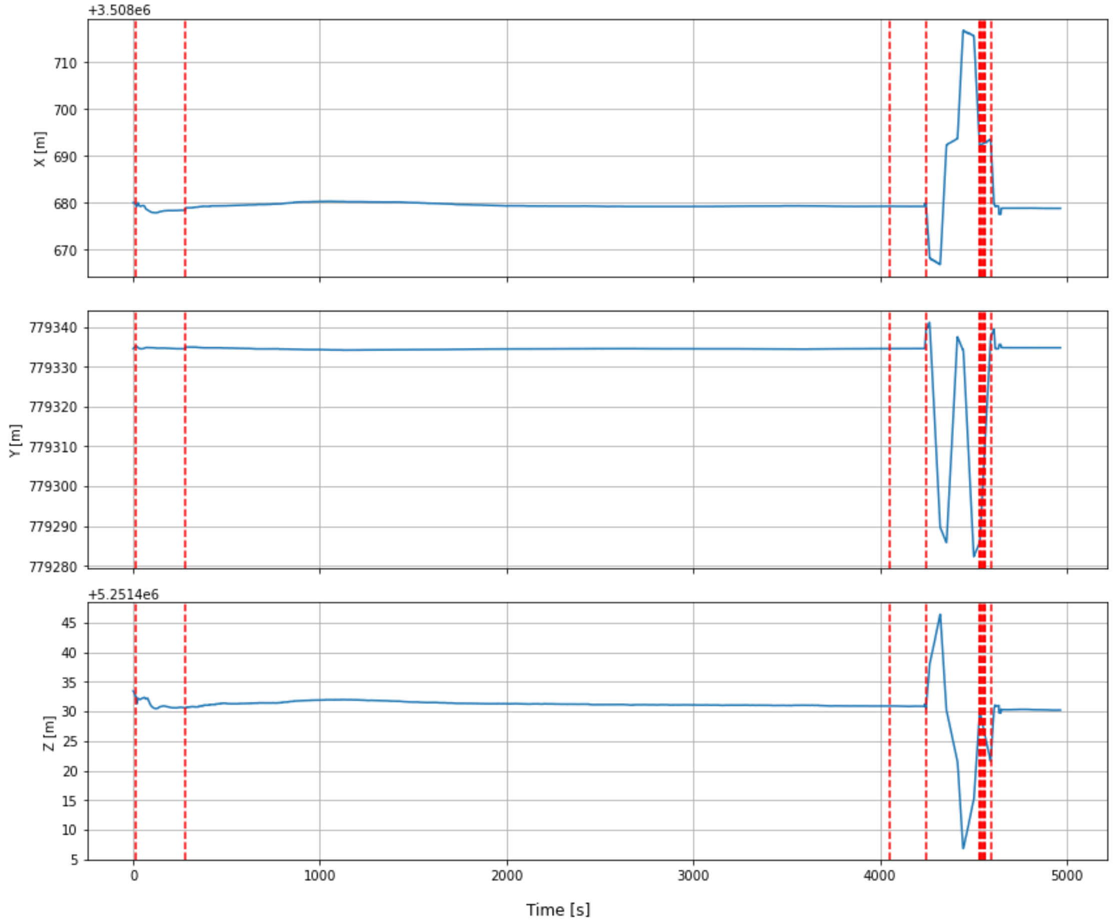
(Zoom-in of the walking segment only)



GALHAS FIX achieved after: 41.0 minutes

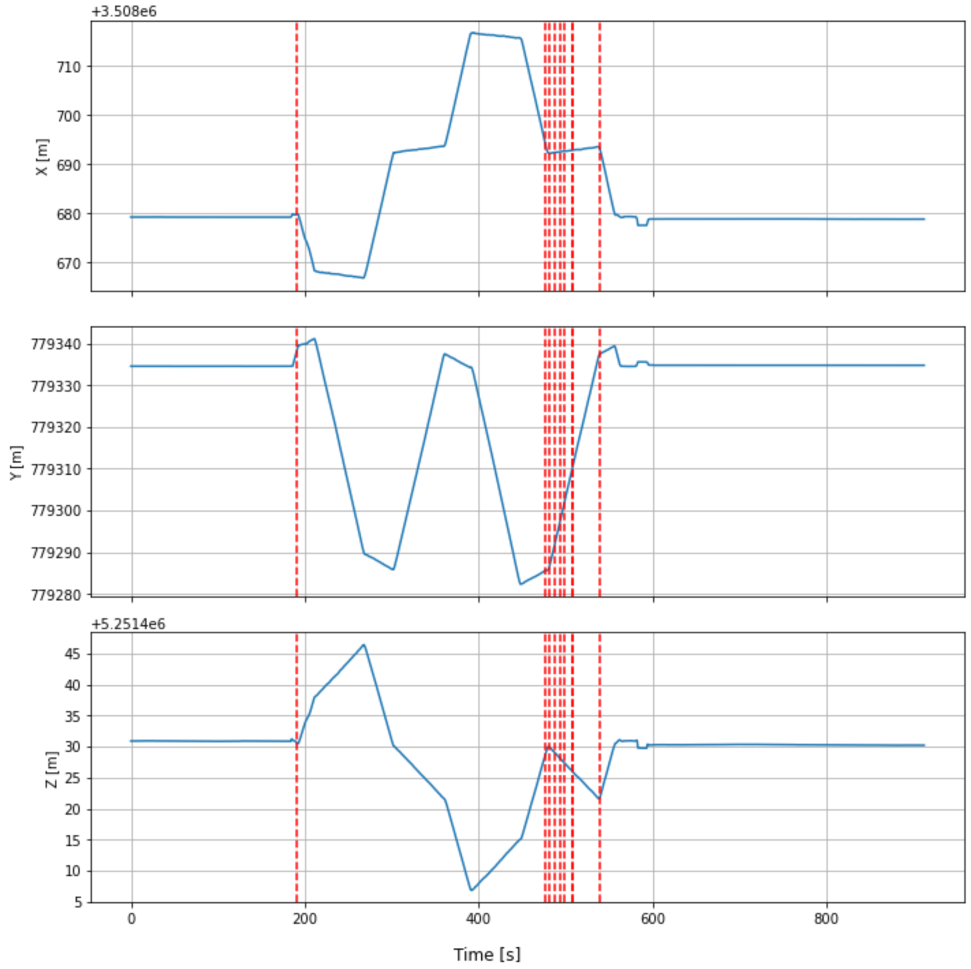


Kinematic test 2

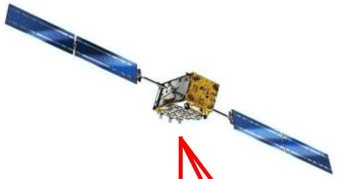


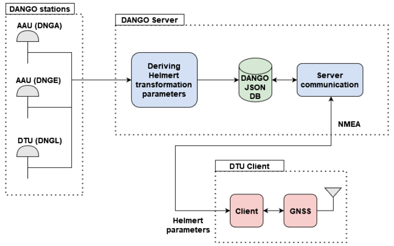
GALHAS FIX achieved after: 67.57 minutes

(Zoom-in of the walking segment only)

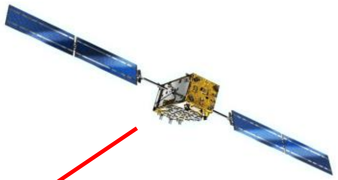


Conclusion

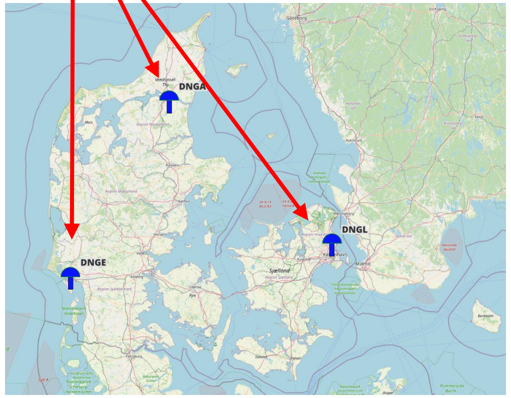




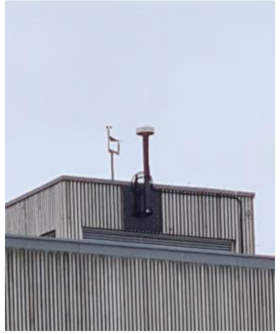
	ITRS -> ETRS89DK
T_x [mm]	876.599
T_y [mm]	-76.52
T_z [mm]	-626.228
D [10^{-9}]	2.197
R_x [mas]	2.878
R_y [mas]	-14.102
R_z [mas]	-20.630



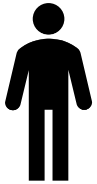
High Accuracy Service (E6-B)

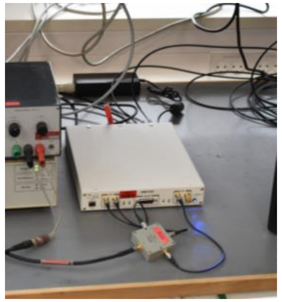


3 DANGO CORS



DANGO Helmert parameters





Validation

DTU