BALTIC+

Geodetic SAR for Height System Unification and Sea Level Research—Results in the Baltic Sea Test Network

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Reference: Gruber et al (2022), Remote Sens. 2022, 14, 3250. https://doi.org/10.3390/rs14143250
Scientific Challenges & Objectives

**Objective 1**
Connect tide gauge markers geometrically with GNSS network by geodetic SAR technique to determine vertical motion and to correct tide gauge readings.

**Objective 2**
Unify height system at tide gauges to compute absolute physical heights with respect to a global reference. Local geoid modelling per tide gauge station.

**Objective 3**
Combination of geometric and physical heights in a common reference frame to determine absolute sea level heights and to connect height systems.

*Reference: Gruber et al (2020), Remote Sens. 2020, 12, 3747; [https://doi.org/10.3390/rs12223747](https://doi.org/10.3390/rs12223747)*
Test Network Baltic Sea (Estonia, Finland, Poland, Sweden & Germany)

- Calibration station
- Co-location station (tide gauge & GNSS)
- Tide gauge station
- GNSS station
- Baseline between tide gauges
- Baseline between GNSS and tide gauge

- Spikarna/Vinberget
- Rauma
- Emäsaloo
- Lovisa
- Forsmark/Kobben
- Loksa
- Vergi
- Mårtsbo
- Wladyslawowo
- Łeba
- Oberpfaffenhofen (DLR)
Several experiments were planned across the Baltic Sea to link:

- GNSS and/or Tide Gauge Stations with Electronic Corner Reflectors
- Tide Gauges across the Baltic Sea.

Delays in the network setup due to the need of national radio frequency licenses

Several issues with ECRs happened during the project: Power supply problems; Water intrusion due to weak sealing of instrument; ECR flooded by ocean waves during storm.
**Geodetic SAR for Ellipsoidal Height Determination**

**Geodetic SAR Technique**

- SAR Image Acquisition for SAR Targets.
- Point Target Analysis to determine Range and Azimuth as primary Observables at Sub-Pixel Level.
- Applying Corrections for Atmosphere, Geodynamics and System Calibration to Observables.
- Solve Range-Doppler Equation to estimate Coordinates in the ITRF2014.

**Active SAR Targets (Electronic Corner Reflectors - ECR)**
Project Results – SAR Data Analysis

SAR Data Acquisition & Point Target Analysis

- Acquisition Success Rate for all Stations: 87%
- Signal Peak Power in average 90 dB, well above 81 dB threshold. Image shows peak power time series for Emäsallo, Finland.
- Sentinel-1 SLC image examples showing the ECR point responses (radar backscatter in dB) for ascending and descending acquisitions.

![Image showing peak power time series for Emäsallo, Finland.](image)

Ascending Image Sample

- Łeba, Poland

Descending Image Sample

- Rauma, Finland

Left columns: Original Sentinel-1 SLC SAR image samples showing an area of 150 m x 150m around ECR peak marked in green.
Right columns: Image areas of 32 x 32 pixels oversampled by a factor of 32 as generated by point target analysis to extract the ECR peak position.
Project Results – Geometric Positioning (SAR)

SAR Positioning

- Minimum temporal resolution are ca. 20 Data takes ~1 Month of observations (latitude dependent)
- More observations lead to more stable performance
- Internal accuracy from least squares estimation about 1 cm per 3D coordinate axis.

Confidence ellipses for all 12 stations using all available observations in the year 2020. The confidence is shown in the local North, East (right image), and East, height (left image) coordinate frame.
Project Results – Geometric Positioning (GNSS) & Tide Gauge Data

GNSS Positioning

- Baltic Sea GNSS stations (IGS: large square, EPN: small square, EUPOS: red square). Network adjustment using the Bernese GNSS Software in Double Differences (DD) mode.
- The final coordinate solutions for all stations are computed in terms of 3D Cartesian Coordinates in ITRF2014 for epoch 2020.50. RMS of coordinate solutions below 1 mm per 3D axis.

Tide Gauge Data Processing

- Tide gauge readings for all stations are provided in EVRS.
- Hourly data checked for outliers and filtered.
- Pre-processed tide gauge data series for year 2020 was used for computing the annual mean sea level estimates in the common EVRS.

Heavy storm with flooding of instrument by high waves
Project Results – Geoid & Standards

Regional Geoid based on common Equipotential Surface

- Least squares modification of Stokes’ formula with additive corrections (LSMSA) is used.
- GOCC06S as satellite-only reference model.
- Computation of topographic RTM effects based on the NKG2015 Digital Elevation Model is used.
- Land uplift correction is applied. Geoid is provided for epoch 2020.5.

Gravity data selected to compute the gravimetric quasigeoid model. Data include gravity datasets of the NKG2015 project from Sweden, Finland and Estonia (plus some other open datasets), new FAMOS marine gravity data from the same countries and the Polish gravity data currently in the NKG2015 gravity database. Pseudo observations (5' x 5') generated by EIGEN-6C4 are plotted as blue dots.

Reference Frames and Standards

- Standards and models for processing the different observations are applied according to IERS Conventions 2010.
- Technique-specific processing standards are applied for the individual observation techniques.
- All ellipsoidal coordinates are computed with respect to the conventional GRS80 ellipsoid.
### Project Results – Height System Unification / Absolute Sea Level

**Absolute Height Experiment: GNSS vs. ECR**

- Comparison of SAR positioning heights at ECR stations to co-located permanent GNSS station height using local tie observed by ground geodetic techniques between both reference points.

| ECR Station          | GNSS Ellipsoidal Height [m] | Local Tie GNSS to ECR [m] | ECR Ellipsoidal Height Computed $h_{com}$ [m] | ECR Ellipsoidal Height observed $h_{obs}$ [m] | ECR Ellipsoidal Height Difference computed – observed $\Delta h$ [m] |
|----------------------|-----------------------------|---------------------------|-----------------------------------------------|-----------------------------------------------|---------------------------------------------------------------|
| Władysławowo         | +34.758                     | -0.135                    | +34.623                                       | +34.640                                       | -0.017                                                        |
| Łeba                 | +37.886                     | -3.932                    | +33.954                                       | +34.389                                       | -0.435                                                        |
| Vergi                | +30.069                     | -0.996                    | +29.073                                       | +28.966                                       | +0.107                                                        |
| Loviisa              | +49.879                     | -3.574                    | +46.305                                       | +46.840                                       | -0.535                                                        |
| Mårtsbo              | +75.558                     | -0.032                    | +75.526                                       | +75.477                                       | +0.049                                                        |
| Spikarna/Vinberget   | +150.206                    | -0.998                    | +149.208                                      | +149.654                                      | -0.446                                                        |

Local tie (levelling) in Władysławowo, Poland
### Project Results – Height System Unification / Absolute Sea Level

#### Absolute Height Experiment: Physical Heights & Absolute Sea Level

- Physical heights of tide gauge zero marker above common vertical reference surface (regional geoid solution).

\[
H^{TG} = h^{ECR} + \Delta h^{TG}_{ECR} - N^{TG}
\]

\[
S^{TG} = h^{ECR} + \Delta h^{TG}_{ECR} - N^{TG} + z^{TG} = H^{TG} + z^{TG}
\]

#### Computation physical height of tide gauge zero marker:

#### Computation absolute sea level height at tide gauge:

**Table:**

| ECR Station   | ECR Ellipsoidal Height observed \(h^{ECR}\) [m] | Local Tie ECR to Tide Gauge \(\Delta h^{TG}_{ECR}\) [m] | Tide Gauge Geoid Height \(N^{TG}\) [m] | Tide Gauge Physical Height \(H^{TG}\) [m] | Tide Gauge Reading \(z^{TG}\) [m] | Tide Gauge Absolute Sea Level \(S^{TG}\) [m] |
|---------------|---------------------------------|---------------------------------|-----------------|-----------------|----------------|-----------------|
| Włodysławowo  | +34.640                         | -5.638                          | +28.883         | +0.119          | +0.253         | +0.372          |
| Łeba          | +34.389                         | -3.049                          | +30.787         | +0.553          | +0.224         | +0.777          |
| Loksa         | +20.076                         | -2.639                          | +16.821         | +0.616          | +0.343         | +0.959          |
| Emäsalo       | +34.293                         | -17.816                         | +16.509         | -0.032          | +0.338         | +0.306          |
| Rauma         | +24.082                         | -5.007                          | +19.096         | -0.021          | +0.258         | +0.237          |
| Forsmark/ Kobben | +25.659                     | -2.961                          | +22.381         | +0.317          | +0.188         | +0.505          |
| Spikarna/ Vinberget | +149.654                 | -123.523                        | +25.065         | +1.066          | +0.175         | +1.241          |

Local tie (levelling) in Loksa, Estonia.
Project Results – Height System Unification / Absolute Sea Level

Relative Baseline Experiment: GNSS Baseline Height Difference vs. ECR Height Difference

- Relative height differences are compared between GNSS stations and those observed with the ECR’s.
- Multiple baselines are possible over long or short distances.
- For the relative comparisons between station A and station B the following formulas are applied.

\[
\Delta h_{\text{GNSS}} = h_{\text{GNSS} - B} - h_{\text{GNSS} - A}
\]
\[
\Delta h_{\text{ECR}} = \left( h_{\text{ECR} - B} - \Delta h_{\text{ECR} - B} \right) - \left( h_{\text{ECR} - A} - \Delta h_{\text{ECR} - A} \right)
\]
\[
\Delta \Delta h_{\text{GNSS-ECR}} = \Delta h_{\text{GNSS}} - \Delta h_{\text{ECR}}
\]

| from Station A | to Station B | GNSS Ellipsoidal Height Difference $\Delta h_{\text{GNSS}}$ [m] | ECR Ellipsoidal Height Difference $\Delta h_{\text{ECR}}$ [m] | Difference Ellipsoidal Height Difference $\Delta \Delta h_{\text{GNSS-ECR}}$ [m] |
|----------------|--------------|-------------------------------------------------|-------------------------------------------------|---------------------------------|
|                |              |                                                 |                                                 |                                 |

Co-location station (tide gauge & GNSS)
GNSS station
Baseline between GNSS stations
Project Results – Height System Unification / Absolute Sea Level

Relative Baseline Experiment: Tide Gauge Baseline Sea Level Difference vs. ECR Tide Gauge Height Difference

- Relative absolute sea level differences are compared between tide gauge stations and those observed with the ECR’s. For the relative comparisons between station A and station B the following formulas are applied. The result corresponds to physical height differences between station A and station B.

\[
\Delta z_{TG} = z_{TG-B} - z_{TG-A} \\
\Delta S_{TG} = S_{TG-B} - S_{TG-A} \\
S_{TG-X} = H_{TG-X} + z_{TG-X} \\
\Delta \Delta S_{TG} = \Delta z_{TG} - \Delta S_{TG} = \Delta \Delta H_{TG}
\]

| from Station A | to Station B | Tide Gauge Height Difference $\Delta z_{TG}$[m] | Absolute Sea Level Height Difference $\Delta S_{TG}$[m] | Difference Sea Level (Height Difference) $\Delta \Delta S_{TG}$ | $\Delta \Delta H_{TG}$[m] |
|----------------|--------------|---------------------------------|-----------------|-----------------|-----------------|
| Emäsalo        | Rauma        | -0.080                           | -0.069           | -0.011          |                 |
| Rauma          | Forsmark/Kobben | 0.070                           | +0.268           | -0.338          |                 |
| Emäsalo        | Forsmark/Kobben | -0.150                           | +0.199           | -0.349          |                 |
| Loksa          | Emäsalo      | 0.005                            | -0.653           | +0.648          |                 |
| Loksa          | Forsmark/Kobben | -0.155                           | -0.454           | +0.299          |                 |

Co-location station (tide gauge & GNSS)
- Tide gauge station
- Baseline between tide gauge stations
### Project Results – Height System Unification / Absolute Sea Level

#### GNSS Baseline Height Difference

| Station          | absolute performance | relative performance GNSS baseline $\Delta h_{\text{GNSS-ECR}}$ [m] | ECR vs. GNSS $\Delta h$ [m] | ECR vs. TG $H^T$ [m] |
|------------------|----------------------|---------------------------------------------------------------|-----------------------------|----------------------|
| Vergi (VERGI)    | -0.107               | -0.642 -0.058 -0.124 -0.542 -0.533                            | VERGI                       |                      |
| Lovisa (LOVI)    | -0.535               | 0.642 0.584 0.518 0.1 0.089                                    | LOVI                        |                      |
| Mårtsbo (MART)   | 0.049                | 0.058 -0.584 -0.066 -0.484 -0.495                              | MART                        |                      |
| Władysławowo (WLAD)* | -0.017 0.119       | 0.124 -0.518 0.066 -0.418 -0.429                              | WLAD*                       |                      |
| Łeba (LEBA)*     | -0.435 0.553         | 0.542 -0.1 0.484 0.418 -0.011                                 | LEBA*                       |                      |
| Vinberget (VINB)*| -0.446 1.066         | 0.533 -0.089 0.495 0.429 0.011                                  | VINB*                       |                      |

- $|\Delta h| \leq 0.15$ (High agreement with GNSS measurement)
- $|H^T| \leq 0.15$ (High agreement with tide gauge measurement and regional geoid solution(TG))
- $|\Delta h| \geq 0.15$ (Low agreement with GNSS measurement)
- $|\Delta h_{\text{GNSS-ECR}}| \leq 0.15$ & $|\Delta h_{\text{rel}}| \leq 0.15$ (High agreement in baseline height difference and high agreement with GNSS at both sites)
- $|\Delta h_{\text{ECR}}| \leq 0.15$ & $|H^T|_{\text{rel}} \leq 0.15$ (High agreement in baseline sea level difference and high agreement with TG at both sites)
- $|\Delta h_{\text{ECR}}| \leq 0.15$ & $|\Delta h_{\text{rel}}| \geq 0.15$ (High agreement in baseline height difference and low agreement with GNSS at both sites)
- $|\Delta h_{\text{ECR}}| \leq 0.15$ & $|H^T|_{\text{rel}} \geq 0.15$ (High agreement in baseline sea level difference and low agreement with TG at both sites)
- $|\Delta h_{\text{ECR}}| \geq 0.15$ & $|\Delta h_{\text{rel}}| \leq 0.15$ (Low agreement in baseline sea level difference and high agreement with TG at both sites)
- $|\Delta h_{\text{ECR}}| \geq 0.15$ & $|H^T|_{\text{rel}} \geq 0.15$ (Low agreement in baseline height difference and low agreement with GNSS at one site)
- $|\Delta h_{\text{ECR}}| \geq 0.15$ & $|H^T|_{\text{rel}} \geq 0.15$ & $|\Delta h| \leq 0.15$ (Low agreement in baseline height difference and low agreement with TG at one site)

#### Tide Gauge Baseline Sea Level Difference

| Station          | absolute performance | relative performance TG baseline $\Delta H^T$ [m] | ECR vs. GNSS $\Delta h$ [m] | ECR vs. TG $H^T$ [m] |
|------------------|----------------------|---------------------------------------------------|-----------------------------|----------------------|
| Loksa (LOKS)     | 0.616                | 0.648 0.637 0.299 0.497 0.063 -0.45                 | LOKS                        |                      |
| Emäsalo (EMAE)   | -0.032               | -0.648 -0.011 -0.349 -0.151 -0.585 -1.098           | EMAE                        |                      |
| Rauma (RAUM)     | -0.21                | -0.637 0.011 -0.338 -0.14 -0.574 -1.087            | RAUM                        |                      |
| Kobben (KOBB)    | 0.317                | 0.299 0.349 0.338 0.198 -0.236 -0.749              | KOBB                        |                      |
| Władysławowo (WLAD)* | -0.017 0.119         | -0.497 0.151 0.14 -0.198 -0.434 -0.947            | WLAD*                       |                      |
| Łeba (LEBA)*     | -0.435 0.553         | -0.063 0.585 0.574 0.236 0.434 -0.513              | LEBA*                       |                      |
| Vinberget (VINB)*| -0.446 1.066         | 0.45 1.098 1.087 0.749 0.947 0.513                 | VINB*                       |                      |

- Stable performance of the ECR with high agreement with GNSS or TG Measurements (≤ 0.15m )
- Stable performance of the ECR with low agreement with GNSS or TG Measurements (≥ 0.15m )
- Unstable performance of the ECR with low agreement with GNSS or TG Measurements (≥ 0.15m )
Summary and Conclusions

- Test network with **12 ECRs installed and operated** since Jan. 2020 in the Baltic Sea area to observe geometric heights. Locations to be selected very carefully to avoid artificial reflectors.
- **Internal accuracy** for average ECR positions at a level of **a few cm**. Minimum temporal resolution 1 month of data.
- **GNSS** coordinates, **tide gauge** sea level records and regional **geoid** heights computed with well established procedures **with cm accuracy** when consistent reference frames and standards are applied.
- **Absolute differences** between ECR and GNSS heights **between a few cm and 50 cm**.
- ECR electronic delay characteristics turned out to be less controllable than anticipated. Separate calibration for each ECR is required.
- **Operability** of ECRs needs **to be improved**: Power supply, sealing, GUI, firmware.
- ECR height **uncertainties** fully **propagate into absolute sea level** and height system observations.
- ECRs could be a **useful supporting technique** collocated with GNSS stations.
- **Valuable data set** has been compiled, which offers the possibility to enhance methods and procedures in order to develop the SAR positioning technique towards operability.

Data set available at: [https://www.asg.ed.tum.de/iapg/baltic/data/](https://www.asg.ed.tum.de/iapg/baltic/data/)
Thank you for your attention!

References:

Gruber et al (2022), Remote Sens. 2022, 14, 3250.
https://doi.org/10.3390/rs14143250

Gruber et al (2020), Remote Sens. 2020, 12, 3747;
https://doi.org/10.3390/rs12223747

Data set available at:
https://www.asg.ed.tum.de/iapg/baltic/data/
Relative Baseline Experiment: GNSS Baseline Height Difference vs. ECR Height Difference

- Relative height differences are compared between GNSS stations and those observed with the ECR’s. There are several of such baselines available, which can be observed over long or short distances. For the relative comparisons between station A and station B the following formulas are applied.

$$\Delta h_{\text{GNSS}} = h_{\text{GNSS-B}} - h_{\text{GNSS-A}}$$

$$\Delta h_{\text{ECR}} = \left( h_{\text{ECR-B}} - \Delta h_{\text{GNSS-B}} \right) - \left( h_{\text{ECR-A}} - \Delta h_{\text{GNSS-A}} \right)$$

$$\Delta \Delta h_{\text{GNSS-ECR}} = \Delta h_{\text{GNSS}} - \Delta h_{\text{ECR}}$$

| from Station A      | to Station B       | GNSS Ellipsoidal Height Difference $\Delta h_{\text{GNSS}}$ [m] | ECR Ellipsoidal Height Difference $\Delta h_{\text{ECR}}$ [m] | Difference Ellipsoidal Height Difference $\Delta \Delta h_{\text{GNSS-ECR}}$ [m] |
|---------------------|--------------------|---------------------------------------------------------------|-------------------------------------------------------------|--------------------------------------------------------------------------------|
| Władysławowo        | Łeba               | +3.128                                                        | +3.546                                                      | -0.418                                                                         |
| Władysławowo        | Vergi              | -4.689                                                        | -4.813                                                      | +0.124                                                                         |
| Władysławowo        | Loviisa            | +15.121                                                       | +15.639                                                     | -0.518                                                                         |
| Władysławowo        | Mårtsbo            | +40.800                                                       | +40.734                                                     | +0.066                                                                         |
| Władysławowo        | Spikarna/Vinberget | +115.448                                                      | +115.877                                                    | -0.429                                                                         |
| Łeba                | Vergi              | -7.817                                                        | -8.359                                                      | +0.542                                                                         |
| Łeba                | Loviisa            | +11.993                                                       | +12.093                                                     | -0.100                                                                         |
| Łeba                | Mårtsbo            | +37.672                                                       | +37.188                                                     | +0.484                                                                         |
| Łeba                | Spikarna/Vinberget | +112.320                                                      | +112.331                                                    | -0.011                                                                         |
| Vergi               | Loviisa            | +19.810                                                       | +20.452                                                     | -0.642                                                                         |
| Vergi               | Mårtsbo            | +45.489                                                       | +45.547                                                     | -0.058                                                                         |
| Vergi               | Spikarna/Vinberget | +120.137                                                      | +120.690                                                    | -0.553                                                                         |
| Loviisa             | Mårtsbo            | +25.679                                                       | +25.095                                                     | +0.584                                                                         |
| Loviisa             | Spikarna/Vinberget | +100.327                                                      | +100.238                                                    | +0.089                                                                         |
| Mårtsbo             | Spikarna/Vinberget | +74.648                                                       | +75.143                                                     | -0.495                                                                         |
Relative Baseline Experiment: GNSS Baseline Height Difference vs. ECR Height Difference

- Relative height differences are compared between GNSS stations and those observed with the ECR’s. There are several of such baselines available, which can be observed over long or short distances. For the relative comparisons between station A and station B the following formulas are applied.

$$\Delta h^{\text{GNSS}} = h^{\text{GNSS} - B} - h^{\text{GNSS} - A}$$

$$\Delta h^{\text{ECR}} = (h^{\text{ECR} - B} - \Delta h^{\text{ECR} - B}) - (h^{\text{ECR} - A} - \Delta h^{\text{ECR} - A})$$

$$\Delta \Delta h^{\text{GNSS-ECR}} = \Delta h^{\text{GNSS}} - \Delta h^{\text{ECR}}$$

### Station A

| Station          | absolute performance | relative performance GNSS baseline $\Delta h_{\text{GNSS-ECR}}^{\text{ECR}}$ [m] |
|------------------|----------------------|-----------------------------------------------|
|                  | ECR vs. GNSS $\Delta h$ [m] | ECR vs. TG $H^G$ [m] | VERGI | LOVI | MART | WLAD* | LEBA* | VINB* |
| Vergi (VERG)     | -0.107               | -0.642 -0.058 -0.124 -0.542 -0.533          |
| Loviisa (LOVI)   | -0.535               | 0.642 0.584 0.518 0.1 0.089                  |
| Mårtsbo (MART)   | 0.049                | 0.058 -0.584 -0.066 -0.484 -0.495           |
| Władysławowo (WLAD)* | -0.017 0.119       | 0.124 -0.518 0.066 -0.418 -0.429           |
| Łeba (LEBA)*     | -0.435 0.553         | 0.542 -0.1 0.484 0.418 -0.011               |
| Vinberget (VINB) | -0.446 1.066         | 0.533 -0.089 0.495 0.429 0.011               |

- $|\Delta h| \leq 0.15m$ (High agreement with GNSS measurement)
- $|\Delta h| \geq 0.15m$ (Low agreement with GNSS measurement)
- $|\Delta h^{\text{GNSS-ECR}}| \leq 0.15m$ (High agreement in baseline height difference and high agreement with GNSS at both sites)
- $|\Delta h^{\text{GNSS-ECR}}| \leq 0.15m$ & $|\Delta h^{\text{GNSS}}| \geq 0.15m$ (High agreement in baseline height difference and low agreement with GNSS at both sites)
- $|\Delta h^{\text{GNSS-ECR}}| \geq 0.15m$ & $|\Delta h^{\text{GNSS}}| \leq 0.15m$ (Low agreement in baseline height difference and low agreement with GNSS at one site)
Relative Baseline Experiment: Tide Gauge Baseline Sea Level Difference vs. ECR Tide Gauge Height Difference

- Relative absolute sea level differences are compared between tide gauge stations and those observed with the ECR’s. For the relative comparisons between station A and station B the following formulas are applied. The result corresponds to physical height differences between station A and station B.

\[
\Delta \zeta^{TG} = \zeta^{TG-B} - \zeta^{TG-A}
\]
\[
\Delta S^{TG} = S^{TG-B} - S^{TG-A}
\]
\[
S^{TG-X} = H^{TG-X} + \zeta^{TG-X}
\]
\[
\Delta \Delta S^{TG} = \Delta \zeta^{TG} - \Delta S^{TG} = \Delta \Delta H^{TG}
\]

| from Station A | to Station B | Tide Gauge Height Difference $\Delta \zeta^{TG}$ [m] | Absolute Sea Level Height Difference $\Delta S^{TG}$ [m] | Difference Sea Level (Height Difference) $\Delta \Delta S^{TG} (\Delta \Delta H^{TG})$ [m] |
|----------------|--------------|-----------------------------------------------------|-----------------------------------------------------|----------------------------------------------------------------------------------|
| Władysławowo   | Łeba         | -0.029                                              | +0.405                                              | -0.434                                                                           |
| Władysławowo   | Loksa        | +0.090                                              | +0.587                                              | -0.497                                                                           |
| Władysławowo   | Emäsalo      | +0.085                                              | -0.066                                              | +0.151                                                                           |
| Władysławowo   | Rauma        | +0.005                                              | -0.135                                              | +0.140                                                                           |
| Władysławowo   | Forsmark/Kobben | -0.065                      | +0.133                                              | -0.198                                                                           |
| Władysławowo   | Spikarna/Vinberget | -0.078                      | +0.869                                              | -0.947                                                                           |
| Łeba           | Loksa        | +0.119                                              | +0.182                                              | -0.063                                                                           |
| Łeba           | Emäsalo      | +0.114                                              | -0.471                                              | +0.585                                                                           |
| Łeba           | Rauma        | +0.034                                              | -0.540                                              | +0.574                                                                           |
| Łeba           | Forsmark/Kobben | -0.036                      | -0.272                                              | +0.236                                                                           |
| Łeba           | Spikarna/Vinberget | -0.049                      | +0.464                                              | -0.513                                                                           |
| Loksa          | Emäsalo      | -0.005                                              | -0.653                                              | +0.648                                                                           |
| Loksa          | Rauma        | -0.085                                              | -0.722                                              | +0.637                                                                           |
| Loksa          | Forsmark/Kobben | -0.155                      | -0.454                                              | +0.299                                                                           |
| Loksa          | Spikarna/Vinberget | -0.168                      | +0.282                                              | -0.450                                                                           |
| Emäsalo        | Rauma        | -0.080                                              | -0.069                                              | -0.011                                                                           |
| Emäsalo        | Forsmark/Kobben | -0.150                      | +0.199                                              | -0.349                                                                           |
| Emäsalo        | Spikarna/Vinberget | -0.163                      | +0.935                                              | -1.098                                                                           |
| Rauma          | Forsmark/Kobben | -0.070                      | +0.268                                              | -0.338                                                                           |
| Rauma          | Spikarna/Vinberget | -0.083                      | +1.004                                              | -1.087                                                                           |
| Forsmark/Kobben | Spikarna/Vinberget | -0.013                      | +0.736                                              | -0.749                                                                           |
# Project Results – Height System Unification / Absolute Sea Level

## Relative Baseline Experiment: Tide Gauge Baseline Sea Level Difference vs. ECR Tide Gauge Height Difference

- Relative absolute sea level differences are compared between tide gauge stations and those observed with the ECR’s. For the relative comparisons between station A and station B the following formulas are applied. The result corresponds to physical height differences between station A and station B.

\[
\Delta z_{TG} = z_{TG-B} - z_{TG-A}
\]

\[
\Delta S_{TG} = S_{TG-B} - S_{TG-A}
\]

\[
S_{TG-X} = H_{TG-X} + z_{TG-X}
\]

\[
\Delta \Delta S_{TG} = \Delta z_{TG} - \Delta S_{TG} = \Delta \Delta H_{TG}
\]

### Station Absolute Performance

| Station          | ECR vs. GNSS Δh [m] | ECR vs. TG H\(^{TG}\) [m] |
|------------------|----------------------|----------------------------|
| Loksa (LOKS)     | 0.616                | 0.648 0.637 0.299 0.497 0.063 -0.45 |
| Emäsaalo (EMAE)  | -0.032               | -0.648 -0.011 -0.349 -0.151 -0.585 -1.098 |
| Rauma (RAUM)     | -0.21                | -0.637 0.011 -0.338 -0.14 -0.574 -1.087 |
| Kobben (KOBB)    | 0.317                | -0.299 0.349 0.338 0.198 -0.236 -0.749 |
| Władysławowo (WLAD)* | -0.017 0.119 | -0.497 0.151 0.14 -0.198 -0.434 -0.947 |
| Łeba (LEBA)*     | -0.435 0.553         | -0.063 0.585 0.574 0.236 0.434 -0.513 |
| Vinberget (VINB)* | -0.446 1.066         | 0.45 1.098 1.087 0.749 0.947 0.513 |

### Station Relative Performance TG baseline ΔΔH\(^{TG}\) [m]

- \(|H^{TG}| \leq 0.15\)m (High agreement with tide gauge measurement and regional geoid solution [TG])
- \(|H^{TG}| \geq 0.15\)m (Low agreement with tide gauge measurement and regional geoid solution [TG])
- \(|\Delta \Delta H^{TG}| \leq 0.15\)m & \(|H^{TG}_{A&B}| \leq 0.15\)m (High agreement in baseline sea level difference and high agreement with TG at both sites)
- \(|\Delta \Delta H^{TG}| \leq 0.15\)m & \(|H^{TG}_{A&B}| \geq 0.15\)m (High agreement in baseline sea level difference and high agreement with TG at both sites)
- \(|\Delta \Delta H^{TG}| \geq 0.15\)m & \(|H^{TG}_{A&B}| \leq 0.15\)m (Low agreement in baseline sea level difference and low agreement with TG at both sites)
- \(|\Delta \Delta H^{TG}| \geq 0.15\)m & \(|H^{TG}_{A&B}| \geq 0.15\)m (Low agreement in baseline sea level difference and low agreement with TG at one site)