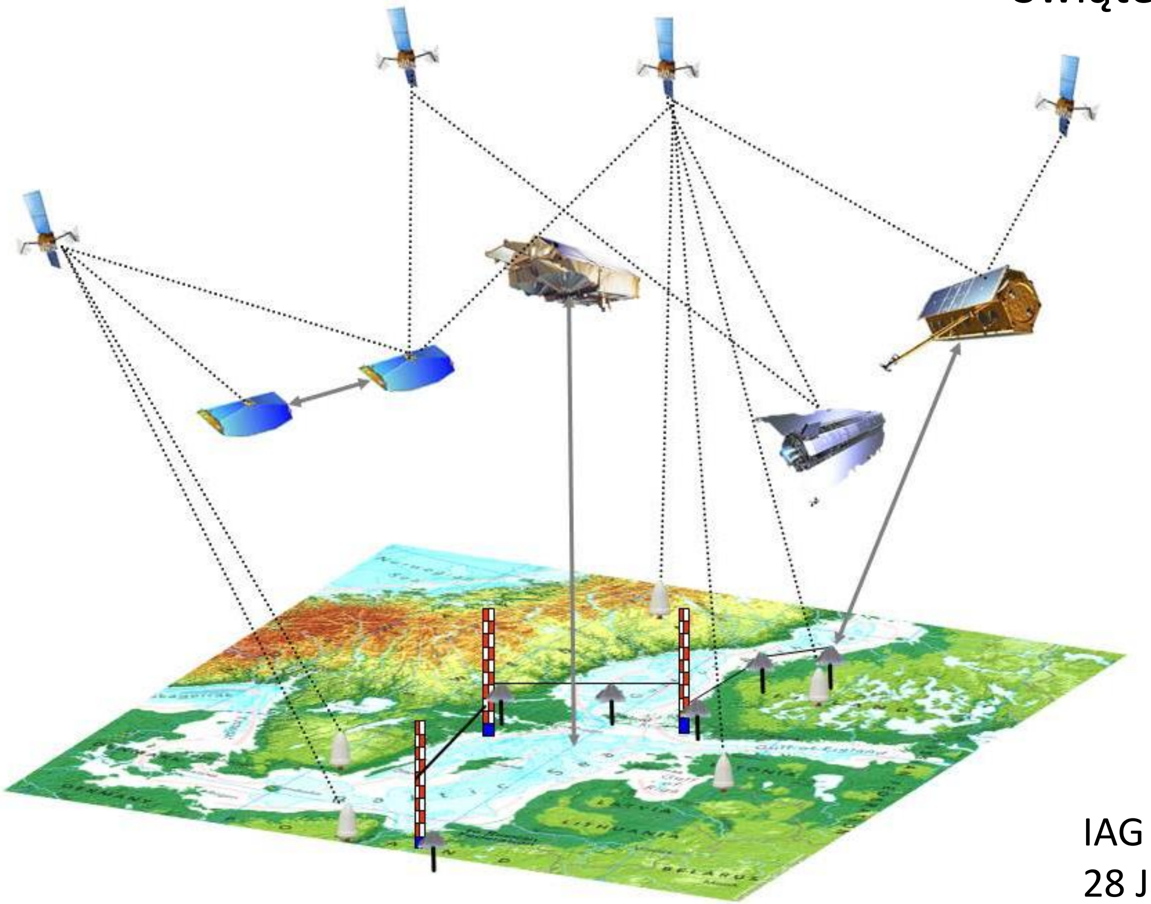
BALTIC+
Geodetic SAR for Baltic Height System Unification and Baltic Sea Level Research

Th. Gruber[(1)], J. Ågren[(2)], D. Angermann[(3)], A. Ellmann[(4)], C. Gisinger[(5)], J. Nastula[(6)], M. Poutanen[(7)], M. Schlaak[(1)], F. Nilfouroushan[(2)], S. Varbla[(4)], R. Zdunek[(6)], S. Marila[(7)], A. Engfeldt[(2)], T. Saari[(7)], Anna Świątek[(6)], X. Oikonomidou[(1)]



(1) Technical University of Munich, Astronomical and Physical Geodesy
(2) Lantmäteriet, Swedish Mapping, Cadastral and Land Registration Authority
(3) Technical University of Munich, German Geodetic Research Institute
(4) Tallinn University of Technology, School of Engineering
(5) German Aerospace Center, Remote Sensing Technology Institute
(6) Space Research Centre, Polish Academy of Sciences
(7) Finnish Geospatial Research Institute

The project was carried out by the project team under ESA contract No. 4000126830/19/I-BG “Baltic+ Theme No. 5 – Geodetic SAR for Baltic Height”.

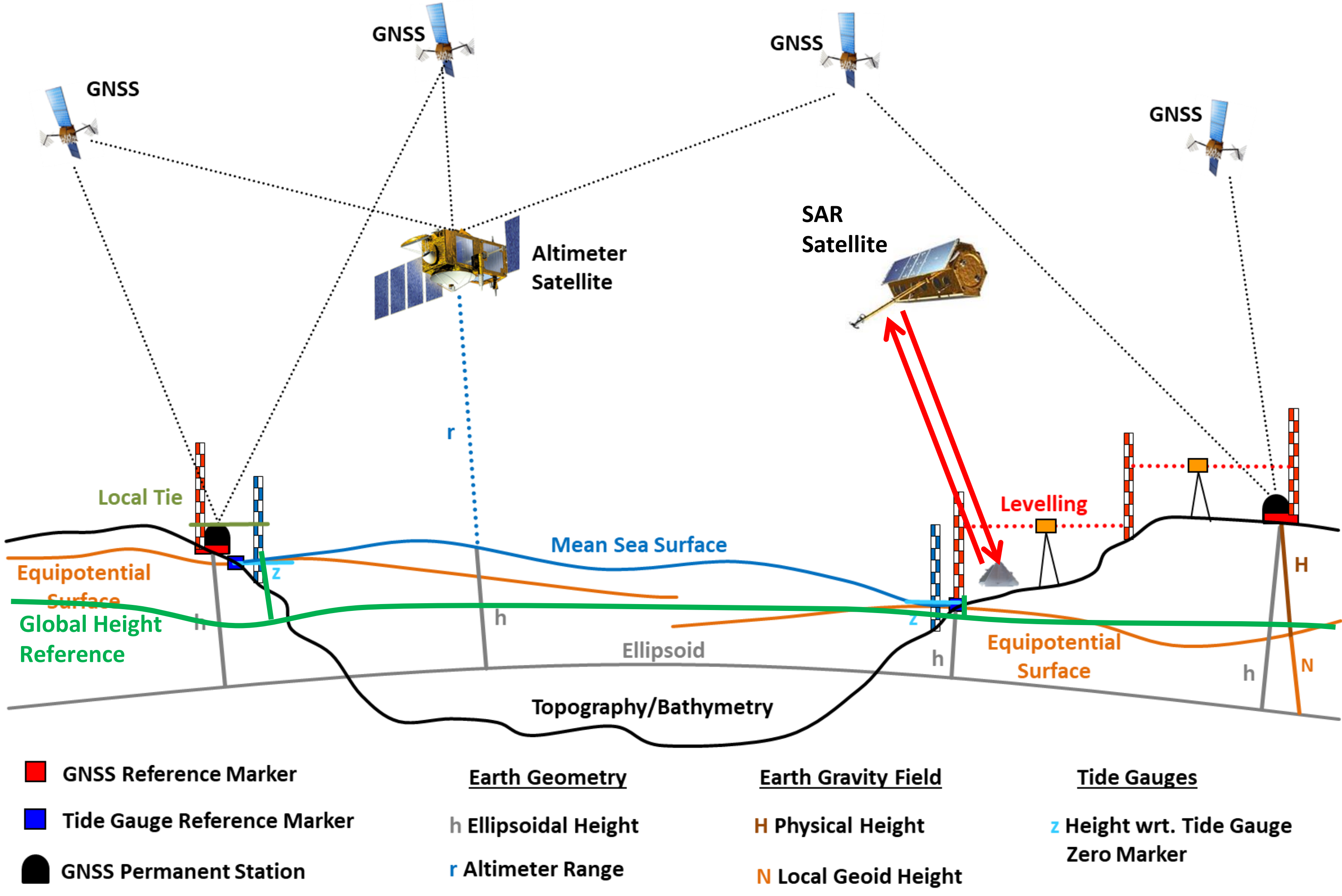
IAG 2021 – Scientific Assembly of the International Association of Geodesy
28 June – 2. July 2021, Beijing, China

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 Sensing 2020, 12, 3747; https://doi.org/10.3390/rs12223747

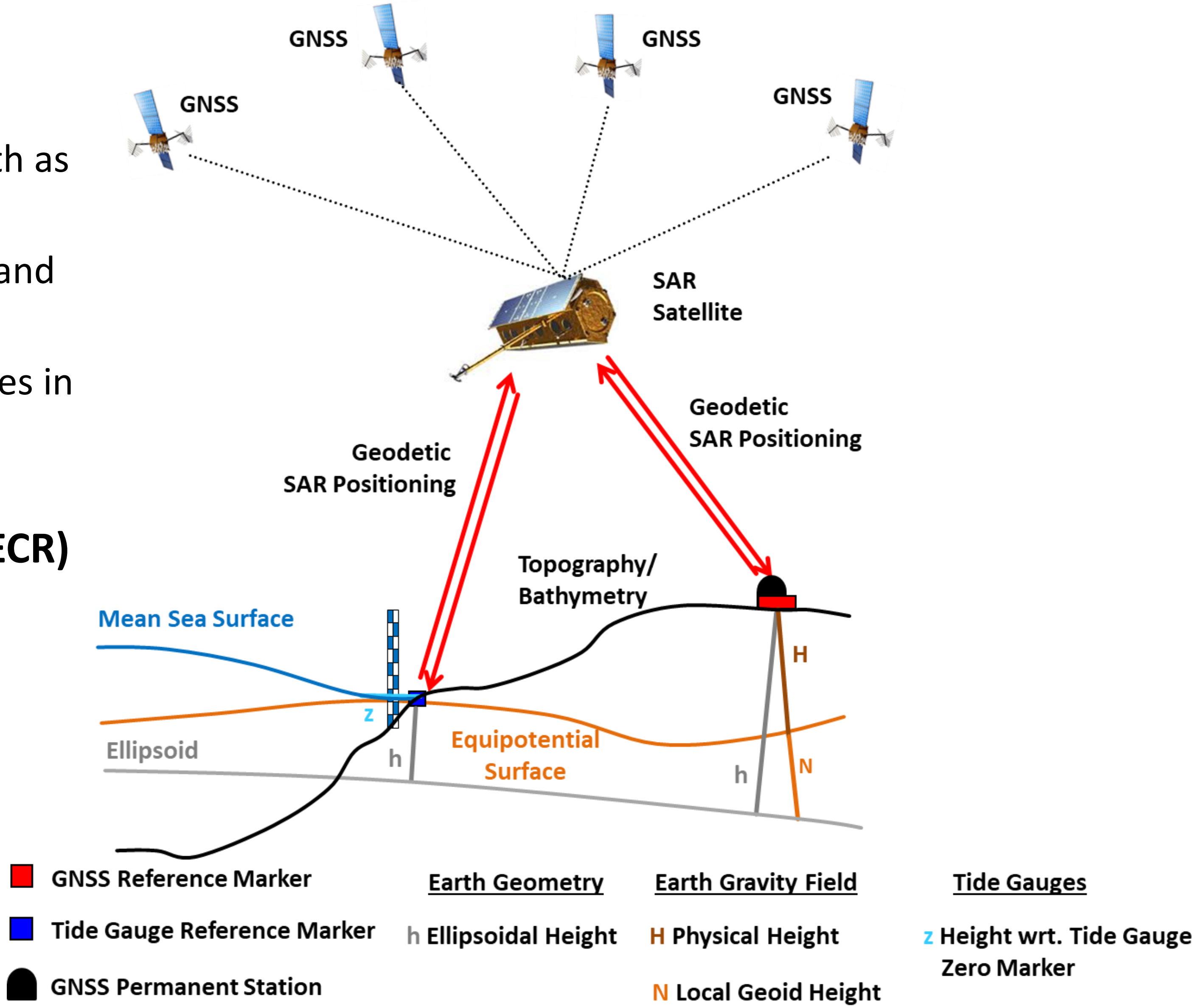
Geodetic SAR for Ellipsoidal Height Determination

Geodetic SAR Technique

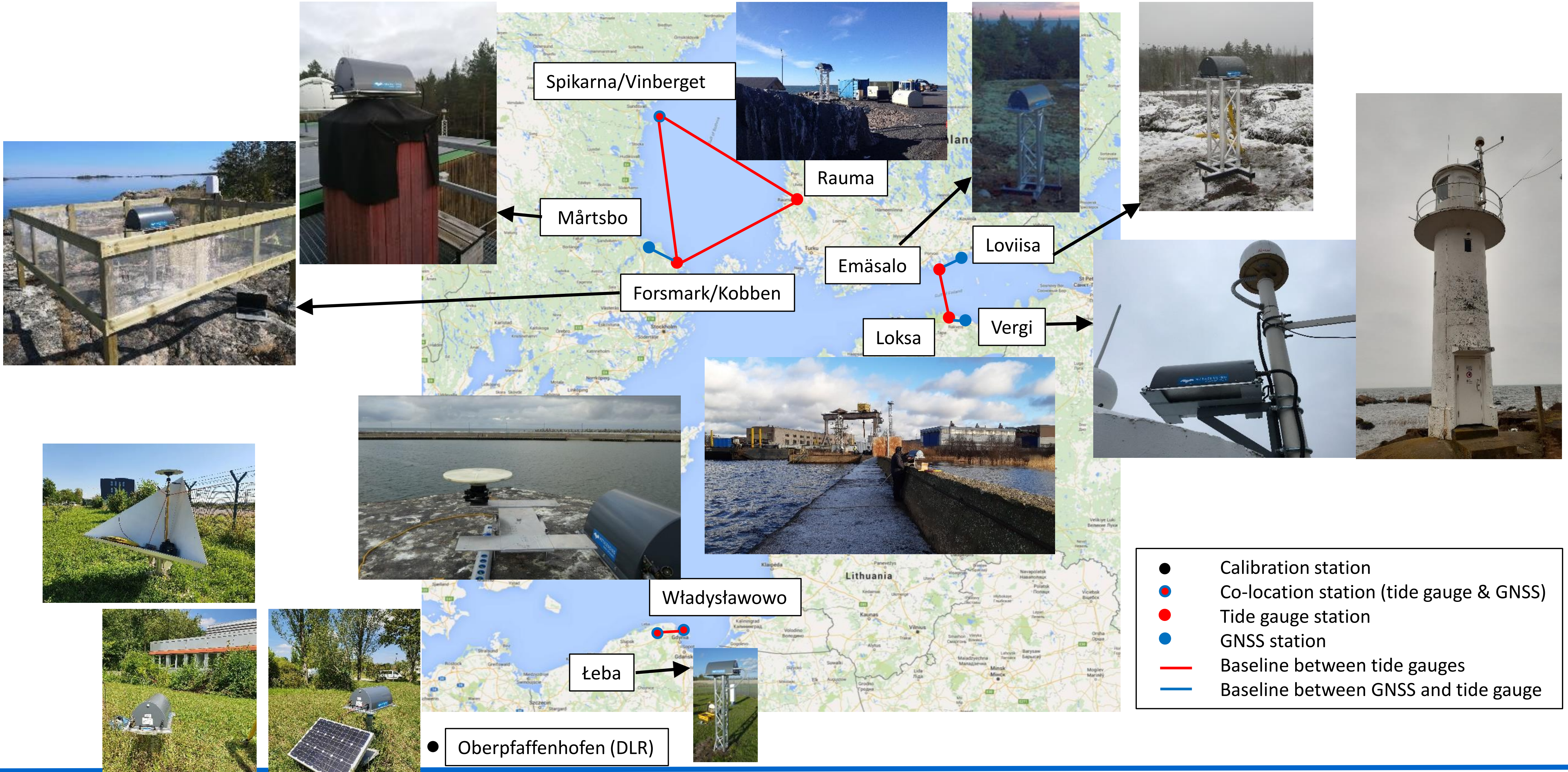
- SAR Image Acquisition for SAR Targets.
- Point Target Analysis to determine Range and Azimuth as primary Observables at Sub-Pixel Level.
- Applying Corrections for Atmosphere, Geodynamics and System Calibration to Observables.
- Solve Range-Doppler Equation to estimate Coordinates in the ITRF2014.

(For details see presentation by M. Schlaak, C. Gisinger, T. Gruber in session 4.1)

Active SAR Targets (Electronic Corner Reflectors - ECR)

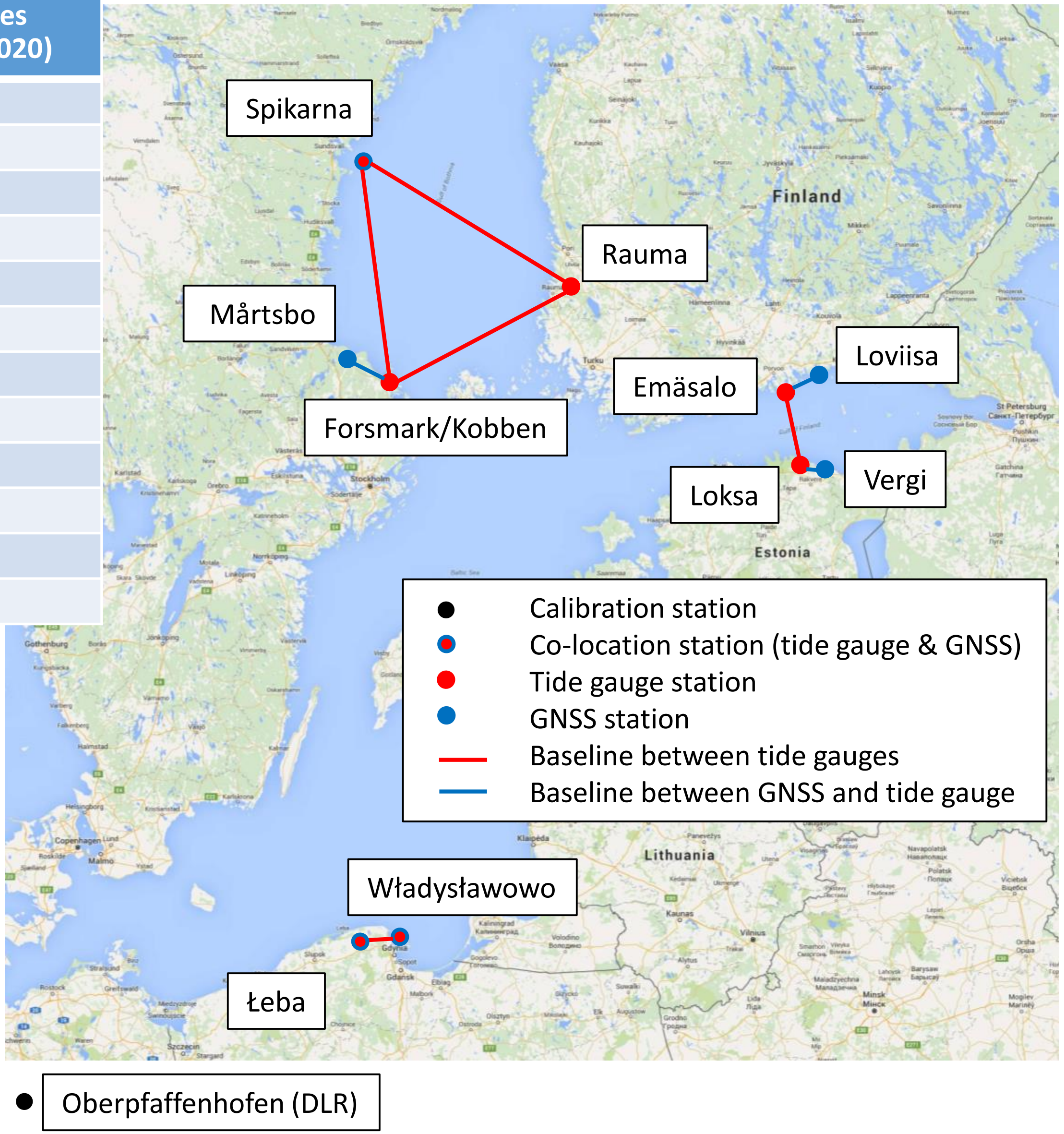


Test Network Baltic Sea (Estonia, Finland, Poland, Sweden & Germany)



Test Network Baltic Sea (Estonia, Finland, Poland, Sweden & Germany)

Location	Local Tie	Operational Since	No. SAR Scenes (Status 31.12.2020)
Mårtsbo, Sweden	GNSS	07.01.2020	218
Oberpfaffenhofen 112, Germany	GNSS	10.01.2020	85
Oberpfaffenhofen 113, Germany	GNSS	10.01.2020	177
Emäsalo, Finland	Tide Gauge	25.01.2020	185
Loviisa, Finland	GNSS	11.02.2020	106
Loksa, Estonia	Tide Gauge	16.02.2020	164
Vergi, Estonia	GNSS	01.03.2020	81
Władysławowo, Poland	Tide Gauge, GNSS	21.03.2020	142
Rauma, Finland	Tide Gauge	26.04.2020	76
Łeba, Poland	Tide Gauge, GNSS	18.05.2020	116
Forsmark/Kobben, Sweden	Tide Gauge	01.06.2020	97
Spikarna/Vinberget, Sweden	Tide Gauge, GNSS	27.09.2020	57

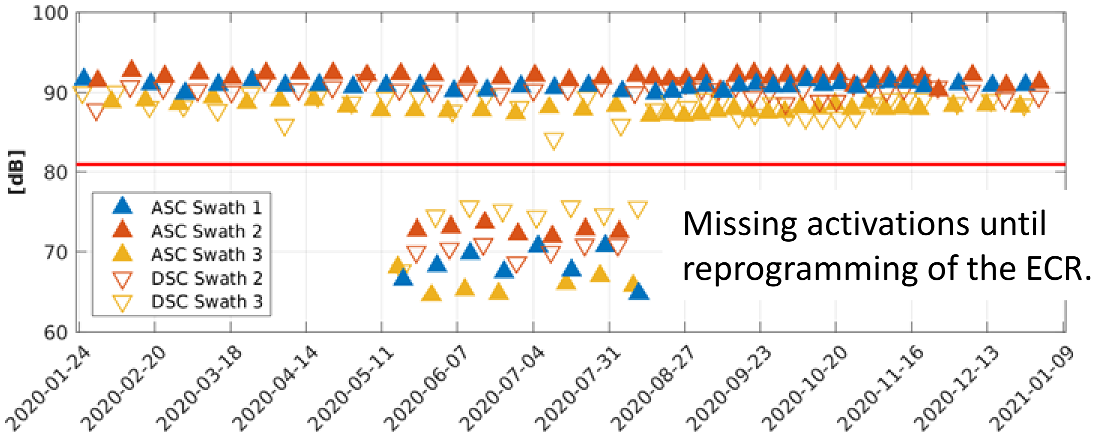


- Several experiments were planned to link GNSS and/or Tide Gauge Stations with Electronic Corner Reflectors and to link Tide Gauges across the Baltic Sea.
- Difficulties to setup the network due to COVID19 and to get radio frequency licenses from national authorities.
- Several issues with ECRs happened during the project: Power supply problems; Water intrusion due to weak sealing of instrument; ECR flooded by ocean waves during storm.

Project Results – SAR Data Analysis

SAR Data Acquisition & Point Target Analysis

- Acquisition Success Rate for all Stations: 84.2%
- Signal Peak Power in average 90 dB, well above 81 dB threshold. Image shows peak power time series for Emäsalo, Finland.
- Sentinel-1 SLC image examples showing the ECR point responses (radar backscatter in dB) for ascending and descending acquisitions.

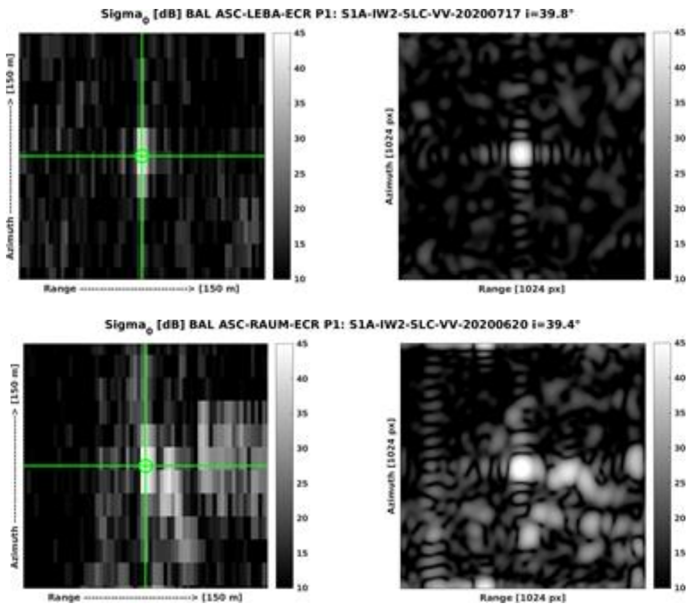


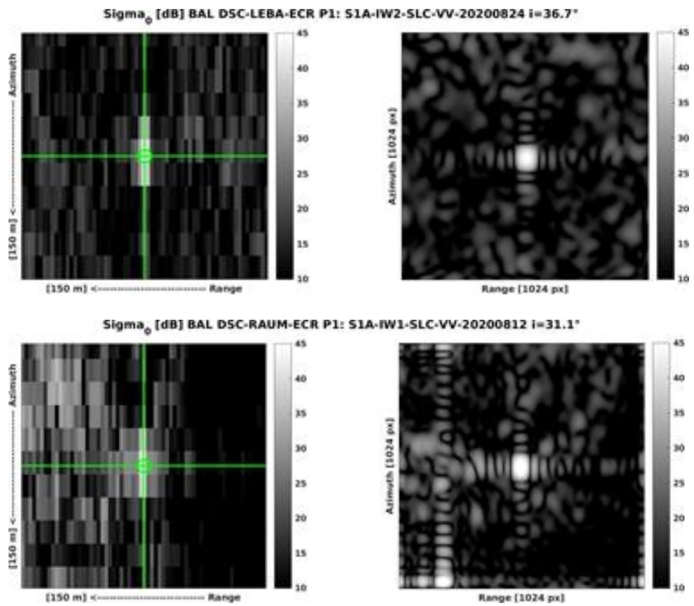
Ascending Image Sample

Descending Image Sample

Łeba
Poland

Rauma,
Finland





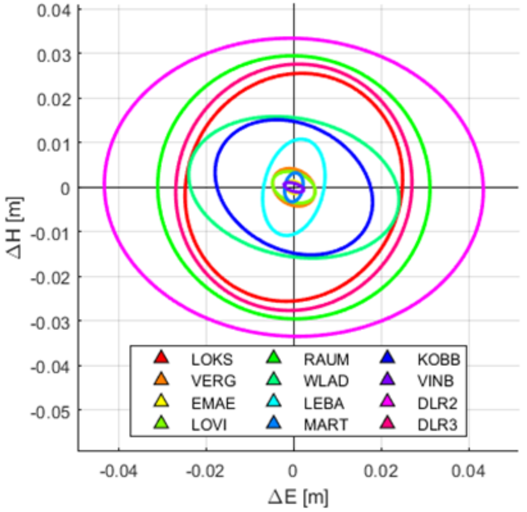
Left columns: Original Sentinel-1 SLC SAR image samples showing an area of 150 m x 150m around ECR peak marked in green.
Right columns: Image areas of 32 x 32 pixels oversampled by a factor of 32 as generated by point target analysis to extract the ECR peak position

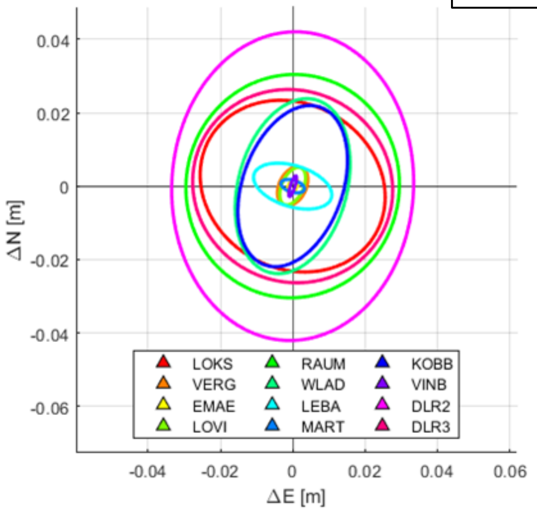
Project Results – Geometric Positioning (SAR & GNSS &)

SAR Positioning

- Internal accuracy from least squares estimation about 1 cm per 3D coordinate axis.

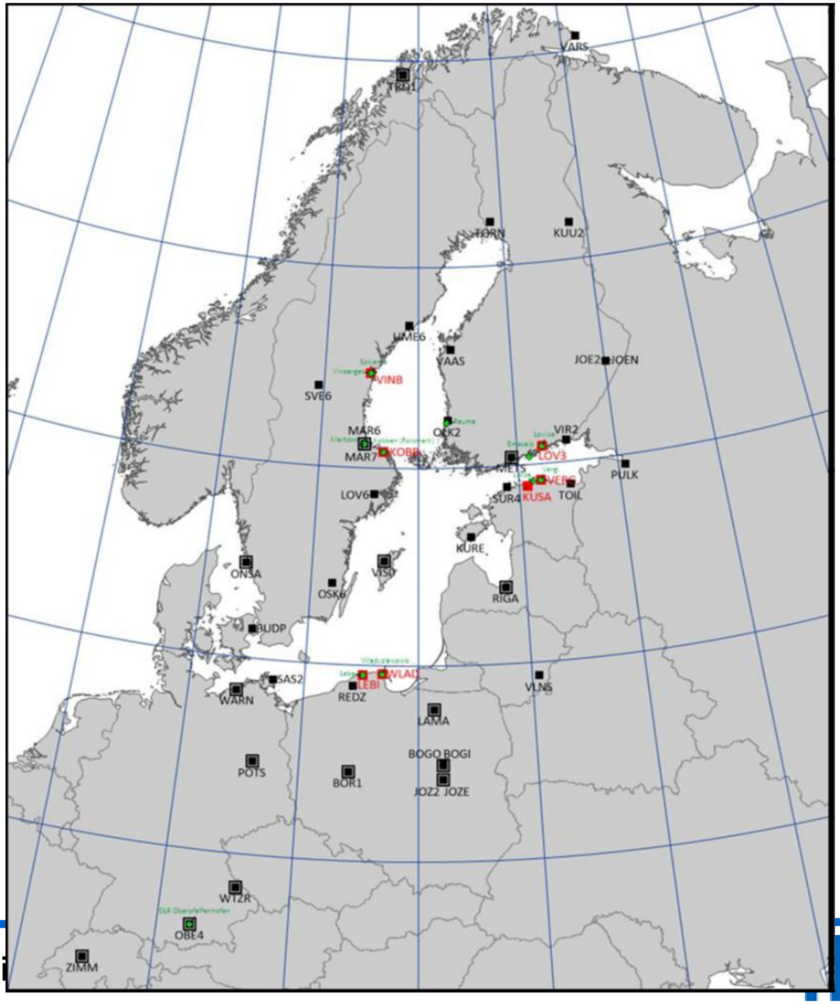
Confidence ellipses for all 12 stations using all available observations in the year 2020. The confidence is shown in the local North, East (right image), and East, height (left image) coordinate frame.
(See presentation by M. Schlaak, C. Gisinger, T. Gruber in session 4.1)





GNSS Positioning

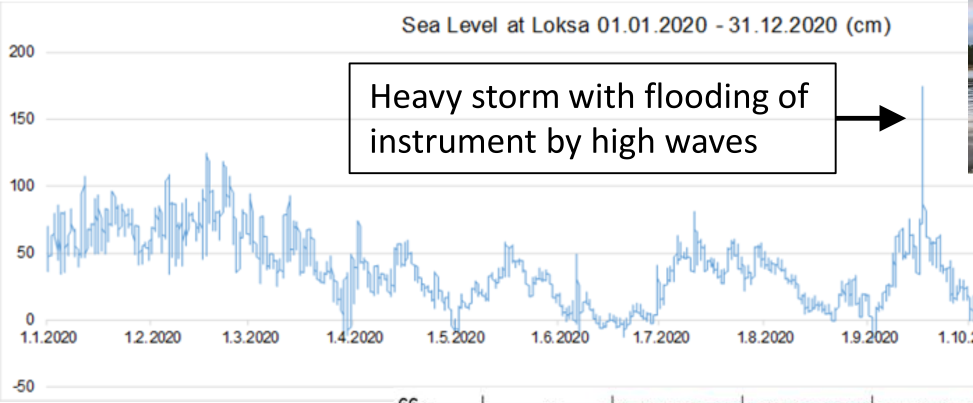
- Baltic Sea GNSS stations (IGS: large square, EPN: small square , EUPOS: red square. Network adjustment using the Bernese GNSS Software in Double Differences (DD) mode.
- The final coordinate solutions for all stations are computed in terms of 3D Cartesian Coordinates in ITRF2014 for epoch 2020.50.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



Project Results – Tide Gauge Data & Geoid

Tide Gauge Data Processing

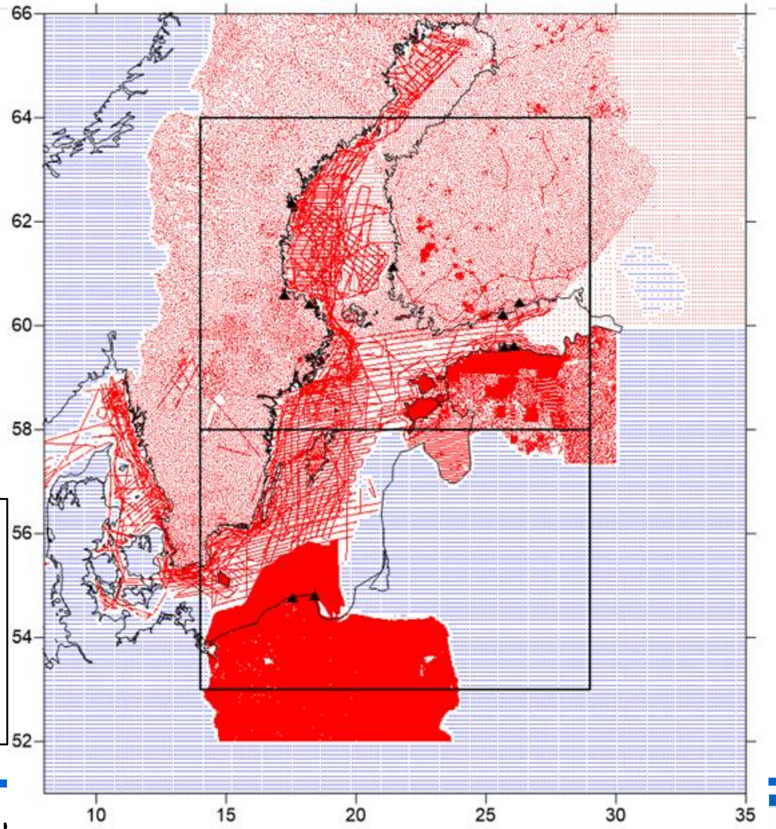
- Tide gauge readings for all stations are provided in EVRS.
- Hourly data checked for outliers and filtered.
- Pre-processed tide gauge data series for year 2020 was used for computing the annual mean sea level estimates in the common EVRS.



Regional Geoid based on common Equipotential Surface

- Least squares modification of Stokes' formula with additive corrections (LSMSA) is used.
- GOCO06S 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' x5') generated by EIGEN-6C4 are plotted as blue dots.



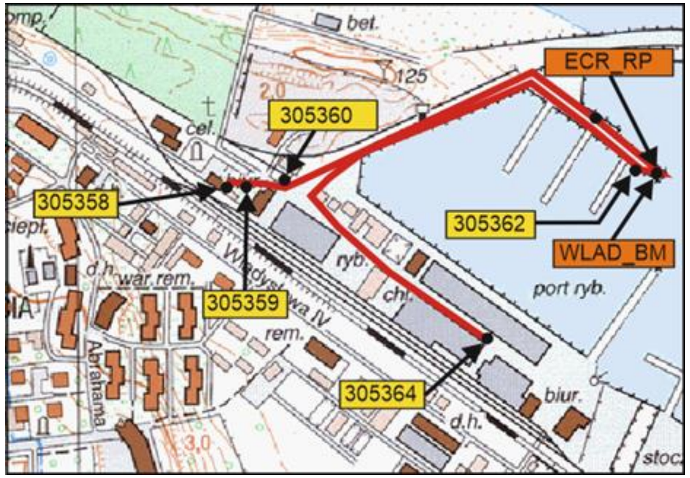
Project Results – Height System Unification / Absolute Sea Level

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.

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.



Local tie (levelling) in Władysławowo, Poland

ECR Station	GNSS Ellipsoidal Height [m]	Local Tie GNSS to ECR [m]	ECR Ellipsoidal Height computed [m]	ECR Ellipsoidal Height observed [m]	ECR Ellipsoidal Height Difference computed – observed [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

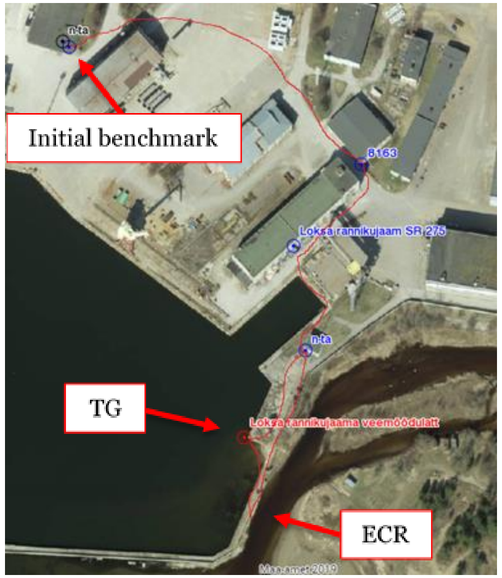
Project Results – Height System Unification / Absolute Sea Level

Absolute Height Experiment: Physical Heights & Absolute Sea Level

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

  Computation physical height of tide gauge zero marker: $H^{TG} = h^{ECR} + \Delta h^{TG}_{ECR} - N^{TG}$

  Computation absolute sea level height at tide gauge: $S^{TG} = h^{ECR} + \Delta h^{TG}_{ECR} - N^{TG} + z^{TG} = H^{TG} + z^{TG}$



Local tie (levelling) in Loksa, Estonia

ECR Station	ECR Ellipsoidal Height observed [m]	Local Tie ECR to Tide Gauge [m]	Tide Gauge Geoid Height [m]	Tide Gauge Physical Height [m]	Tide Gauge Reading [m]	Tide Gauge Absolute Sea Level [m]
Władysławowo	+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**

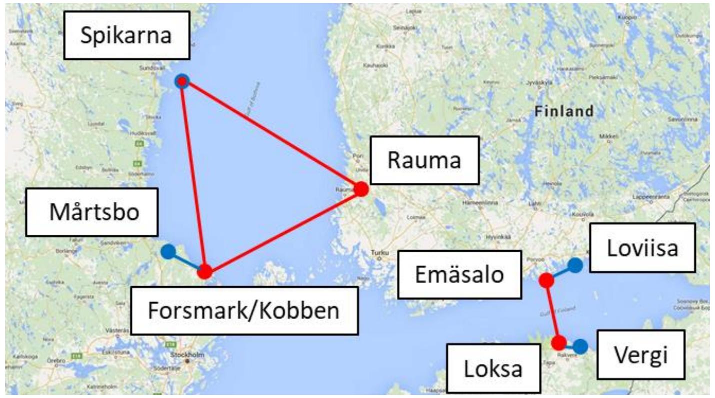
Relative Baseline Experiment: GNSS Baseline Height Difference vs. ECR Height Difference

- 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.

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

$$\Delta h^{ECR} = \left(h^{ECR-B} - \Delta h^{ECR-B}_{GNSS-B}\right) - \left(h^{ECR-A} - \Delta h^{ECR-A}_{GNSS-A}\right)$$

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



from Station A	to Station B	GNSS Ellipsoidal Height Difference [m]	ECR Ellipsoidal Height Difference [m]	Difference Ellipsoidal Height Difference [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

Project Results – Height System Unification / Absolute Sea Level

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

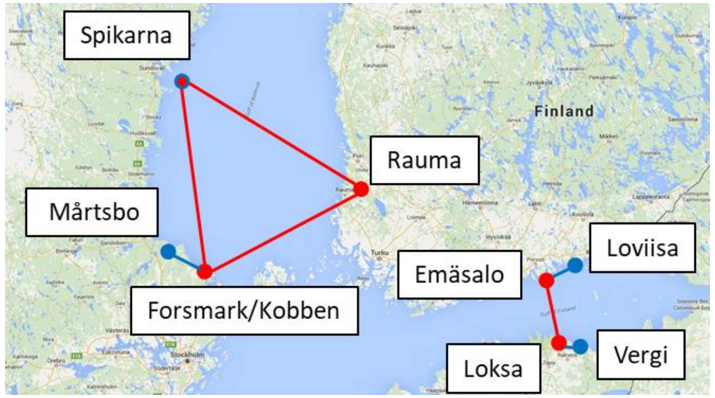
- Relative absolute sea level differences are compared between tide gauge stations and those observed with the ECR´s. For the relative comparisons between station A and station B the following formulas are applied. The result corresponds to physical height differences between station A and station B.

$$\Delta z^{TG} = z^{TG-B} - z^{TG-A}$$

$$\Delta S^{TG} = S^{TG-B} - S^{TG-A}$$

$$S^{TG-X} = H^{TG-X} + z^{TG-X}$$

$$\Delta\Delta S^{TG} = \Delta z^{TG} - \Delta S^{TG} = \Delta\Delta H^{TG}$$



from Station A	to Station B	Tide Gauge Height Difference [m]	Absolute Sea Level Height Difference [m]	Difference Sea Level/Height Difference [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

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