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

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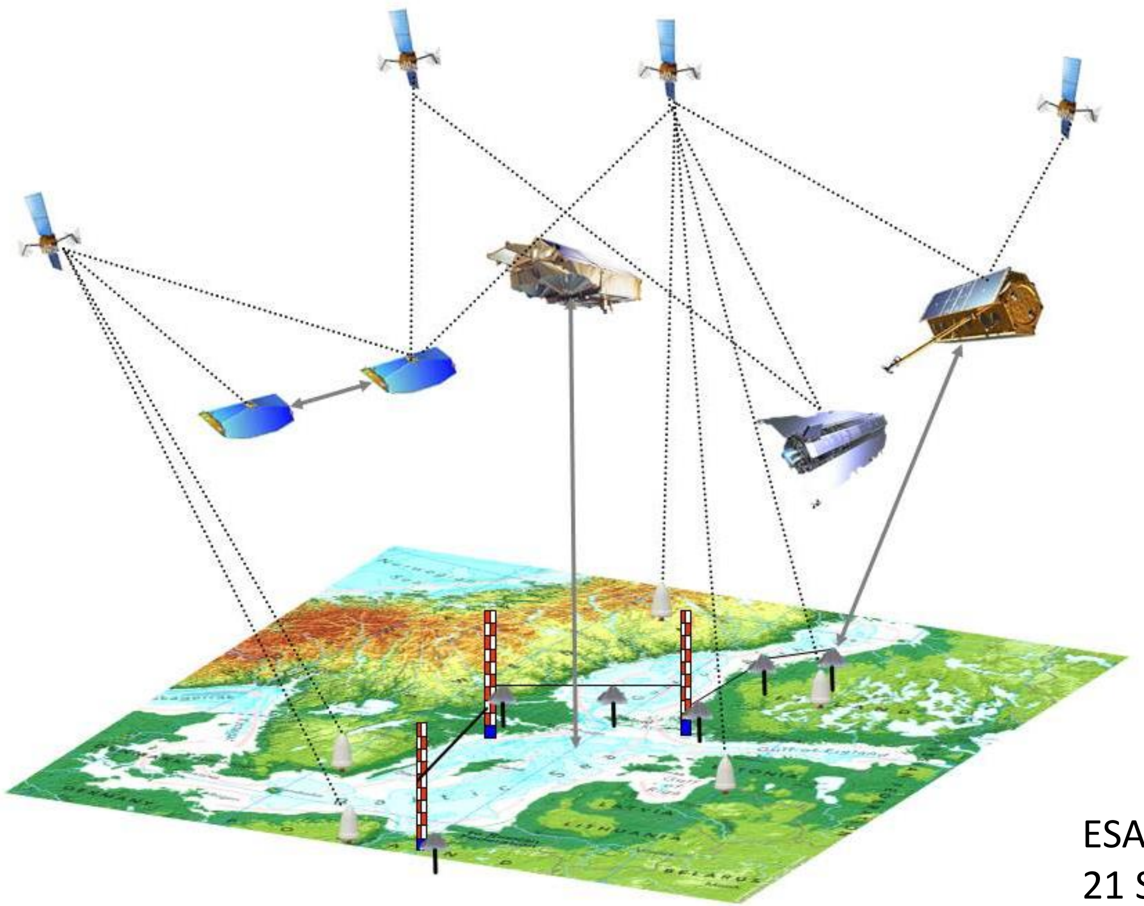

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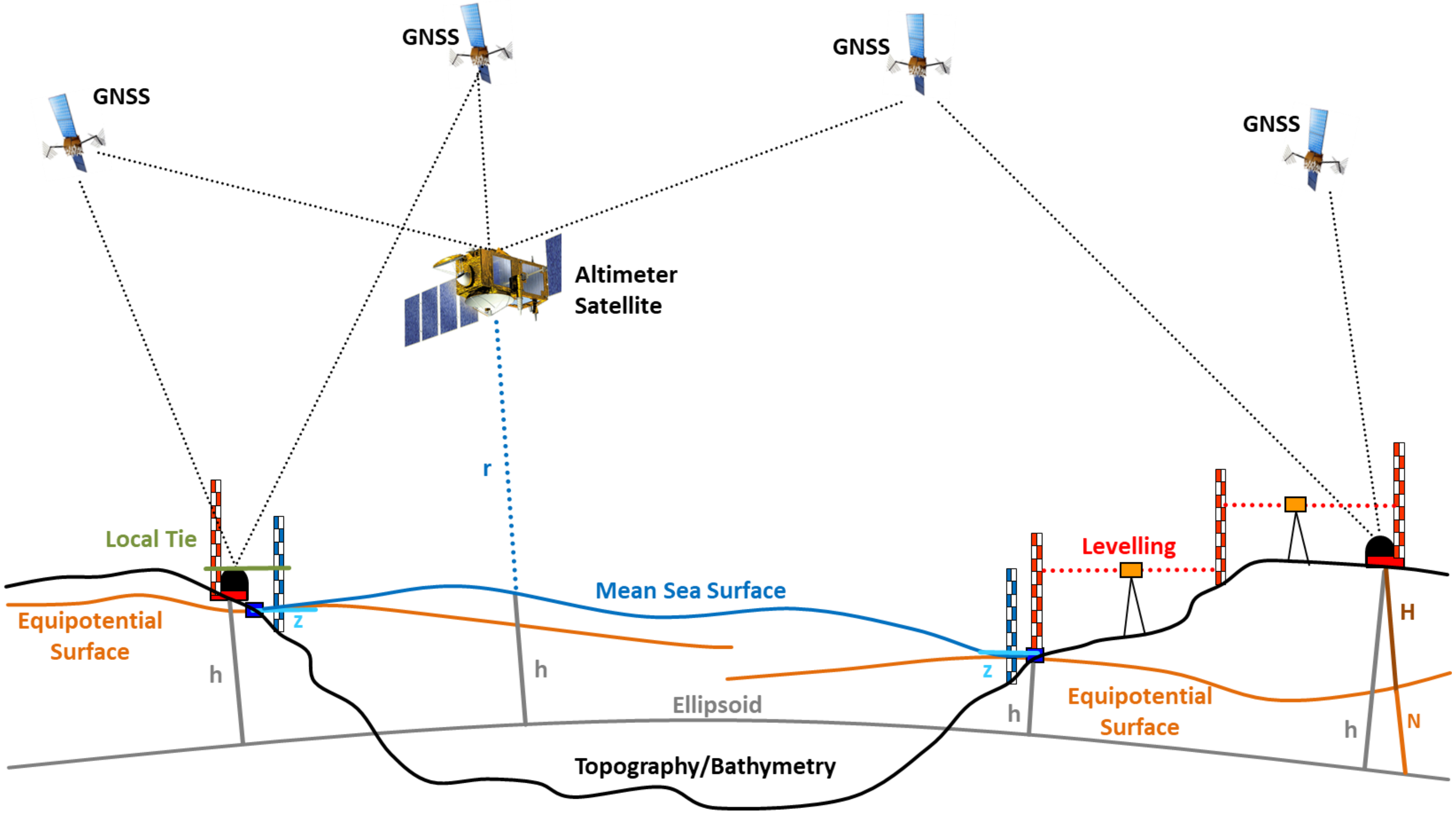
# Overview Height System & Sea Level




GNSS Reference Marker

Tide Gauge Reference Marker

GNSS Permanent Station

**Earth Geometry**

h Ellipsoidal Height

r Altimeter Range

**Earth Gravity Field**

H Physical Height

N Local Geoid Height

**Tide Gauges**

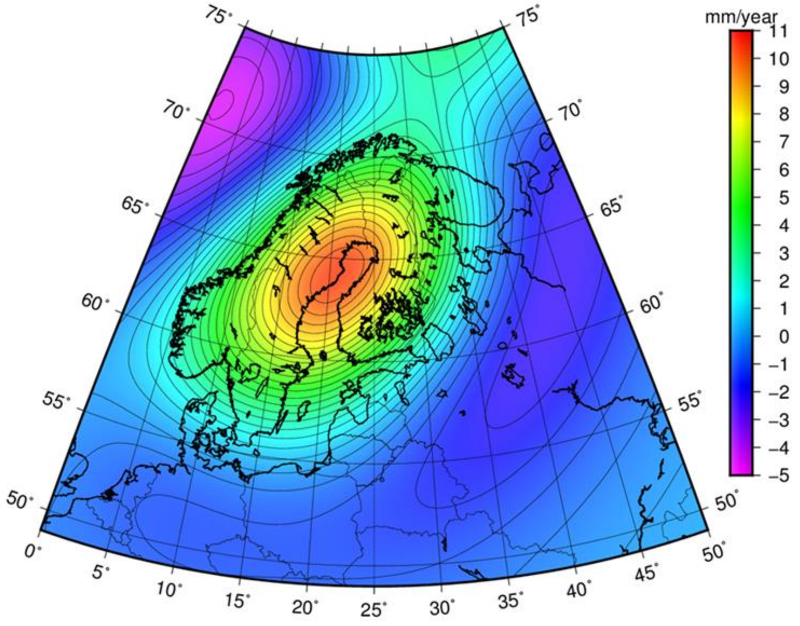
z Height wrt. Tide Gauge Zero Marker

# Scientific Challenges & Objectives

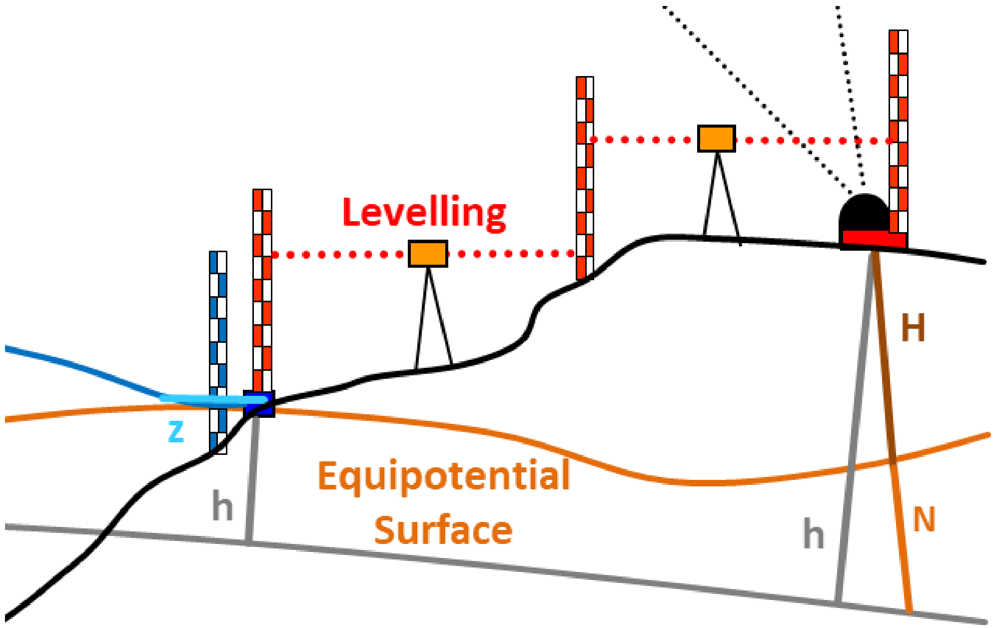
**Vertical Land Movement (Geometry)**
- Post-glacial rebound
- Subsidence
- any other cause ….

**Tide Gauge Vertical Movement**
- Only relative sea level observations
- Permanent monitoring needed

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




Gridded vertical displacement rate
(Steffen & Ågren, pers. comm.)

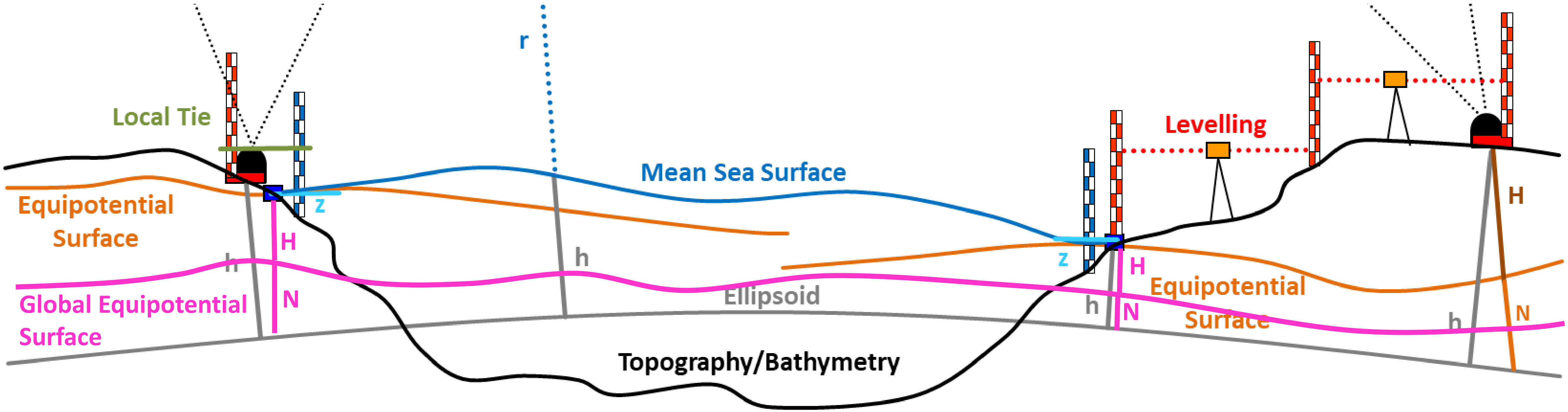


# Scientific Challenges & Objectives

**Height Systems (Gravimetry)**
- Different height systems in countries
- Mass Redistribution

**Height System Unification**
- Unique height reference surface for all countries
- Local geoid modelling per tide gauge station

**Objective 2**
Geoid heights at tide gauges to compute absolute physical heights with respect to a global reference equipotential surface.



# Scientific Challenges & Objectives

$$S^{TG}(t) = h^{TG}(t) - N^{TG}(t) + z^{TG}(t) = H^{TG}(t) - N^{TG}(t)$$

**Geometry**

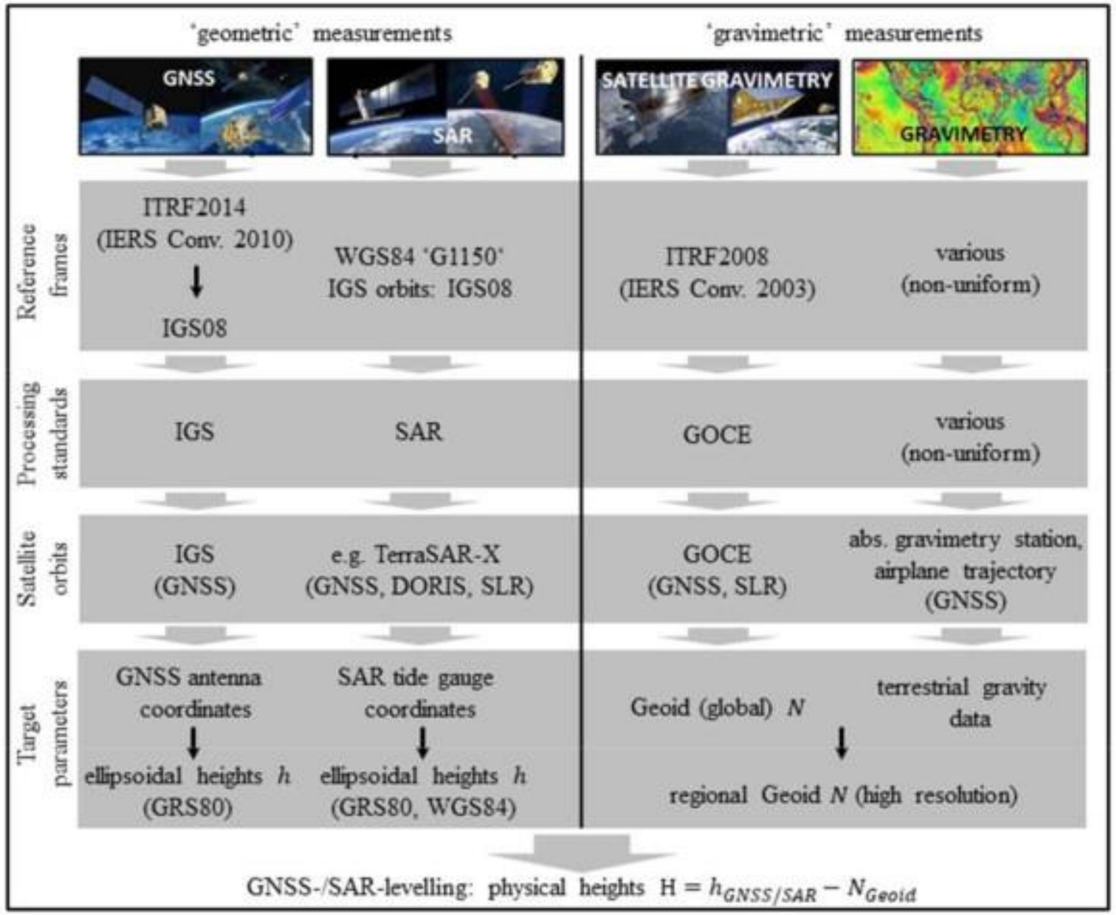
- Geometric height tide gauge zero marker per epoch
- Tide gauge readings relative to zero marker per epoch

**Gravimetry**

- Tide gauge geoid height wrt. a global equipotential surface per epoch
- Physical height per epoch

**Objective 3**

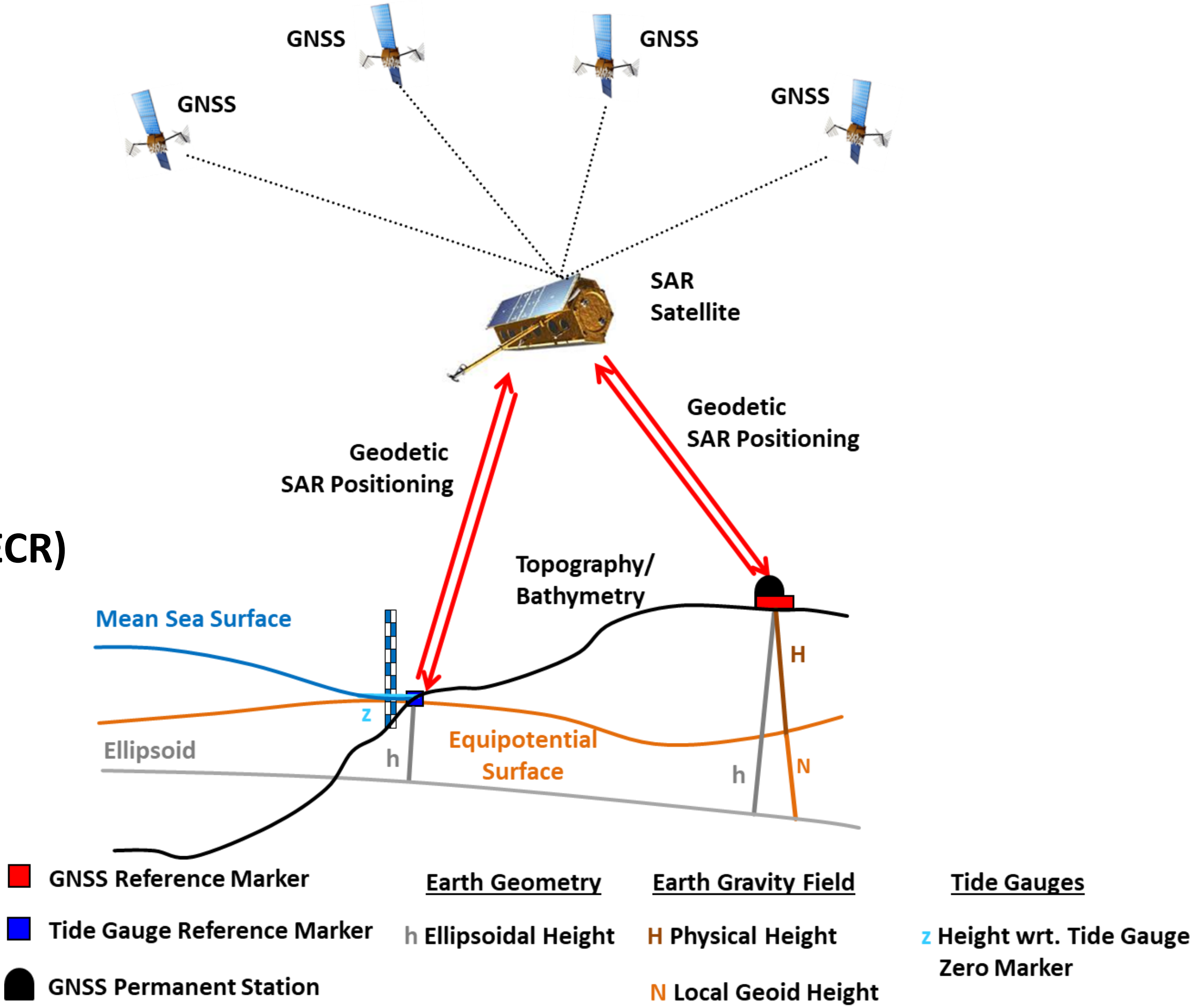
Combination of geometric and physical heights in a common reference frame to determine absolute sea level heights.



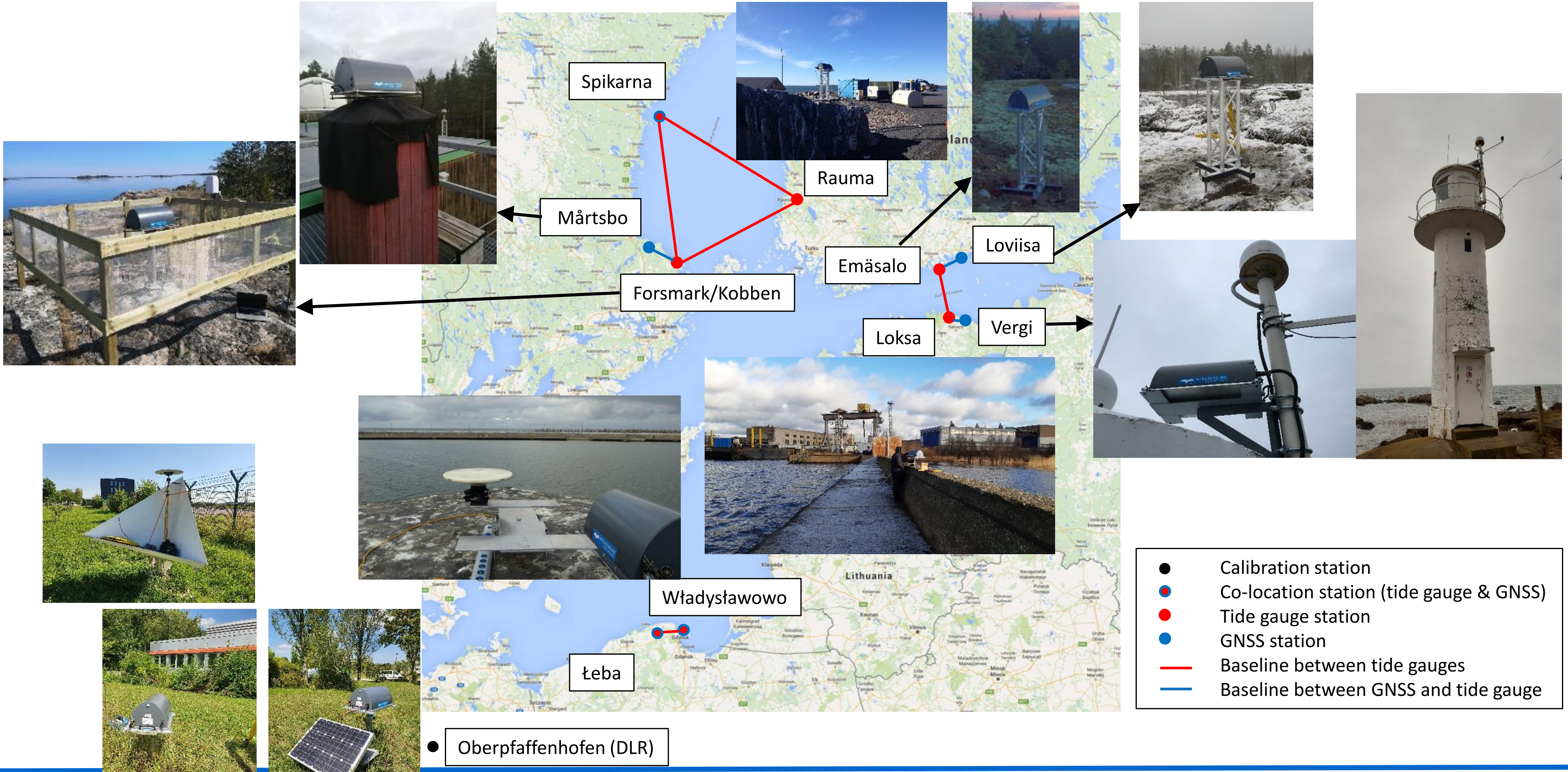
# Geodetic SAR for Ellipsoidal Height Determination

## Passive SAR Targets (Corner Reflectors)

## Active SAR Targets (Electronic Corner Reflectors - ECR)

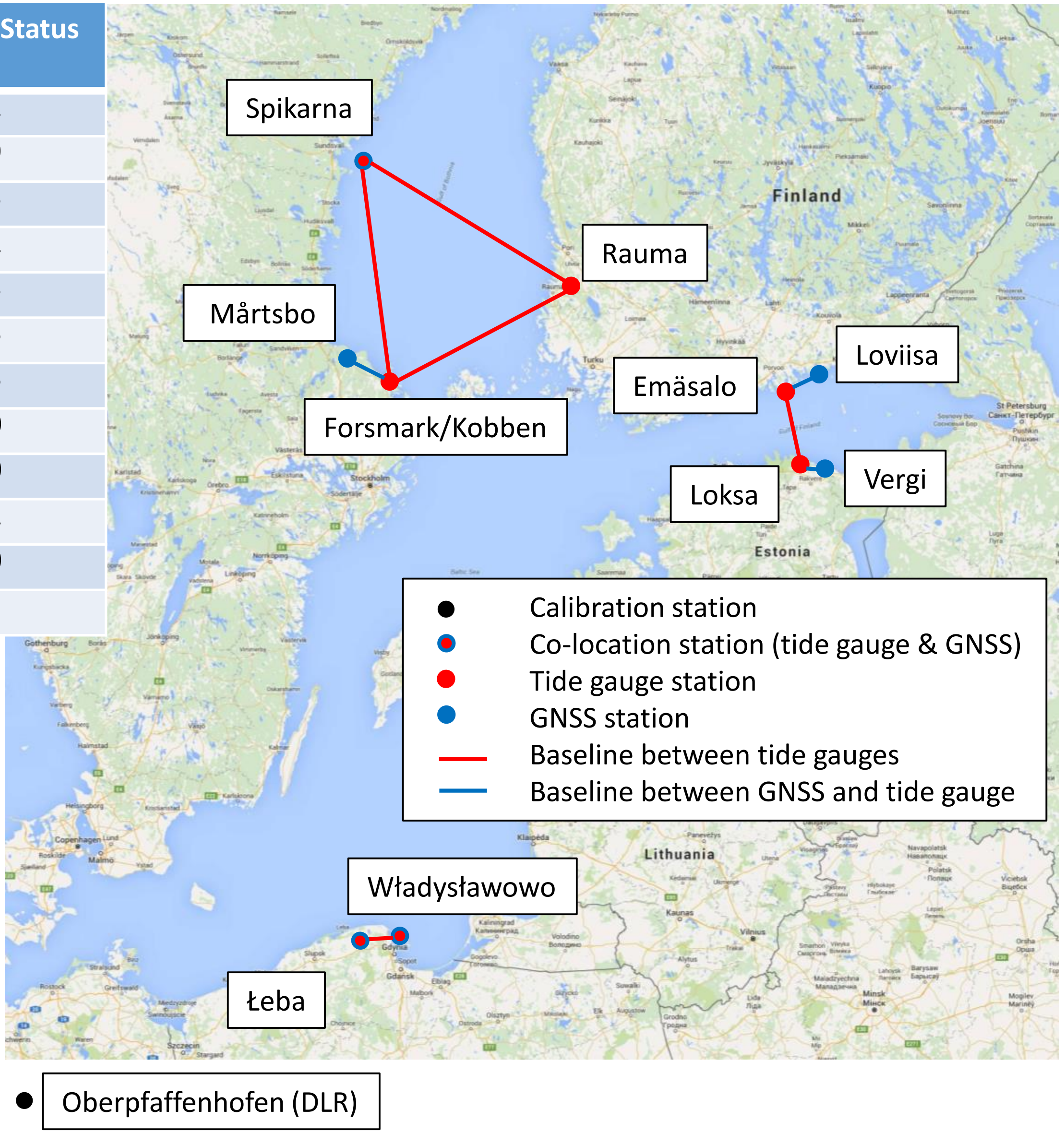



# Test Case Baltic Sea



# Test Case Baltic Sea

| Location | Local Tie | Operational Since | No. SAR Scenes (Status 7.8.2020) |
|---|---|---|---|
| Loksa, Estonia | Tide Gauge | 16.02.2020 | A: 66 D: 62 |
| Vergi, Estonia | GNSS | 06.03.2020 | A: 40 D: 39 |
| Emäsalo, Finland | Tide Gauge | 25.01.2020 | A: 48 D: 33 |
| Loviisa, Finland | GNSS | 06.02.2020 | A: 30 D: 31 |
| Rauma, Finland | Tide Gauge | 21.04.2020 | A: 28 D: 13 |
| Oberpfaffenhofen 112, Germany | GNSS | 10.01.2020 | A: 68 D: 35 |
| Oberpfaffenhofen 113, Germany | GNSS | 10.01.2020 | A: 68 D: 35 |
| Władysławowo, Poland | Tide Gauge, GNSS | 26.03.2020 | A: 29 D: 30 |
| Łeba, Poland | Tide Gauge, GNSS | 15.05.2020 | A: 20 D: 20 |
| Mårtsbo, Sweden | GNSS | 07.01.2020 | A: 47 D: 61 |
| Forsmark/Kobben, Sweden | Tide Gauge | 01.06.2020 | A: 30 D: 20 |
| Spikarna, Sweden | Tide Gauge, GNSS | Not yet installed | - |

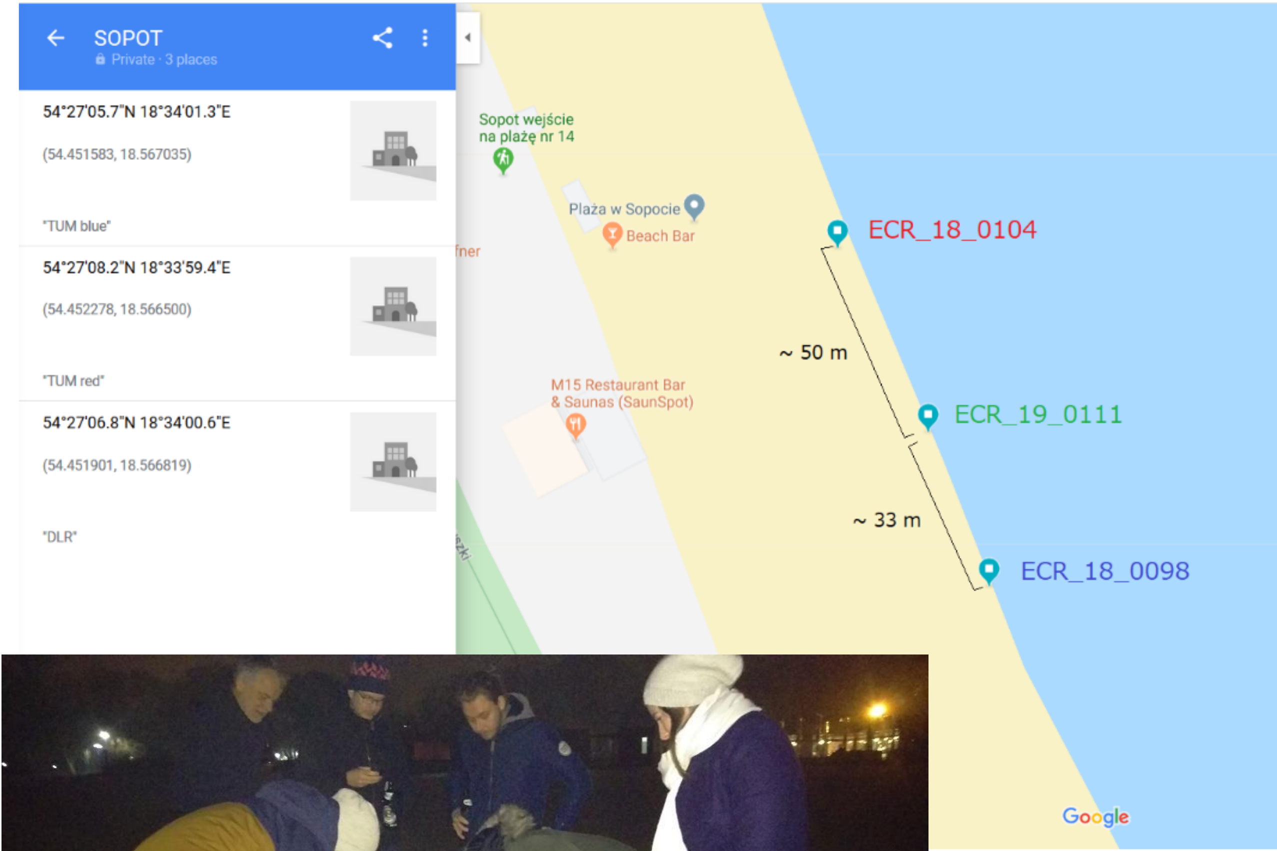


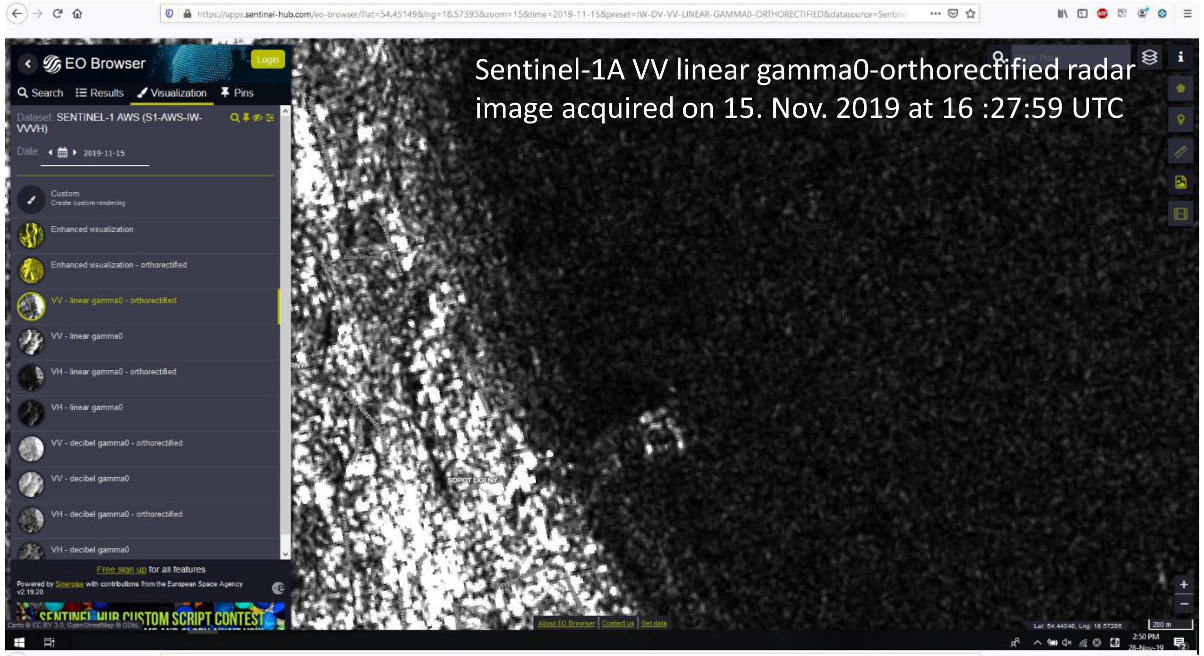

<u>Experiments Plan</u>:

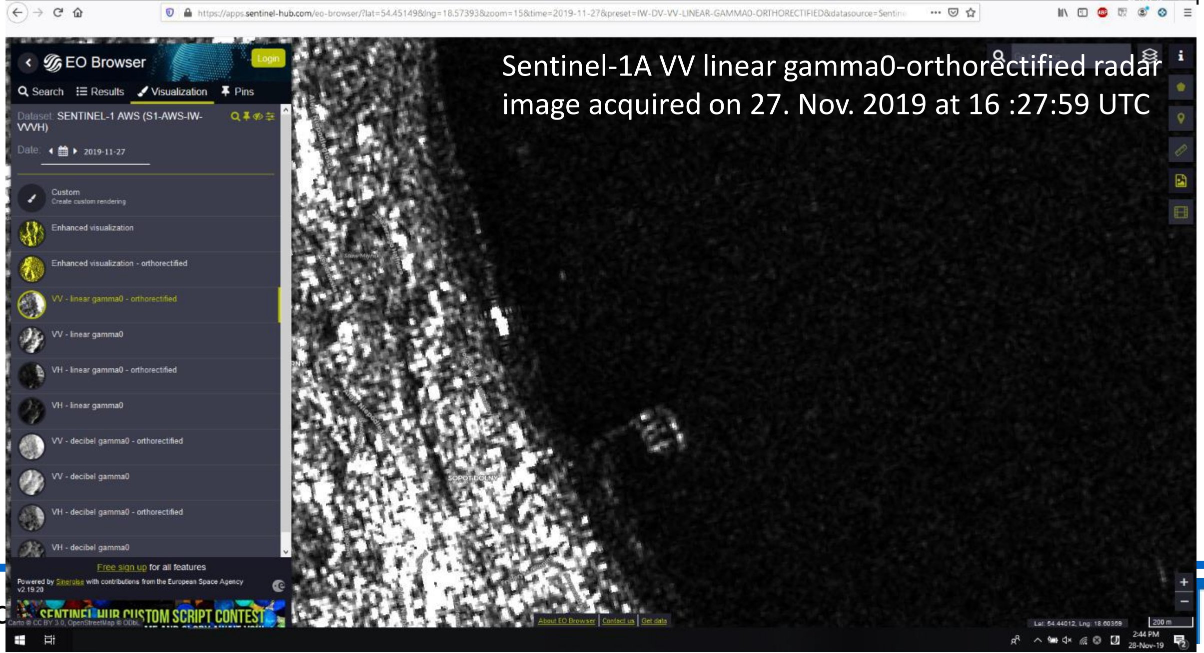
1. ECR Calibration at DLR Oberpfaffenhofen
2. Collocation Sites: Tide Gauges and permanent GNSS
3. Tide Gauge Sites
4. Permanent GNSS Sites – Short Baselines
5. Long Baselines (Finland to Estonia, Sweden to Finland)
6. Tide Gauge Linking (Polish Stations)
7. Absolute vs. Relative SAR for short Baselines

# Test Case Baltic Sea

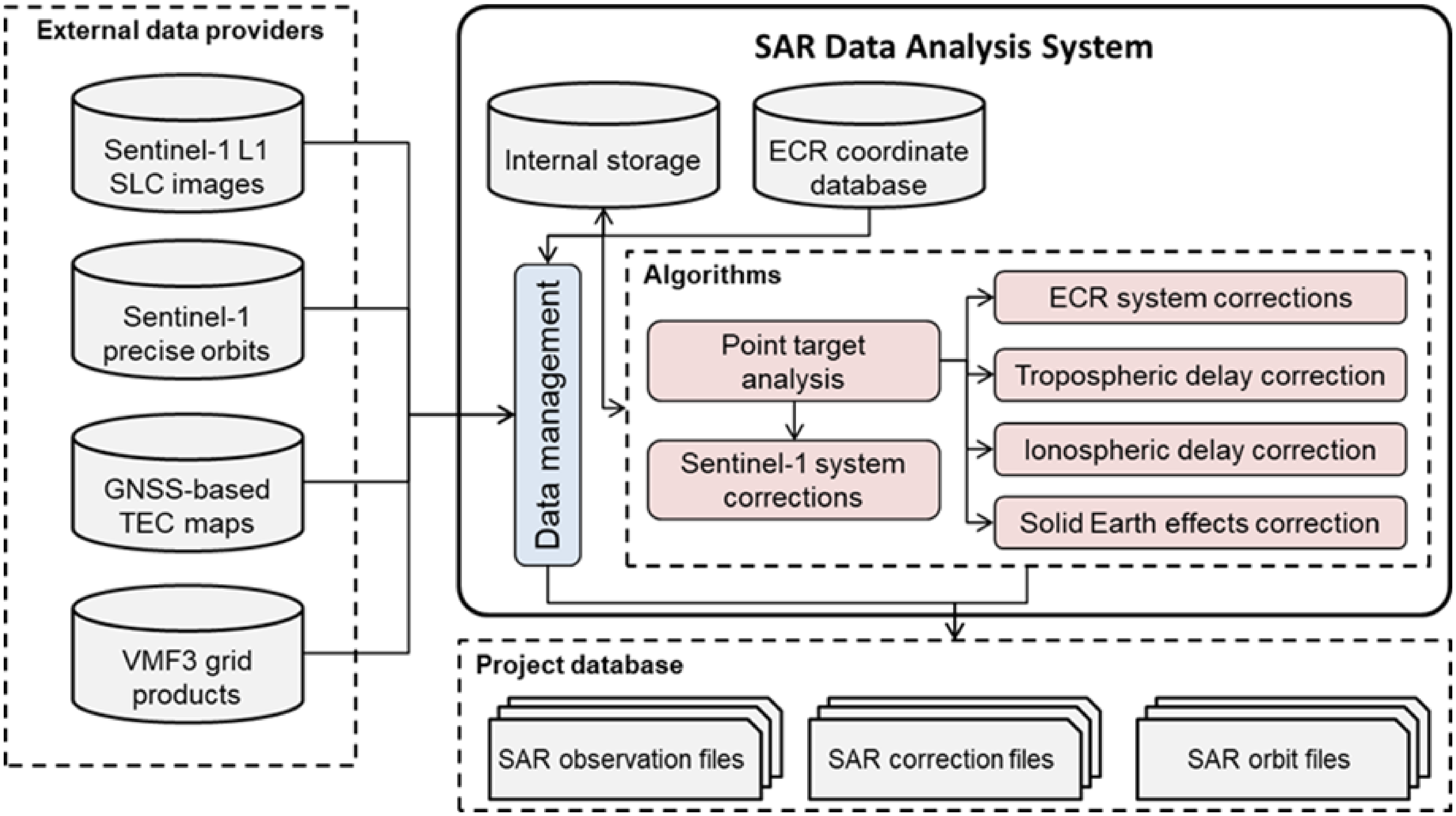
## ECR Testing at Sopot/Gdansk, Poland (27. Nov. 2019)



# SAR Data Analysis

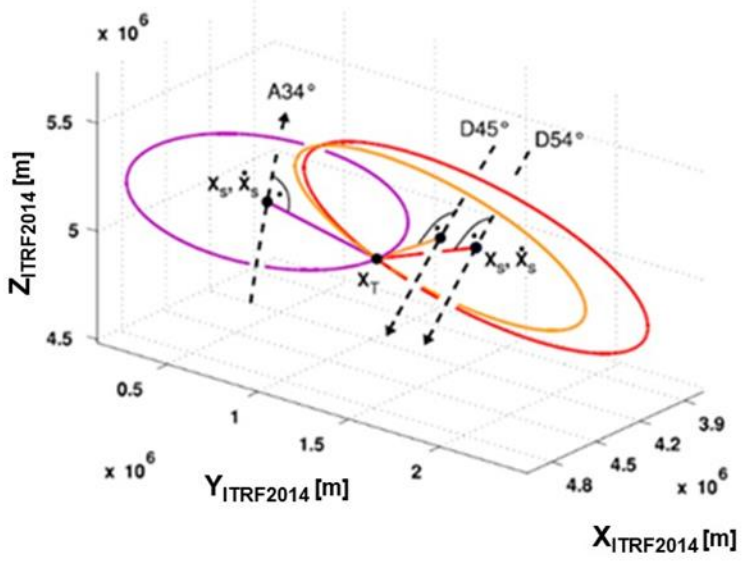


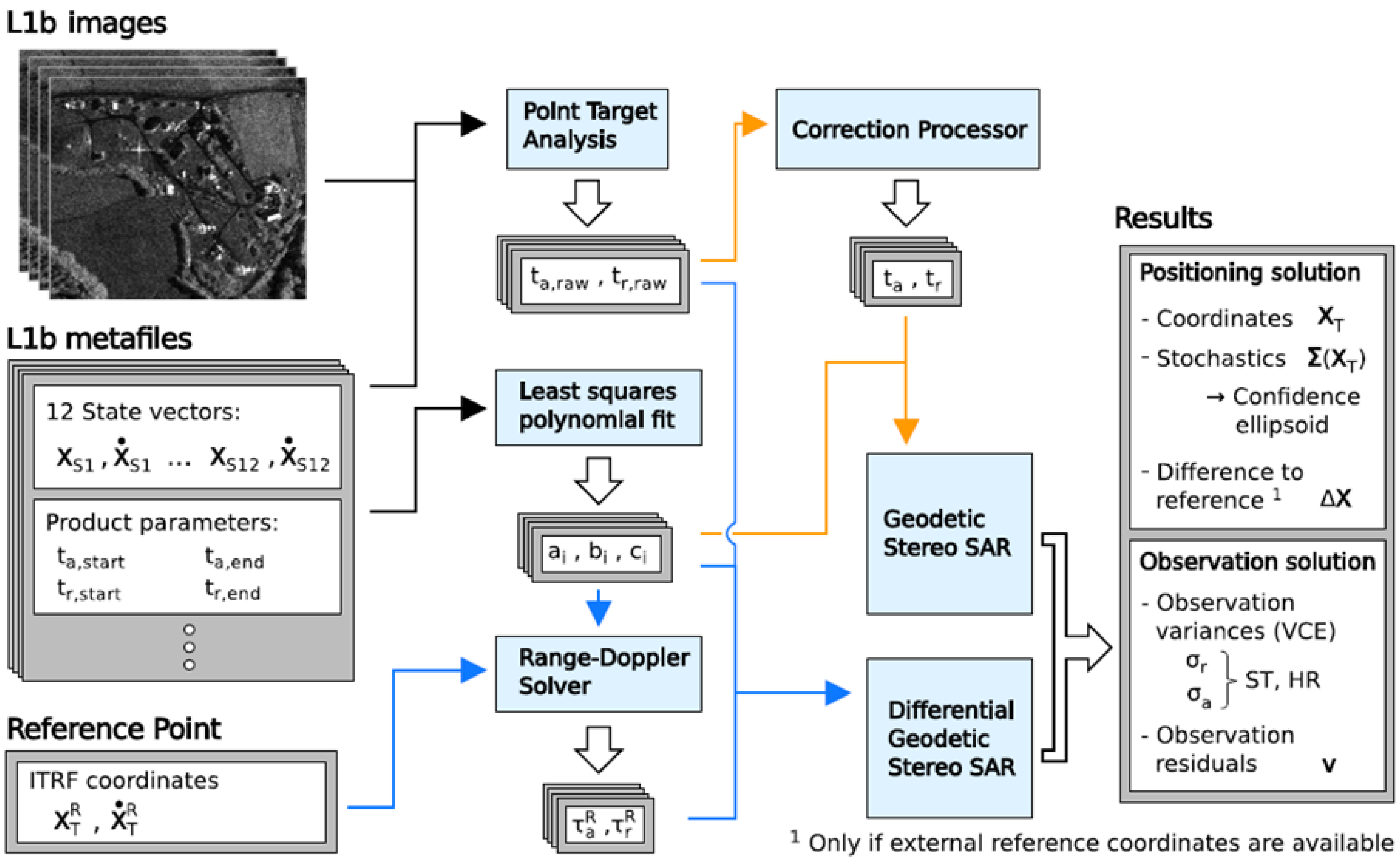
# SAR Positioning

Range-Doppler Equation System

$$|\mathbf{X_S}(t) - \mathbf{X}| - \frac{c}{2} \cdot \tau$$

$$\frac{\dot{\mathbf{X}}_\mathbf{S}(t)(\mathbf{X} - \mathbf{X_S}(t))}{|\dot{\mathbf{X}}_\mathbf{S}(t)||\mathbf{X} - \mathbf{X_S}(t)|} = sin\alpha$$

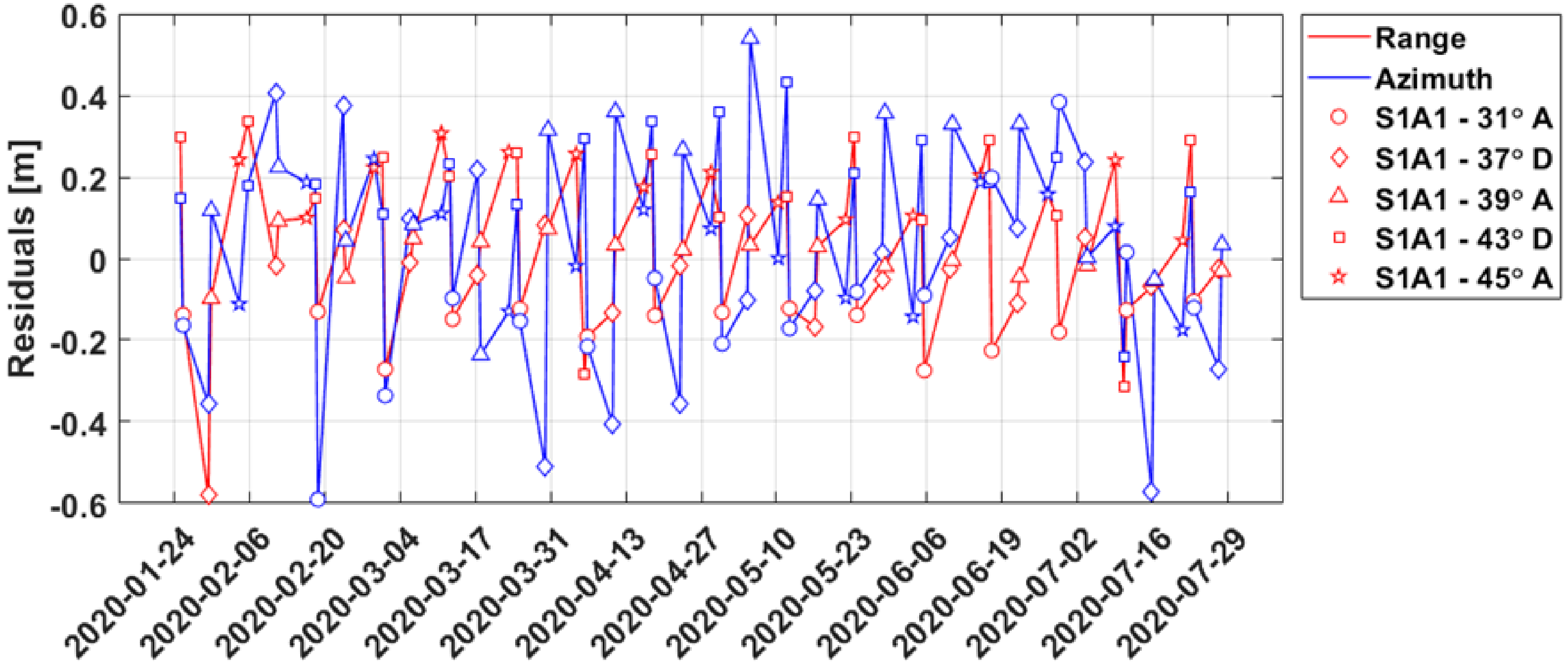


# SAR Positioning – First Results

Absolute positioning: without compensation for outliers and biases per incidence (original approach)

| Station | X [m] | Y [m] | Z [m] | $\sigma_X$ [m] | $\sigma_Y$ [m] | $\sigma_Z$ [m] |
|---|---|---|---|---|---|---|
| Emäsalo (original) | 2864911.2403 | 1374214.0007 | 5511816.3914 | 0.0182 | 0.0304 | 0.0252 |

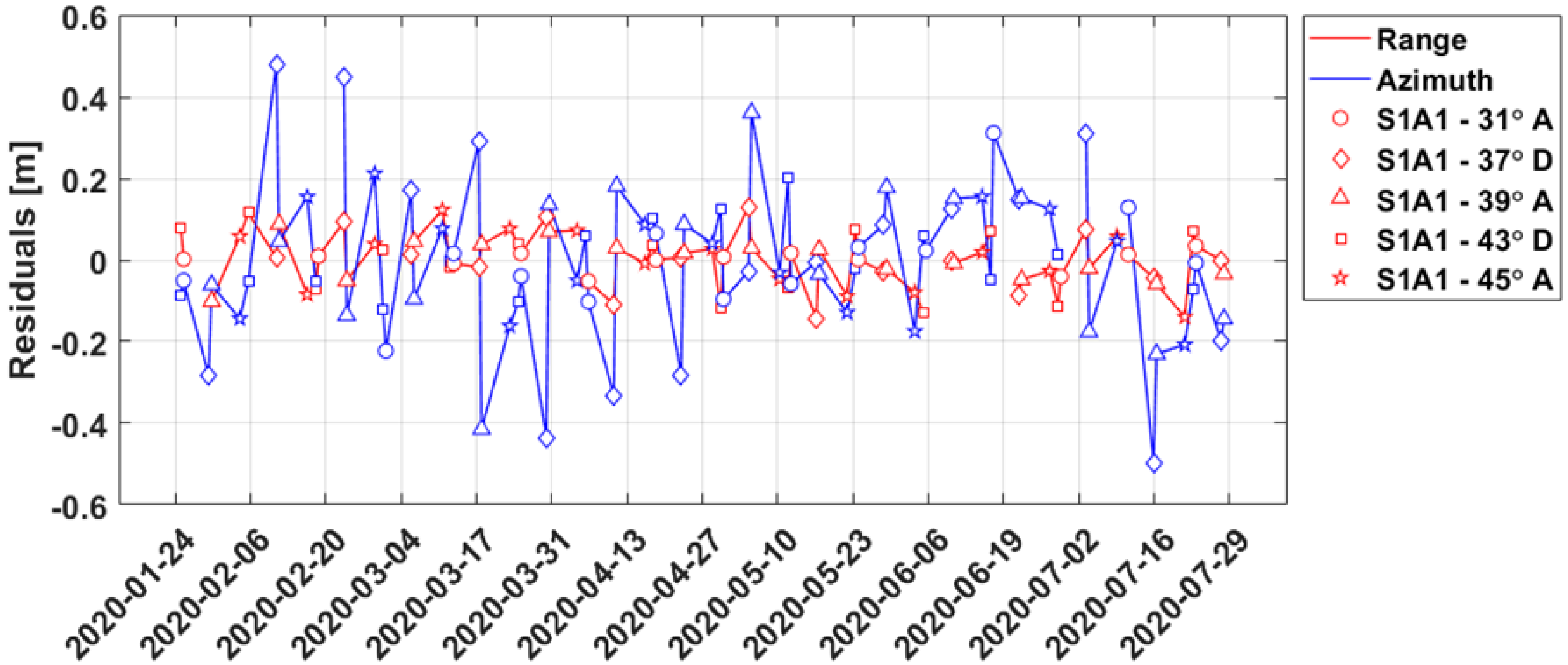



Least squares minimized residuals of the range and azimuth observations per incidence angle. The azimuth timings are expressed in meters by multiplication with the flight velocity of Sentinel-1.
Legend: S1A1: Sentinel-1A image, Incidence angle in degrees, A/D: Ascending/Descending arc.

# SAR Positioning – First Results

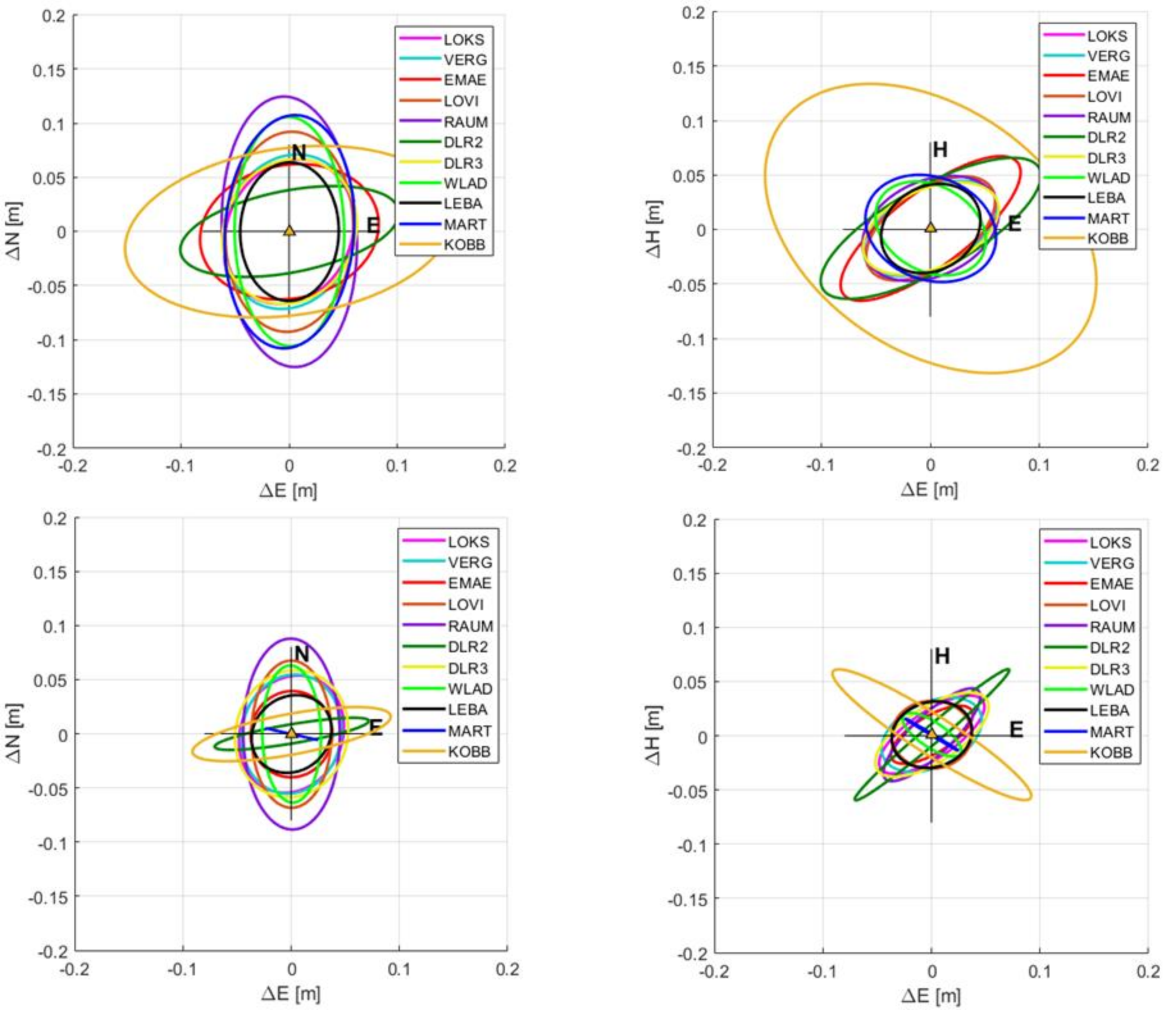
Absolute positioning: without (original) and with (refined) compensation for outliers and biases per incidence angle

| Station | X [m] | Y [m] | Z [m] | $\sigma_X$ [m] | $\sigma_Y$ [m] | $\sigma_Z$ [m] |
|---|---|---|---|---|---|---|
| Emäsalo (original) | 2864911.2403 | 1374214.0007 | 5511816.3914 | 0.0182 | 0.0304 | 0.0252 |
| Emäsalo (refined) | 2864911.2403 | 1374214.0007 | 5511816.3914 | 0.0110 | 0.0142 | 0.0119 |




Least squares minimized residuals of the range and azimuth observations per incidence angle. The azimuth timings are expressed in meters by multiplication with the flight velocity of Sentinel-1.
Legend: S1A1: Sentinel-1A image, Incidence angle in degrees, A/D: Ascending/Descending arc.

# SAR Positioning – First Results




95% confidence ellipsoids in the horizontal North-East (left column) and vertical height-East view (right column) using the original (upper row) and refined (bottom row) absolute positioning technique.

Estimated coordinate standard deviations for all stations of the Baltic ECR stations applying the refined positioning technique.

| Station | $\sigma_X$ [m] | $\sigma_Y$ [m] | $\sigma_Z$ [m] | # Images |
|---|---|---|---|---|
| Loksa | 0.0150 | 0.0180 | 0.0167 | 122 |
| Vergi | 0.0159 | 0.0167 | 0.0161 | 75 |
| Emäsalo | 0.0110 | 0.0142 | 0.0119 | 77 |
| Loviisa | 0.0186 | 0.0146 | 0.0174 | 72 |
| Rauma | 0.0230 | 0.0190 | 0.0224 | 28 |
| DLR2 | 0.0064 | 0.0259 | 0.0182 | 21 |
| DLR3 | 0.0149 | 0.0194 | 0.0192 | 99 |
| Władysławowo | 0.0166 | 0.0099 | 0.0162 | 55 |
| Łeba | 0.0113 | 0.0126 | 0.0123 | 36 |
| Mårtsbo | 0.0034 | 0.0080 | 0.0055 | 102 |
| Forsmark/Kobben | 0.0248 | 0.0260 | 0.0163 | 43 |

# Summary, Conclusions & Future Work (1)

- For absolute Sea Level and Height System Unification tide gauges need to be connected with global geometric and physical height reference networks.
- Very crucial for such an observing system is the monitoring of the tide gauge stations for vertical movements and the determination of physical heights referring to a global physical reference surface.
- Only a few tide gauge stations nowadays are permanently equipped with GNSS receivers. Therefore, as a new technique, the 3D geodetic SAR positioning with active transponders (ECRs) for densifying existing permanent GNSS networks is introduced.
- The effort and costs for installing, maintaining and operating active SAR transponders is much less than for a permanent GNSS receiver. Data are collected via the SAR satellites and there is no need to store and transmit data.
- Three different heights need to be combined (tide gauge records, ellipsoidal heights, geoid heights). To avoid systematic errors in the resulting absolute sea level heights it is needed to use same standards and reference systems.
- For a feasibility study an observing system has been installed by the project team in the Baltic Sea area. All in all, 12 ECRs are installed.
- A number of experiments has been identified. This includes among others ECR calibration, absolute and relative positioning, short baseline and long baseline coordinate transfer across the sea.
- Absolute positioning experiments for 11 stations have been performed in order to identify the performance of the active transponders in the sense of achievable internal accuracies.

# Summary, Conclusions & Future Work (2)

- The internal accuracy of 3D absolute positions applying a simple outlier detection procedure is at a level of about 4.3 cm for the station in Emäsalo.
- Post-fit range residuals depend on the incidence angle of radar image. Refined procedure estimates biases per incident angle class. 3D position accuracy improved to about 2.1 cm for Emäsalo (similar for other stations).
- Error ellipses in a local horizontal coordinate system (North-East-Height) are computed. Ellipses with larger eccentricities indicate correlations between coordinate axes.
- Absolute positions are very stable disregarding the applied approach. This is an indicator that the absolute coordinate estimation is robust and that it delivers meaningful results.
- ECR locations need to be selected very carefully such that possible other artificial reflectors are avoided.
- Analyses to be performed: (1) Refinement of SAR positioning for phase center variations and electronic antenna behavior; (2) Application of relative SAR positioning; (3) Calibration of ECR and identification of possible systematic delays; (4) Local geoid refinement at the tide gauge stations; (5) Processing tide gauge observations; (6) Transformation of coordinates into a unique reference frame; (7) Computation of absolute sea level heights at tide gauge stations and identification of height system offsets; (8) Validation of height system differences by comparison to levelled heights.
- There is still a lot to be done to meet the 1 cm requirement in height. ECRs can help to systematically observe vertical movement of tide gauge stations. Then tide gauges can also be used for determining the absolute sea level.