BALTIC+

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

Executive Summary

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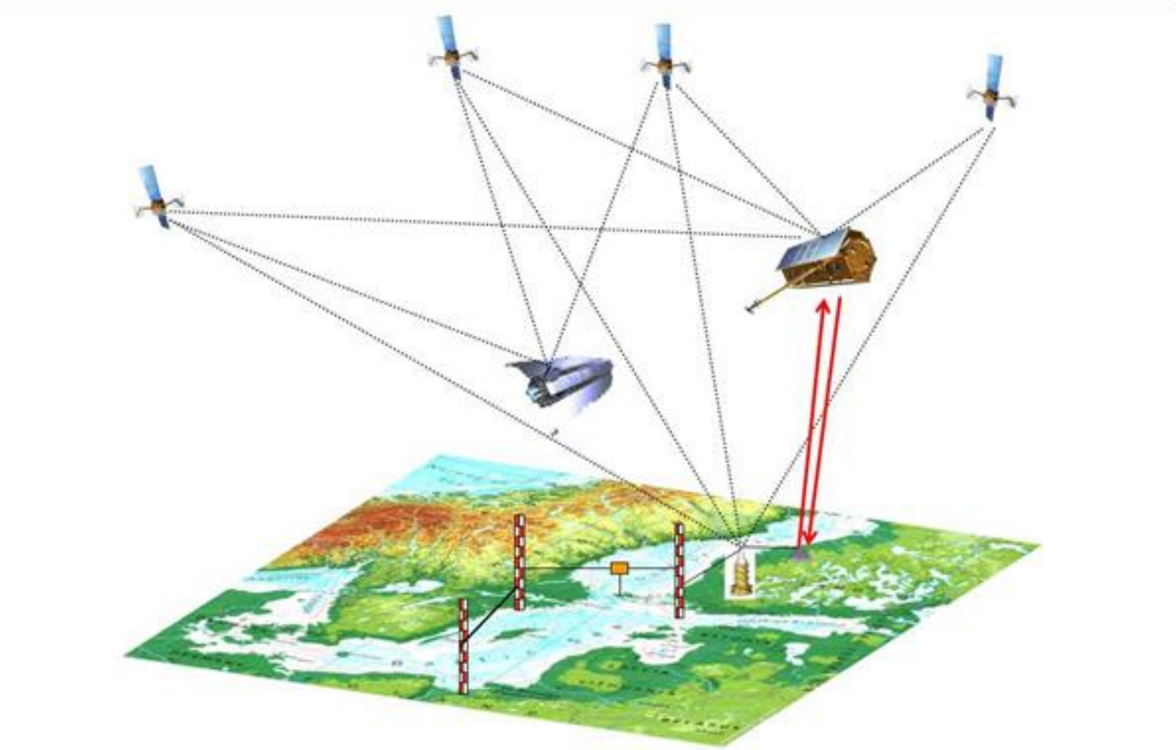

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Abbreviations and Acronyms

CBK-PAN	Centrum Badań Kosmicznych Polskiej Akademii Nauk
CR	Corner Relector
DLR	Deutsches Zentrum für Luft- und Raumfahrt
ECR	Electronic Corner Reflector
EUREF	Regional Reference Frame Sub-Commission for Europe
FGI	Finnish Geospatial Research Institute
GNSS	Global Navigation Satellite System
IERS	International Earth Rotation and Reference Systems Service
IGS	International GNSS Service
ITRF	International Terrestrial Reference Frame
LM	Lantmäteriet, Swedish Mapping, Cadastral and Land Registration Authority
SAR	Synthetic Aperture Radar
SAR-HSU	Geodetic SAR for Baltic Height System Unification and Baltic Sea Level Research
TUM	Technical University of Munich
TUT	Tallinn University of Technology

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1 INTRODUCTION

1.1 Purpose

The purpose of this document is to summarize the work performed in this project and to define the main conclusions. All details are provided in the final report of the project.

1.2 Project Overview

Traditionally, sea level is observed at tide gauge stations, which usually also serve as height reference stations for national levelling networks and therefore define a height system of a country. Thus, sea level research across countries is closely linked to height system unification and needs to be regarded jointly. The project aims to make use of a new observation technique, namely SAR positioning, which can help to connect the GNSS basic network of a country to tide gauge stations and as such to link the sea level records of tide gauge stations to the geometric network. By knowing the geoid heights at the tide gauge stations in a global height reference frame with high precision, one can finally obtain absolute sea level heights of the tide gauge stations in a common reference system and can link them together. By this method, on the one hand national height systems can be connected and on the other hand the absolute sea level at the tide gauge stations can be determined. By analysing time series of absolute sea level heights their changes can be determined in an absolute sense in a global reference frame and the impact of climate change on sea level can be quantified (e.g. by ice sheet and glacier melting, water inflow, global warming).

The major scientific challenges to be addressed by this project then can be summarized as follows:

(1) Connection of the tide gauge markers with the GNSS network geometrically in order to determine the relative vertical motion and to correct the tide gauge readings. For this the new technique of SAR positioning is applied.
(2) Determination of a GOCE based high resolution geoid at tide gauge stations in order to deliver absolute heights of tide gauges with respect to a global equipotential surface as reference.
(3) Joint analysis of geometrical and physical reference frames to make them compatible, and to determine corrections to be applied for combined analysis of geometric and physical heights.

In order to provide answers to these challenges the project has been structured accordingly (Figure 1-1).

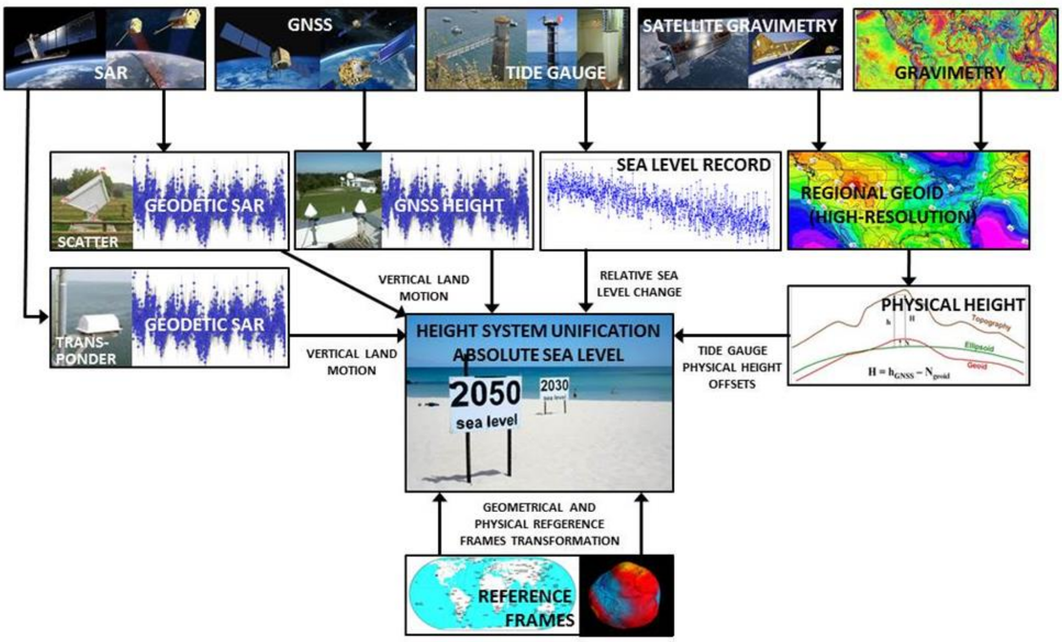

Figure 1-1: Overview of observations and their combination needed to reach the project goals. The boxes at the top line represent the observations needed to estimate the absolute sea level and its changes at tide gauge locations. All observations need to be processed consistently by applying common standards and reference frames in order to compute the absolute sea level at tide stations and its changes. Further-on this information then can be used for height system unification between different countries.

1.3 Applicable Documents

[AD-1] Final Report, SAR-HSU-FR-0022, Issue 1.1, dated 07.07.2021
[AD-2] Electronic Corner Reflector Station Description, Issue 1.1, dated 07.07.2021
[AD-3] Dataset User Manual, SAR-HSU-TN-0019, Issue1.1, dated 07.07.2021

2 EXECUTIVE SUMMARY

2.1 Scientific Challenges, Data Base and Network Design

The overall goal of the project is to establish an integrated observing system to monitor sea level change in an absolute sense and to enable height system unification across countries. For this purpose, various types of observations need to be combined consistently. In particular, these are the geometric heights and the geoid height of tide gauge stations and the tide gauge readings. Consistency means that reference frames and processing standards need to be identical for all components, which is crucial as the geometric network intrinsically is defined by a set of reference station coordinates (centre of figure), while gravimetric quantities as the geoid per definition are defined in a physical reference frame defined by the mass distribution of the Earth (centre of figure). As the Earth is a dynamic system the reference frames are not fixed, but undergo temporal variations. This usually is fixed by defining a reference system epoch and by applying transformations between the different frames.

One of the critical issues is vertical land motion, or more general vertical station movements. For this purpose, optimally, a permanent geodetic accuracy GNSS receiver needs to be collocated next to the tide gauge station in order to observe such vertical movements. The number of tide gauge stations collocated with a permanent GNSS station is very limited and by far is not sufficient to monitor vertical station movements at the coast on a systematic basis. Alternatively, regular local surveys to the closest permanent GNSS stations (high effort and costly) or geophysical models (high uncertainty) can be used for this purpose. Therefore, in this study the technique of geodetic SAR positioning is used. Active electronic corner reflectors are installed close to the tide gauge stations and nearby permanent GNSS stations in order to monitor the geometric heights.

Using tide gauge readings and geometric heights determined either by GNSS or SAR positioning still is not sufficient to enable comparisons of sea level from different stations in an absolute sense. This is only possible if one knows the vertical offsets of each tide gauge station from a global high resolution equipotential surface. With the results of the GOCE mission a highly precise global geoid with centimetre accuracy and a spatial resolution of 80–100 km is available. In order to refine the global geoid a local geoid modelling for each tide gauge station is required, which optimally combines the global GOCE gravity field model with local terrestrial gravity observations.

In summary, three major scientific challenges are addressed by the study in order to enable height system unification or absolute sea level computation from tide gauge observations. These are:

(1) Connecting the tide gauge markers with the GNSS network geometrically in order to determine the relative vertical motion and to correct the tide gauge readings.
(2) Determine a GOCE based high resolution geoid height at tide gauge stations in order to deliver absolute heights of tide gauges with respect to a global equipotential surface as reference.
(3) Joint analysis of geometrical and physical reference frames to make them compatible and to determine corrections to be applied for combined analysis of geometric and physical heights.

The main focus is given to the connection of the tide gauge reference marker with the geometric GNSS network applying the geodetic SAR positioning technique. With flexible and compact active transponders, it offers a relatively cheap and simple possibility to connect all tide gauges for an ocean area to the global geometric network. In order to investigate the feasibility of using active SAR transponders for geometric positioning and to use these observations for height system unification and absolute sea level determination, some tide gauge stations in the Baltic Sea area located in different countries are selected as test cases.

For geodetic SAR positioning SAR images captured by the Sentinel-1 mission are used. Both spacecraft, Sentinel-1A and Sentinel-1B, regularly capture the Baltic Sea area and offer unrestricted access to all the data acquired at our study region. Level 1 SLC products, which contain the focused but otherwise unmodified Sentinel-1 SAR data are the main input for the study. Over land areas, Sentinel-1 mainly uses the Interferometric Wide Swath (IW) SAR mode, that covers a swath-width of approximately 250 km on ground. This yields a coverage of each test sites by at least two ascending and two descending pass geometries per site. With a repeat cycle of 6 days. the number of Sentinel-1 SAR observations per test site amounts to some 180 measurements for one year.

For connecting the tide gauge stations to the GNSS network via the SAR targets, a GNSS network covering the study area needs to be defined. After definition of the experiments the reference stations for the double difference method are selected, based on the criteria for optimizing the geometry of the GNSS station network, observation quality, station stability over time, quality of coordinate determination and station velocity vectors, as well as free access for the data. For a few cases, separate agreements with the station/data owners need to be done. Tide gauge readings are acquired from the national authorities operating the tide gauges in each participating country. The project establishes agreements with these authorities and has full access to the pre-processed tide gauge data time series (usually as hourly values). For geoid modelling the fundamental global model is available from the International Centre of Global Earth Gravity Models (ICGEM). For the study the GOCO06S model combining all reprocessed GRACE and GOCE data is used. Local gravity data around the Baltic Sea have for a long time been collected by the Nordic and Baltic countries within the Nordic Geodetic Commission (NKG). A cleaned database including latest gravity datasets observed by different institutions formed is used for the local geoid modelling.

For the Baltic Sea test network, the SAR transponders are installed as close as possible to the tide gauge and, depending on the experiment, to the nearby permanent GNSS station as well. From the perspective of the SAR, the installation sites are selected considering the surroundings of the site. Obstacles above 20° elevation shall be avoided, as well as bright background or spurious signals arising from nearby structures like buildings. Based on the defined test cases, the following installation sites are selected. Collocation sites with local ties of SAR transponder to permanent GNSS station and tide gauge (Władysławowo and Łeba in Poland and Spikarna/Vinberget in Sweden). Tide gauge sites with local ties of SAR transponder to tide gauge (Emäsalo and Rauma in Finland, Loksa in Estonia and Forsmark/Kobben in Sweden). Permanent GNSS network sites with local tie of SAR transponder to permanent GNSS stations (Vergi in Estonia, Mårtsbo, in Sweden and Loviisa in Finland). Transponder calibration site with local ties to permanent GNSS stations and passive corner reflectors (two stations in Oberpfaffenofen, Germany). All together 12 active SAR transponders have been purchased by the project team and are installed at the indicated sites.

2.2 Basic Algorithms

The SAR data analysis algorithms involve accurate extraction of all SAR transponder locations from the acquired Sentinel-1 level 1 single-look complex (SLC) images as well as preparation of dedicated corrections. These corrections comprise the Sentinel-1 systematic effects not accounted for during SAR image generation, the atmospheric path delays, and the solid Earth deformation signals. Moreover, systematic effects of the SAR transponders need to be calibrated (internal signal delay, eccentricity of antennas). The applied computation methods require as data input the SLC Sentinel-1 SAR images, the Sentinel-1 precise orbit solution, the global total electron content (TEC) maps based on GNSS, and the global gridded data for the Vienna mapping function (VMF) model. The analysis system uses approximate coordinates of ECRs to download the applicable SAR image products. Orbit products matching the dates of the SAR images are obtained from the Sentinel-1 PDGS (Payload Data Ground Segment). The same procedure is applied to the atmospheric model data for which the files corresponding to the date of the SAR product are downloaded and ingested into the system. As a result radar observations (range and azimuth) and required corrections for the targets are provided. The geometric relationship between the radar sensor and the radar target is mathematically expressed by the well-known Range-Doppler equations system. For a given epoch, the equations relate the position vector of the radar target with the sensor's state vector (sensor position and sensor velocity) in a Cartesian reference frame. Using range and azimuth and the corresponding corrections finally yields coordinates of the targets and their estimated uncertainties. The process is implemented as an iterative least squares procedure applying pre-selected convergence criteria.

Since heights of the GNSS stations near the SAR transponder stations need to be determined with the highest possible accuracy, GNSS observations with the lowest possible cut off for the elevation angle of the registered satellites are used. Daily observational data ensure the stability of the resulted coordinates. Also for that reason it was decided to apply network computation of GNSS observations in Double Differences (DD) mode, but not Precise Point Positioning (PPP). Before performing calculations, first the network is defined. It contains all necessary permanent GNSS stations useful for the needs of the project – some of them as reference stations and some of them located in close proximity to the SAR transponder stations and/or the selected tide gauge stations. The network should have good and stable in time geometry for determining the coordinates of the stations included in the project and contain GNSS stations as reference points, having long and stable time series of coordinates of these stations, with well-defined parameters of their movements - velocity vectors. The computation process is performed using the Bernese GNSS Software (actually in version 5.2) assuring most precise and stable results. It is clear that for the precise coordinate computation all possible models according to IERS Conventions 2010 must be used and computation are made using dual frequency solutions. For this the standard algorithms for GNSS data processing are applied. Due to the current number of satellites available in orbits and the fact that the GNSS system is in the operational phase, the highest accuracy for the determination of station coordinates is now possible using observational data from GPS or GPS+GLONASS satellites. Galileo is not yet considered as the system still is in its pre-operational phase.

For observing the absolute sea level and enabling unification of height systems, physical heights of the tide gauge stations referring to a common equipotential surface are needed. This is achieved by combining a GOCE based Earth Gravity Model (EGM) with local/regional gravity data (land, airborne and/or marine) and a Digital Elevation Model (DEM). Two regional geoid determination methods are compared, both in a pointwise sense at the tide gauges and over a rectangular area covering the tide gauges (comparison of regular grids). The methods are, three-dimensional Least Squares Collocation (3D LSC method) with Residual Terrain Modeling (RTM) of the topographic corrections, and least squares modification of Stokes' formula with additive corrections (LSMSA method), where the remove-compute-restore philosophy is used for gridding of the surface gravity anomalies. Both methods are tested and it could be shown, that the expected 1 cm geoid accuracy can be achieved. Time variability of the geoid due to vertical land motion is very small, hence negligible for the purpose of the present project as it only covers an analysis period over one year.

Sea level at the coastline is observed with tide gauges that deliver instantaneous sea surface heights relative to a zero marker of the tide gauge station. The standard hourly tide gauge data are the primary data set used for analysis. For reliable mean sea level (MSL), estimation of the sea level measurements should be performed over an adequate time period to filter out data blunders and obtaining statistically meaningful results. An annual water cycle period is assumed to be sufficient for the purpose of the present study. The accuracy of contemporary tide gauge readings remains within 0.2…1.0 cm. However, readings of such sensors need to be compensated due the instrumental phenomena, e.g., drift. Accordingly, the tide gauge data need to be checked for the inclusion of such instrumental corrections. The drift corrected data are to be further filtered in order to remove data blunders and gross errors. In order to filter out data blunders the tide gauge series are statistically analyzed. The standard deviation (STD) of the readings reflects the inner consistency (for the entire period, or seasonally) of the time series at each tide gauge station. Typically, the larger STD is associated with the rougher sea conditions at individual stations, whereas the smaller STD may also reveal sea sheltered locations. The final mean sea level for the tide gauges will be computed centrally, applying the same methodology and considering also interconnections between the tide gauges and geodetic infrastructure.

In order to compute absolute sea level heights for tide gauge markers with respect to a chosen physical height reference system (an equipotential surface), all individual observation types need to be combined in a consistent way securing that common standards are applied during all processing steps. This includes the geometric heights from GNSS and/or SAR positioning, the geoid heights and the averaged tide gauge readings.

2.3 Data Analyses and Scientific Assessment

The SAR data analysis is performed with the surveyed transponder origin coordinates corrected for the geometric transponder phase centre offsets specified for ascending and descending passes. The estimated offsets then mainly show electronic delays of the active transponder, with additional bias contributions from the orbit, the finite correction accuracy and the surveyed coordinates. Several conclusions can be drawn from these results. The SAR range observations of the active transponder generally have a high precision when considering only the individual geometries. Only a few transponders provide relatively homogeneous data across all incidence angles and there is low consistency among the different ECR delay patterns. Despite being built to same specification and stemming from one manufacturing series, the transponder delays can vary between 1.2 m and 3 meters. The experimentally determined electronic delay model can remove the delay effects only within ±0.5 m and only for a limited number of transponders. Absolute SAR positioning accuracy is limited to decimetres if these systematic effects are not compensated for. Some stations perform worse because of their less common delay patterns. The azimuth observations are much more consistent and seem less affected by the transponder electronic characteristics. In summary, the attainable precision of Sentinel-1 SAR observations of active transponders is largely equivalent to observations of passive corner reflectors, but absolute accuracy is limited by the delay effects introduced by the active transponder electronics. The effects vary between the individual instruments, which makes an ensemble characterization impossible. In order to achieve better absolute accuracy and improve feasibility for SAR positioning, the active transponders need to be electronically characterized and calibrated by the manufacturer.

For each station the available data since the start of operation of a transponder until the end of 2020 is used. The precision (internal accuracy) of the positioning solutions varies between a few millimetres and one centimetre. The precision is fairly stable, even though the number of data takes vary per stations. This independency is due to the fact that the estimator becomes already stable when more than 20 data takes per station are used. The confidence ellipses of the position solutions only spread over a couple of millimetres or few centimetres. The eccentricity of the ellipses is related to the ratio of observations taken in ascending and descending geometry. The more balanced the number of observations per geometry the more circular the confidence ellipse will become. The confidence ellipses can also be presented with respect to reference coordinates showing the absolute (external) offsets between reference and estimated coordinates. The absolute accuracy in height varies between centimetre offsets and a few decimetres, corresponding to the findings of the initial SAR data analysis. In order to identify if coordinate (height) variations can be observed, position solutions for monthly, bi-monthly, 3-monthly and 4-monthly data sets are computed. In general, one can observe the trend of increasing internal accuracies with increasing number of observations. 3-monthly and 4-monthly solutions perform for most stations as good as the solutions using all available observations. Results show that the time series of transponder position solutions exhibit much larger variability than the IGS trend model for these stations. This indicates, that coordinate variations of a few cm per year so far hardly can be estimated with the current active transponders due to their limited performance.

The processing of GNSS daily observations is performed as daily network solutions using the Bernese GNSS Software ver. 5.2 in the double-difference mode (DD method). As the reference frame the ITRF2014 is used, in which all IGS global products are available for the calculations: precise orbits, the Earth's rotation parameters and the corrections of GNSS satellite clocks. The daily network solutions are related to the middle of the development period of each daily session. Based on these solutions, time series of X, Y, Z Cartesian coordinates covering the entire year 2020 are generated. From these series, for the purposes of the project, time series of B, L, h geodetic coordinates are then created, related to the GRS80 geocentric ellipsoid. The averaged coordinate solutions for all stations and the complete year 2020 is computed from the daily solutions and provided for epoch 2020.50 in terms of geodetic coordinates referred to the GRS80 ellipsoid. Error estimates dhow that the 1 centimetre goal easily can be achieved for all stations.

Tide gauge data series for the year 2020, also relevant station documentation and metadata are delivered by the national authorities operating the tide gauges. All tide gauge data are un-normalized, i.e. presenting the actual hourly sea level heights at the tide gauge stations. Vertical land motion estimates (reaching up to 9 mm/year) were either embedded in the tide gauge records (Sweden) or accounted for separately (Estonia, Finland, Poland). In order to filter out data blunders the tide gauge series are statistically analysed. The initial TG time series are quality checked in several tests for identifying gross errors and systematic biases. Typically, the standard deviation of the annual sea level series remains within 2 decimetre, whereas the larger standard deviation is associated with the rougher sea conditions at individual tide gauge station. The smaller standard deviation revealed sea sheltered locations of certain tide gauges. The data series is used for computing the mean sea level estimates for each TG station averaged over the year 2020.

For the regional geoid computation, the least squares modification of Stokes' formula approach is applied. The computed model is then converted to the project mean epoch 2020.5 by applying a land uplift correction. The final geoid heights in the Swedish, Finnish and Estonian tide gauges are given by this model. As can be judged from the comparison to GNSS/levelling, the standard uncertainty of the geoid heights in Sweden, Finland and Estonia is estimated to be approximately 0.010 m in a relative sense. The GNSS/levelling fit standard deviation after correction of country biases is 0.013–0.015 m. Considering that there are also errors in the GNSS ellipsoidal heights and in the levelled heights, 0.010 m should be a reasonable estimate. In order to get consistent geoid heights for the whole test area, the geoid model is selected also for the Polish stations. For these stations, however, the uncertainty should be somewhat higher due to a slightly reduced terrestrial data quality.

In order to ensure consistent results for the different products, it is essential that any differences regarding the underlying reference frames and inconsistencies with respect to the implemented standards and models are taken properly into account. The standards and models used for the processing of the different observations used within this project are applied accordingly with the IERS Conventions 2010. In addition, technique-specific processing standards are applied for the individual observation techniques (e.g., IGS- and EPN-Standards, SAR Standards, GOCE Standards, standards for gravity and tide gauge data). For the transformation between 3-D Cartesian coordinates and ellipsoidal coordinates it was specified that the conventional GRS80 parameters are used.

For the transponder stations co-located to a permanent GNSS station the resulting heights are compared by applying the relative height difference between the GNSS antenna reference point and the ECR reference point. Results show that the absolute height differences between the 2 techniques are varying. While three stations exhibit good to reasonable agreement at decimetre level or below, for three other stations height differences are at a level of several decimetres to half a meter. As one can assume that the GNSS derived heights are accurate at a level of a few centimetres, the transponder derived heights are the main driver for the absolute performance results. From the ECR stations co-located to a tide gauge station the resulting physical heights of the tide gauge zero markers above the reference equipotential surface are computed with equation. The results show that some stations seem to provide very good results with only a few centimetres offset, while other stations exhibit an offset of several decimetres up to a meter. These results need to be further analysed together with the performance of the individual active transponder stations and also with respect to the length of the data time series. There seems to be some correlation of the physical height results with the SAR observation quality, the SAR residuals and the length of the SAR observation time series. Relative height differences are compared between GNSS or tide gauge stations and those observed with the active transponders. The results again show a diverse behaviour. Basically, the differences between GNSS and ECR observed height differences vary between a few centimetres and some decimetres. For stations, which exhibit a large absolute offset the differential height error between these stations becomes small, while the differential error between one of these stations with the other stations becomes significantly larger. This indicates, that there is a systematic height offset in the ECR positioning results with the same sign, as it is also shown in the absolute comparisons.

2.4 Conclusions

The active transponders are designed such that they shall be able to operate without the need of on-site user interaction and with energy supply either by connecting it to the electrical power supply at a station or, if not available, by charging the batteries with solar panels. The project team operated 12 transponders from late 2019 until now and made a lot of experiences, which led to some conclusions related to operability and calibration of the devices. Generally, it can be stated that a consistent long-term operation of the transponders in the demanding environment of the Baltic sea region is not possible with the present transponder design. The current design requires improvements related of the hardware and software. In particular, major points of concern are the sealing of the instrument against water intrusion, the power supply, the remote access to transponder by electronic means (WiFi or others), the transponder software for user interaction and time synchronization. Because the transponder is an active electronic instrument, an initial calibration after fabrication by the manufacturer is advised in order to correct for possible system delays. Ideally, this calibration shall be identical for all transponders of the same design. From the results obtained during the project there are indicators that each transponder somehow has its own characteristics and individual calibration sessions need to be performed. A major limitation for obtaining very good geodetic positioning results from this technique comes from the delays introduced by the active transponder electronics which was found to vary significantly between 1.2 m and 3 m for different pass geometries and different devices. This is a very critical items and needs to be solved. The transponders should be investigated by the manufacturer and if possible calibrated in laboratories to determine their individual electronic characteristics.

The project gives a good overview on possibilities of geodetic SAR and possible applications. With the results, the potential of the method, a way to develop the technique in future, and a lot of information how to improve it in future has been achieved. As such, it fulfilled the goals one may expect with such a new technique. Active transponders can give additional information for areas of no previous observations, but cannot replace current positioning techniques. In a wider perspective, the number of observations is very small comparing to GNSS observations. Therefore, the geodetic SAR technique in general is not suitable to observe temporal coordinate variations with shorter temporal resolution than a month, except more C-band SAR satellites become available. But, it can be used for observations of large movement

(>decimeter/month) in areas with critical slopes undergoing landslides, for volcanos and fast subsidence. Additionally, it might be applicable for determining absolute reference coordinates to fix the orientation of SAR interferometry.

The project team learned about these new geodetic devices, and the geodetic SAR project was the first step to add such electronic corner reflectors to geodetic infrastructure and co-locate them with other geodetic instruments/benchmarks. Having such transponders co-located with GNSS (for example) can provide additional data for local deformation monitoring at the site, 3D absolute positioning and atmospheric studies and can be compared with GNSS data and time series in long run. In addition, such reflectors as artificial persistent scatterers (PS) co-located with GNSS permanent stations can be useful for future calibration of the European ground motion service (EGMS) products and to transform the deformation maps and rates into a global reference frame.

Within the project a very 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. The data set will be publicly available and can attract new users to develop processing strategies and to investigate new possible applications for the SAR positioning technique.