The Swedish Sea Level network

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Introduction

The Swedish Sea Level network, operated by the Swedish Maritime Administration (SMA), Swedish Meteorological and Hydrological Institute (SMHI), Swedish Nuclear Fuel and Waste Management Company (SKB), Chalmers Technical University (CTH) and Gothenburg harbour (GBG) records sea level at 59 locations (Figure 1 and Appendix 1). The Swedish sea level records constitute some of the longest and most robust sea level records in the world (Table 1).

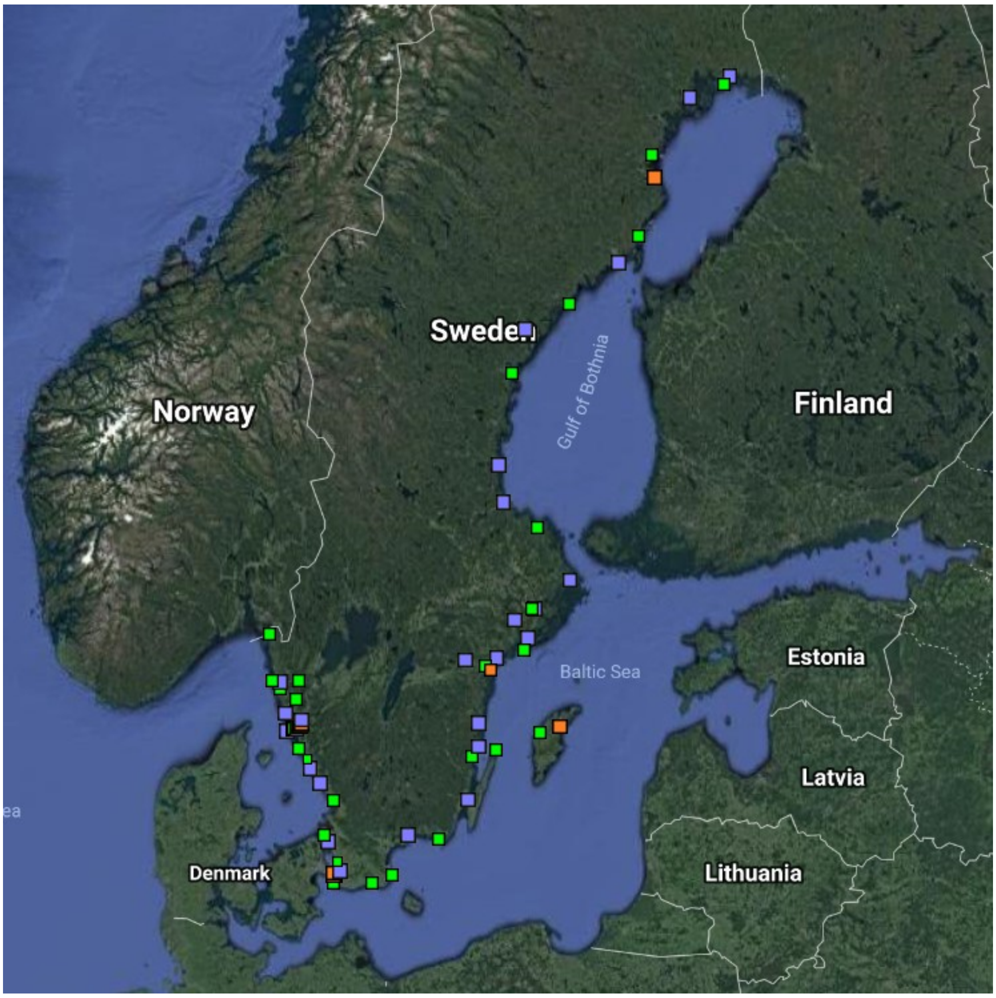

Figure 1. The Swedish Sea Level network in March 2019.

The Swedish Sea Level network

The first systematic Swedish observations of the sea level started 1774 at the sluice in the harbour of Stockholm. New stations were established in the 1840-ties to investigate the mechanism behind what was during that time called the “water sinking effect”, nowadays referred to as the land-uplift, due to the isostatic adjustment since the last glacial period. The first results of the observation activities ended up in a wider acceptance that it is the land that rises from the sea.

At the end of 19th century, the Swedish king, Oscar the second, decided to establish seven mareographs, primarily to investigate the land uplift effect. Several of these mareographs are still in operation or have been substituted by other stations. In 1889 the Nautical-Meteorological Bureau, a predecessor of SMHI, established a continuously recording sea level station (mareograph) in the bedrock on the island Skeppsholmen (Figure 2), located close to the sluice. This mareograph has since then recorded the Stockholm sea level. The sea level series in Stockholm constitutes the longest sea level record in the world (Figure 3).

Figure 2. The Swedish GLOSS-station (mareograph) in Stockholm.

During the 20th century several more stations were established. The technique used from the beginning was the stilling well technique. The Sea Level network was completely modernised during the 1980s. The traditional stilling well was still used, but the gauges were converted from analogue to digital with automatic data transfer to SMHI. Earlier the recording was only done with a chart recording apparatus. In the beginning of 21th century (2001-2005), a new upgrade of the stations was completed and shaft encoder were installed at almost all stations. The chart apparatus was kept as a backup for the digital recording equipment, mainly to prevent gaps in the time-series.

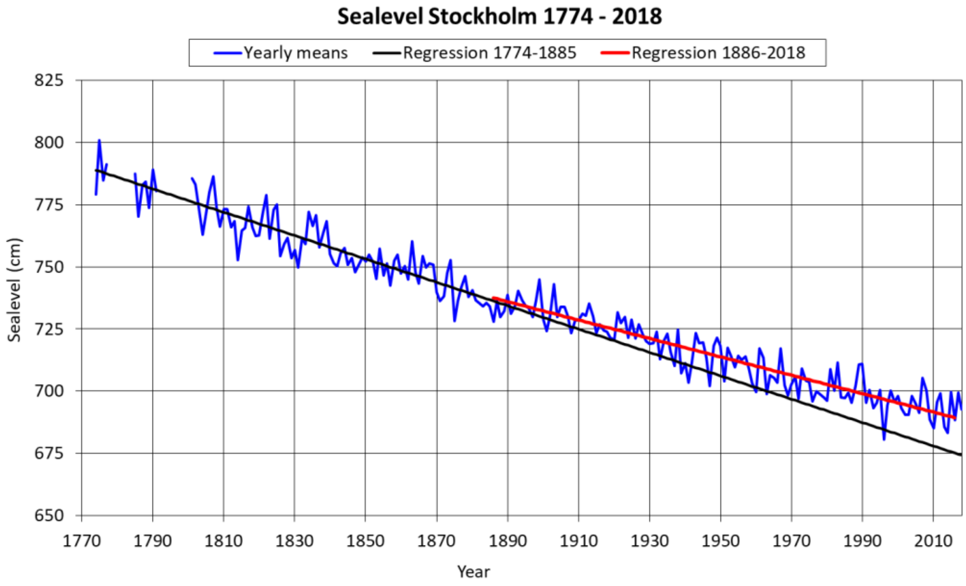

Figure 3. Annual mean sea levels in Stockholm since 1774, with the black regression line corresponding to the land uplift 1774-1885 and its extension into modern times. The increased sea level rise since the late 19th century appears as the deviation from the black regression line.

Climate changes in sea level data

From the long Swedish time series of sea level we can detect the global sea level rise after reducing the yearly means with the land-uplift effect (Figure 4). A regression analysis indicates a sea level rise around 3 mm per year for the last 30 years and approximately 1.7 mm per year since 1886. Where the land-uplift is small, as around the coasts of southern Sweden, the sea level has risen by more than 20 centimetres since 1886.

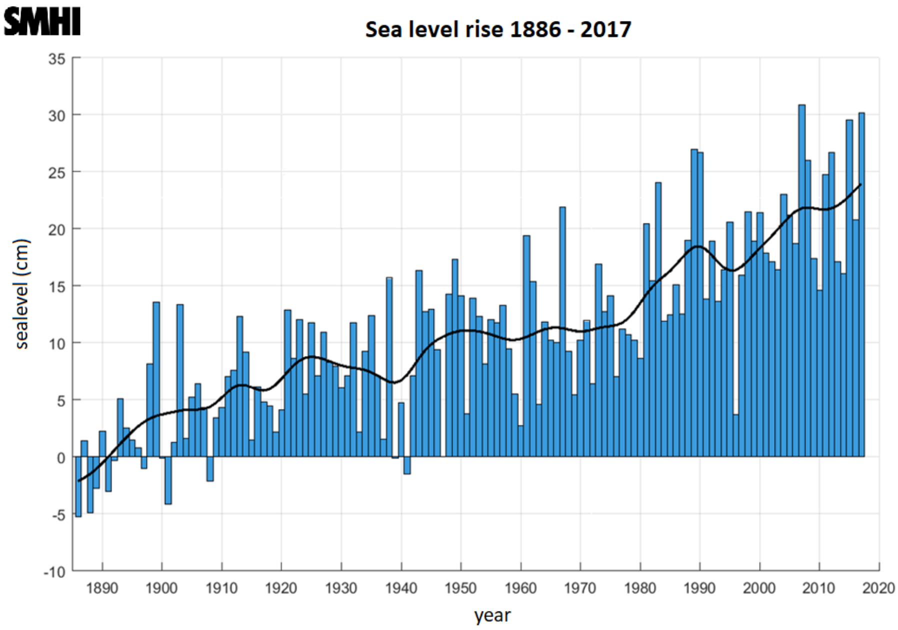

Figure 4. Sea levels corrected for the levelled land uplift (glacial isostatic adjustment). Blue bars show the annual sea level averaged for 14 sea level records, compared to the 1886 level. The black line shows the gauss-filtered (smoothed) average.

Upgrade of the Swedish Sea Level network (SHIP)

For several years, SMA and SMHI have had a close cooperation on oceanographic observations. In the EU-finance FAMOS Odin-project (2017-2019), SMA and SMHI have decided to establish one common Swedish Sea Level network (Figure 1). The new network is named SHIP. The existing stations have been upgraded with new sensors and the communication to the stations have been improved. New sensors and data loggers was installed that is more capable of delivering near real time data. The data recorded by the measurement equipment is transferred to SMA every minute and stored in a database. From there, the data can be presented in real-time on websites and be distributed further to the users. SMHI is responsible for the delayed mode quality control and long-term storage of the data in a database. A software application connected to the database is used for validation and correction of the data. It is also possible to subtract a constant offset to the data. Data are distributed to users via national and international data exchange (Table 2) on a continuous basis.

A classification is done for the stations in the new network. The stations are now divided into four different classes, based upon user needs. Class 1-stations consist of stations with duplicated sensors (two radar sensors or one radar and one pressure sensor), a logger installed at the stations and a battery backup making it possible to re-collect data missing in real-time. Class 2-stations will also have duplicated sensors (one radar and one pressure sensor), including a logger and without battery backup and hence without the possibility to recover data missing in real-time. Class 3-stations will be unchanged and Class 4-stations will be dismantled. Dismantled stations are mostly located at places where both SMA and SMHI measures today. The stations will be moved or be replaced by one upgraded station only.

The long time series at SMHI mareograph's, starting in the late 19th century have been classified as Class 1-stations and the long time series will be continued. At the Class 1-stations, an observer will visit the station every week and check the status of the station and validate real-time data. It will be 53 upgraded Class 1- and 2- stations in the new Swedish Sea Level network and six Class 3-stations. Summarized, in March 2019, the Swedish Sea Level network consists of 59 stations. In addition, several sea level stations, established by private partners and local harbour offices, will be included in the network in a near future. For example, three stations owned and operated by the Gothenburg harbour have already been included in the network in 2018.

Each sea level station is connected to several Bench Marks. The Swedish mapping, cadastral and land registration authority (Lantmäteriet) does the precise levelling, i.e. they are responsible for determining the distance between the Contact Point and the Bench Marks. SMA and SMHI shared the responsibility for the maintenance and 'local' levelling of the stations. The Tide Gauge Zero (TGZ) will be kept at a fixed distance below the Contact Point. Most of the gauges are installed in the bedrock, but some are located in slightly unstable areas. Levelling is done every three years. The levelling often shows no significant vertical motion on the majority of the sea level stations.

Co-location of geodetic observing system at mareographs

The Swedish mapping cadastral and land registration authority (Lantmäteriet) has developed the geodetic infrastructure at several of the mareographs (Figure 5) to include connection to the national height levelling network, continuous GNSS as well as absolute gravimetric measurements. GNSS at mareographs was first done as a GPS-campaign during the European project EUVN in 1997. The monuments have later been equipped with CGPS (Table 1), and are now part of the Swedish CORE network named SWEPOS™.

The main purpose of these techniques has been to develop a model to describe the post glacial rebound. One of the main tasks for the geodetic research division at Lantmäteriet is to develop, monitor and maintain the national reference systems and frames in all dimensions (3D, horizontal, height) as well as gravity so that the need of the society is satisfied. The national levelling network was levelled during the third precise levelling of Sweden during 1978-2001 and resulted in the height system RH2000, which is the Swedish realization of the European Vertical Reference System (EVRS), which is referred to Normaal Amsterdams Peil (NAP).

Lately, several different Nordic institutions as well as other international actors have observed gravity with absolute gravimeters in the Nordic and Baltic area. These efforts have been co-ordinated through the working group of geodynamic within NKG (Nordic Commission of Geodesy). The main purpose of these measurements has been to detect the change of gravity over time, mainly caused by the post glacial rebound. Several mareographs are today equipped with an absolute gravity platform (Figure 5).

Figure 5. Smögen, a mareograph (hut to the left) also combined with CGPS (monument to the right) and absolute gravity platform (hut in the middle).

Station	Latitude	Longitude	Digital data available from	Installation and type of CGPS	Distance to CGPS (km)	Install-ation of AG
KALIX STORÖ	65º 41' 49'' N	23º 05' 46'' E	1974	No	-	No
FURUÖGRUND	64º 54' 57'' N	21º 13' 50'' E	1916	1993A	9.5	1992
RATAN	63º 59' 10'' N	20º 53' 42'' E	1891	2006A	0.06	2007
SKAGSUDDE	63º 11' 26'' N	19º 00' 45'' E	1982	No	-	No
SPIKARNA (Draghällan)	62º 21' 48'' N	17º 31' 52'' E	1968 (1897)	No	-	No
FORSMARK (Björn)	60º 24' 31'' N	18º 12' 39'' E	1975 (1891)	No	-	No
STOCKHOLM (Nedre Stockholm)	59º 19' 27'' N	18º 04' 54'' E	1889 (1774)	1992A/B	15.3/3.4	No
LANDSORT NORRA (Landsort)	58º 46' 08'' N	17º 51' 32'' E	2004 (1886)	No	-	No
MARVIKEN	58º 33' 13'' N	16º 50' 14'' E	1964	No	-	No
VISBY	57º 38' 21'' N	18º 17' 04'' E	1916	1993A	5.2	2004
ÖLANDS NORRA UDDE	57º 21' 58'' N	17º 05' 50'' E	1851	2004B	13.5	No
OSKARSHAMN	57º 16' 30'' N	16º 28' 41'' E	1960	No	-	No
KUNGSHOLMSFORT	56º 06' 19'' N	15º 35' 22'' E	1886	2004A	0.1	No
SIMRISHAMN (Ystad)	55º 33' 27'' N	14º 21' 28'' E	1982 (1886)	No	-	No
SKANÖR (Ystad)	55º 25' 00'' N	12º 49' 46'' E	1992 (1886)	2002B	1.8	No
KLAGSHAMN (Malmö)	55º 31' 20'' N	12º 53' 37'' E	1929 (1924)	No	-	No
BARSEBÄCK	55º 45' 23'' N	12º 54' 12'' E	1937	2002B	5.9	No
VIKEN	56º 08' 32'' N	12º 34' 45'' E	1976	No	-	No
RINGHALS (Varberg)	57º 14' 59'' N	12º 06' 45'' E	1967 (1886)	1991A	19.7	1993
ONSALA (Varberg)	57º 23' 31'' N	11º 55' 09'' E	2013 (1886)	1991A	0.1	1993
GÖTEBORG-TORSHAMNEN (Ringön-Klippan)	57º 41' 05'' N	11º 47' 26'' E	1967 (1887)	2004B	12.8	1976
STENUNGSUND	58º 05' 36'' N	11º 49' 57'' E	1962	No	-	No
SMÖGEN	58º 21' 13'' N	11º 13' 04'' E	1910	2002A	0.02	2004
KUNGSVIK	58º 59' 48'' N	11º 07' 38'' E	1976	2005B	7.4	No

Table 1. List of stations in the Swedish Sea Level network operated by SMHI. Stations in brackets are older discontinued stations located close to the continued station. CGPS marks places where Continuous Global Positioning is installed and measurements of the absolute land uplift are being carried out. Type of CGPS: A denotes complete stations (EUREF reference stations with antennas placed on solid bedrock), B simplified stations (mounted on buildings). AG means that the station has a platform for observing Absolute Gravity. A complete station list of Swedish sea level stations is presented in Appendix 1.

Historical sea level data

All data in the new Swedish Sea Level network will be available for free. From an INSPIRE-oriented web-site it is possible to download the long time series of data (1-minute values): https://www.smhi.se/klimatdata/oceanografi/ladda-ner-oceanografiska-observationer/#param=sealevelMinutes,stations=all

In April 2019, the sea level database at SMHI contained more than 3000 years with digital sea level observations, where about 1800 years are from continued stations, including the sea level stations operated by SMA. Most of the data are hourly values, but for the past years, the resolution has been increased to 1-minute values. A complete station list showing the content of the data base for the stations operated by SMHI, on a yearly basis can be found here: http://www.smhi.se/hfa_coord/BOOS/dbkust/Availability_Sealevel_SMHI.htm

International data exchange

Both real-time data and delayed mode data are routinely made available through several national and international programmes (Table 2). Real-time and delayed mode has been screened and quality controlled using the procedures described by GLOSS, IODE, CMEMS, QUARTOD and others.

Programme	Data host	Frequency	Resolution	Media	Notes
PSMSL	NOC	Yearly	Month	Mail	All stations (27 SMHI, 32 SMA)
GLOSS	VLIZ	Hourly	HiRes*	FTP	GLOSS stations (3 SMHI)
BOOS/NOOS	SMHI	Hourly	Hour	FTP	All stations (27 SMHI, 32 SMA)
CMEMS	IFREMER	Daily	Hour	FTP	All stations (27 SMHI, 32 SMA)
EMODNET	SMHI	Daily	Hour	FTP	All stations (27 SMHI, 32 SMA)
SEADATANET	SMHI	Yearly	Hour	FTP	SMHI stations (27 SMHI)
VIVA	SMA	Every minute	HiRes*	www	All stations (27 SMHI, 32 SMA)
www.smhi.se	SMHI	Hourly	Hour	www	All stations (27 SMHI, 32 SMA)
www.boos.org	DMI	Hourly	Hour	www	All stations (27 SMHI, 32 SMA)

* 1-minute values.

Table 2. Sea level data are routinely made available through these programmes. Swedish GLOSS Core Network stations are; Stockholm, Göteborg-Torshamnen and Smögen.

Baltic Sea Oceanographic System (BOOS)

The exchange of oceanographic data in the Baltic Sea is very well developed. Within the Baltic Operational Oceanographic System (BOOS), an exchange of data between the different institutions on a routinely basis, usually every hour, has been developed. The time resolution of the data is from 1 minute up to several hours, with the highest resolution for sea level data.

Data is mainly used for model assimilation and validation, forecasts and warnings, scientific research and for operational use. SMHI is responsible for coordination of the data exchange and to implement routines for real-time quality control, validation and distribution of all sea level data coming from the Baltic Sea. The BOOS station network, consists of about 200 sea level stations (Figure 6).

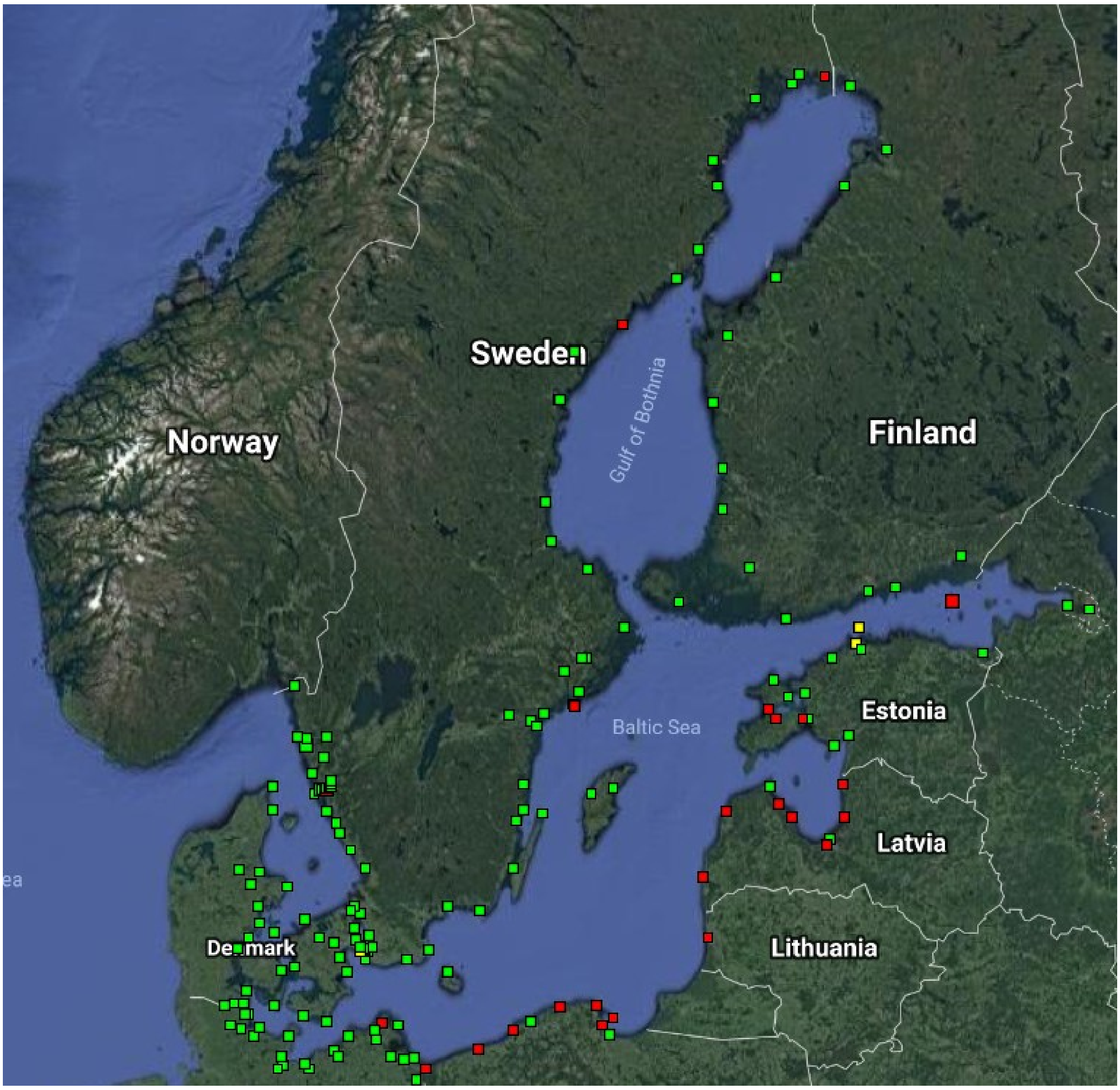

Figure 6. Sea level stations available through the BOOS Community. Stations marked in green are available in near real time. Stations marked in red are not available for different reasons.

Baltic Sea Hydrographic Commission (BSHC)

The Baltic Sea Hydrographic Commission (BSHC) is an integrant part of the International Hydrographic Organisation (IHO). One task within the BSHC is to implement one common reference datum for nautical charts and sea level information. SMA is responsible to coordinate this work within the BSHC Chart Datum Working Group.

IHO-BSHC has approved the name and the adoption of the Baltic Sea Chart Datum 2000 (BSCD2000) as the common reference datum for all countries surrounding the Baltic Sea. The datum refers to each Baltic country´s realization of the European Vertical Reference System (EVRS) with land-uplift epoch 2000, which is connected to the Normaal Amsterdams Peil (NAP). The national realization´s differs maximum two centimetres to each other. The differences between the calculated mean sea level (MSL) and BSCD2000 at the sea level stations located in the Baltic Sea can be found in this table.

All data from the Swedish sea level stations will from 3rd June 2019 be presented in the Swedish national survey datum RH2000 or BSCD2000. In Sweden, the difference between the calculated Mean Sea Level (MSL) in the year of 2019 and BSCD2000 is about +15 cm in the central parts of the Baltic coast and -5 cm in the northern parts of the Swedish west coast (North Sea). A fact sheet describing the Swedish transition into the new reference system (Figure 7), for sea level information and nautical charts, is available here.

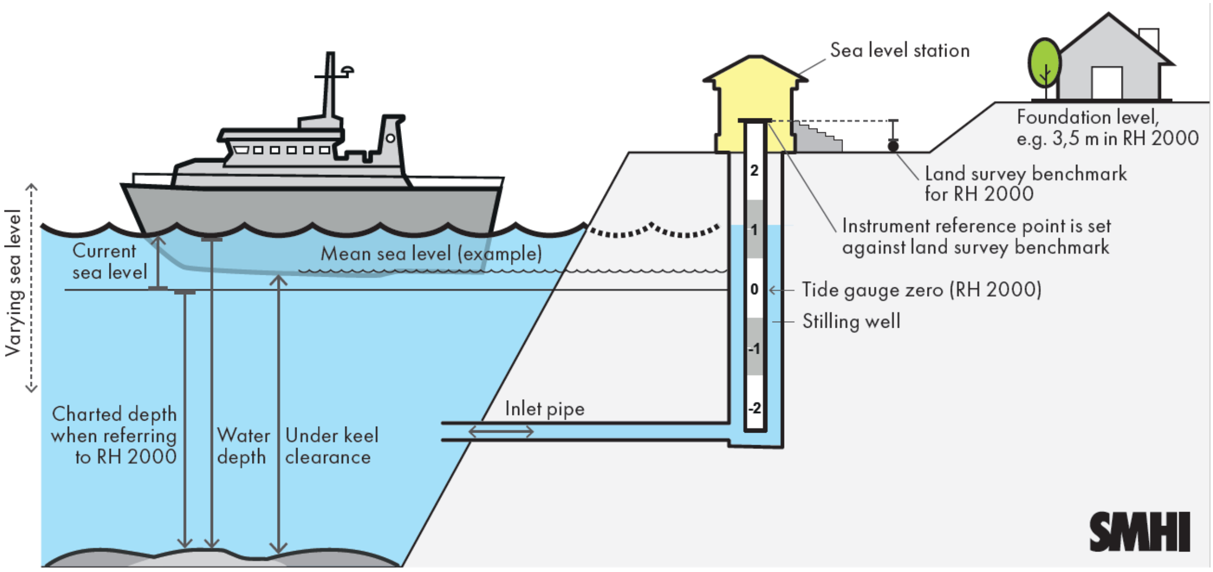

Figure 7. A uniform reference system from land to sea.

Onsala mareograph

In 2015, a new mareograph (Figure 8) was installed at Råö on the Onsala peninsula, just south of Göteborg. This has been done in close cooperation between SMHI and Chalmers Technical University in Göteborg. The station will be located close to a continuous GPS station (A-type), which is operated by Chalmers. Close to the mareograph, there is also a GNSS-reflectometer (Figure 9) measuring sea level, installed in 2010.

The station is now delivering high-resolution values of sea level (1-minute values). A very precise levelling of the station has been performed and the station is very well connected to the national height system RH2000 as for the rest of the locations. The mareograph has been a part of the Swedish Sea Level network (Figure 1 and Appendix 1) since 2015.

Figure 8. The Onsala mareograph installed in 2015.

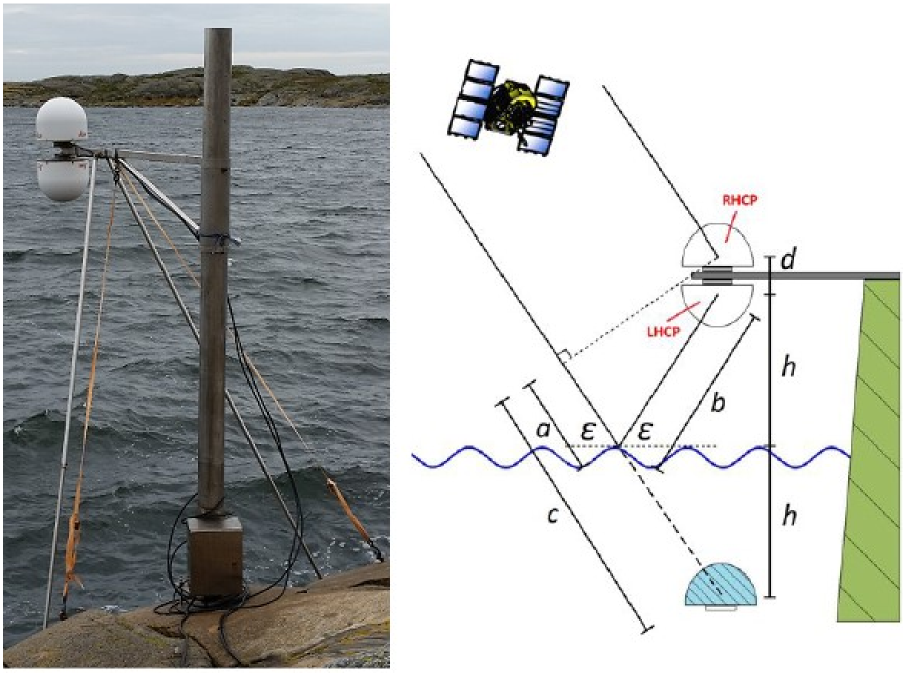

Figure 9. An upward- and downward looking GNSS-reflectometer.

Appendix 1.

Swedish sea level stations owned and operated by the Swedish Maritime Administration (SMA), Swedish Meteorological and Hydrological Institute (SMHI), Swedish Nuclear Fuel and Waste Management Company (SKB), Chalmers Technical University (CTH) and Gothenburg harbour (GBG). Class 1-stations consist of stations with duplicated sensors (two radar sensors or one radar and one pressure sensor), a logger installed at the stations and a battery backup making it possible to re-collect data missing in real-time. Class 2-stations will also have duplicated sensors (one radar and one pressure sensor), including a logger and without battery backup and hence without the possibility to recover data missing in real-time. Class 3-stations will be unchanged and Class 4-stations will be dismantled.

STATION	LATITUD	LONGITUD	START YEAR	CLASSIFICATION
KALIX KARLSBORG (SMA)	65° 47' 20''	23° 18' 12''	2009	2
KALIX STORÖ (SMHI)	65° 41' 49''	23° 05' 46''	1974	1
STRÖMÖREN (SMA)	65° 32' 59''	22° 14' 18''	2009	2
FURUÖGRUND (SMHI)	64° 54' 57''	21° 13' 50''	1916	1
GÅSÖREN (SMA)	64° 40' 43''	21° 14' 57''	2009	3
RATAN (SMHI)	63° 59' 10''	20° 53' 42''	1891	1
HOLMSUND (SMA)	63° 41' 45''	20° 20' 50''	2009	2
SKAGSUDDE (SMA)	63° 11' 26''	19° 00' 45''	2009	1
SVANÖ (SMA)	62° 52' 50''	17° 52' 35''	2009	2
SPIKARNA (SMHI)	62° 21' 48''	17° 31' 52''	1968	1
LJUSNE ORRSKÄRSKAJEN (SMA)	61° 12' 25''	17° 08' 44''	2009	2
BÖNAN (SMA)	60° 44' 19''	17° 19' 07''	2009	2
FORSMARK (SMHI)	60° 24' 31''	18° 12' 39''	1975	1
LOUDDEN (SMA)	59° 20' 29''	18° 08' 14''	2009	2
STOCKHOLM (SMHI)	59° 19' 27''	18° 04' 55''	1889	1
NYNÄSHAMN (SMA)	58° 55' 03''	17° 58' 20''	2009	2
LANDSORT NORRA (SMHI)	58° 46' 08''	17° 51' 32''	2004	1
E4 BRON SÖDERTÄLJE (SMA)	59° 11' 05''	17° 38' 34''	2009	2
OXELÖSUND (SMA)	58° 39' 42''	17° 07' 29''	2009	2
JUTEN (SMA)	58° 38' 03''	16° 19' 29''	2009	2
MARVIKEN (SMHI)	58° 33' 13''	16° 50' 14''	1964	1
ARKÖ (SMHI)	58° 29' 03''	16° 57' 38''	2015	3
VÄSTERVIK (SMA)	57° 44' 54''	16° 40' 31''	2009	2
VISBY (SMHI)	57° 38' 21''	18° 17' 04''	1916	1
SLITE (SMA)	57° 42' 21''	18° 48' 36''	2009	3
SIMPEVARP (SKB)	57° 24' 37''	16° 40' 33''	2009	2
ÖLANDS NORRA UDDE (SMHI)	57° 21' 58''	17° 05' 50''	1851	1
OSKARSHAMN (SMHI)	57° 16' 30''	16° 28' 41''	1960	2
KALMAR (SMA)	56° 39' 32''	16° 22' 42''	2009	2
KUNGSHOLMSFORT (SMHI)	56° 06' 19''	15° 35' 22''	1886	1
KARLSHAMN (SMA)	56° 09' 15''	14° 49' 17''	2009	2
SIMRISHAMN (SMHI)	55° 33' 27''	14° 21' 28''	1982	1
YSTAD (SMA)	55° 25' 00''	13° 49' 00''	2018	1

STATION	LATITUD	LONGITUD	START YEAR	CLASSIFICATION
SKANÖR (SMHI)	55° 25' 00''	12° 49' 47''	1992	1
KLAGSHAMN (SMHI)	55° 31' 20''	12° 53' 37''	1929	1
FLINTEN 16 (SMA)	55° 33' 40''	12° 48' 34''	2009	3
FLINTEN 7 (SMA)	55° 35' 22''	12° 50' 40''	2009	3
MALMÖ HAMN (SMA)	55° 36' 49''	12° 59' 51''	2009	2
BARSEBÄCK (SMHI)	55° 45' 23''	12° 54' 12''	1937	1
HELSINGBORG (SMA)	56° 02' 41''	12° 41' 14''	2009	2
VIKEN (SMHI)	56° 08' 32''	12° 34' 45''	1976	1
HALMSTAD (SMA)	56° 38' 56''	12° 50' 09''	2009	1
FALKENBERG VA (SMA)	56° 53' 31''	12° 29' 22''	2009	2
VARBERG (SMA)	57° 06' 40''	12° 06' 45''	2009	2
RINGHALS (SMHI)	57° 14' 59''	12° 06' 45''	1967	1
ONSALA (CTH)	57° 23' 31''	11° 55' 09''	2014	1
VINGA (SMA)	57° 37' 54''	11° 36' 32''	2009	2
MÅVHOLMSBÅDAN (SMA)	57° 40' 20''	11° 42' 27''	2009	3
GÖTEBORG-TORSHAMNEN (SMHI)	57° 41' 05''	11° 47' 26''	1967	1
TORSHAMNEN GBG HAMN (SMA)	57° 40' 50''	11° 47' 18''	2009	4
TÅNGUDDEN GBG HAMN (SMA)	57° 40' 55''	11° 52' 20''	2019	2
GBG-ERIKSBERG (GBG)	57° 41' 48''	11° 54' 32''	2012	2
GÖTAÄLVBRON (SMA)	57° 42' 52''	11° 58' 03''	2009	4
GÖTEBORG-GÖTAÄLVBRON (GBG)	57° 42' 53''	11° 58' 01''	2010	*
GÖTEBORG-TINGSTADSTUNNELN (GBG)	57° 43' 23''	11° 59' 13''	2012	2
GÖTEBORG-LÄRJEHOLM (GBG)	57° 45' 57''	12° 00' 20''	2010	*
GÖTEBORG-AGNESBERG (GBG)	57° 47' 23''	12° 00' 36''	2012	2
MARSTRAND (SMA)	57° 53' 13''	11° 35' 37''	2009	2
STENUNGSUND (SMHI)	58° 05' 36''	11° 49' 57''	1962	1
UDDEVALLA (SMHI)	58° 20' 51''	11° 53' 41''	2010	1
KRISTINEBERG (GU)	58° 15' 00''	11° 24' 17''	2012	*
BROFJORDEN (SMA)	58° 20' 10''	11° 24' 17''	2009	2
SMÖGEN (SMHI)	58° 21' 13''	11° 13' 04''	1910	1
KUNGSVIK (SMHI)	58° 59' 48''	11° 07' 38''	1973	1

* Stations not yet included in the network.