The Swedish Sea Level Network

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Introduction

The Swedish Sea Level Network, operated by the Swedish Maritime Administration (SMA) and Swedish Meteorological and Hydrological Institute (SMHI), records sea level at 60 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).

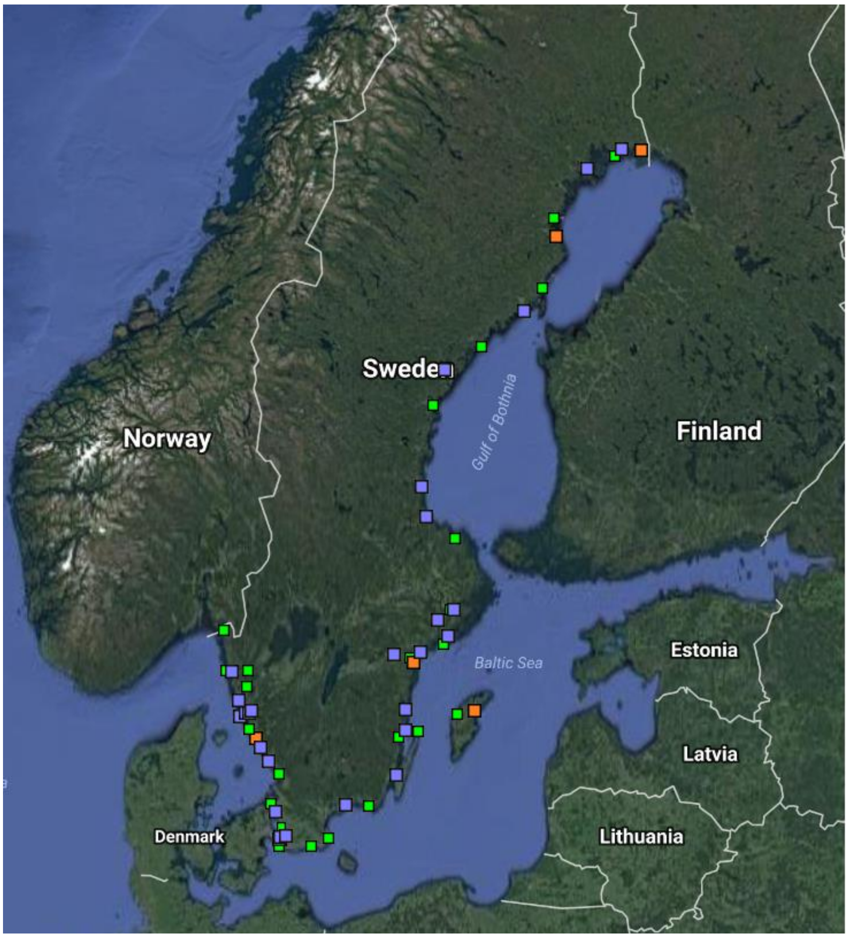

Figure 1. The Swedish Sea Level Network operated by SMA and SMHI in June 2017.
Stations marked in blue are operated by SMA, green are operated by SMHI.
Orange coloured stations are mobile, temporary stations, operated by SMHI.

Figure 2. Two Swedish GLOSS-stations; Göteborg-Torshamnen and Stockholm.

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 another Swedish king, Oscar II 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, right), 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).

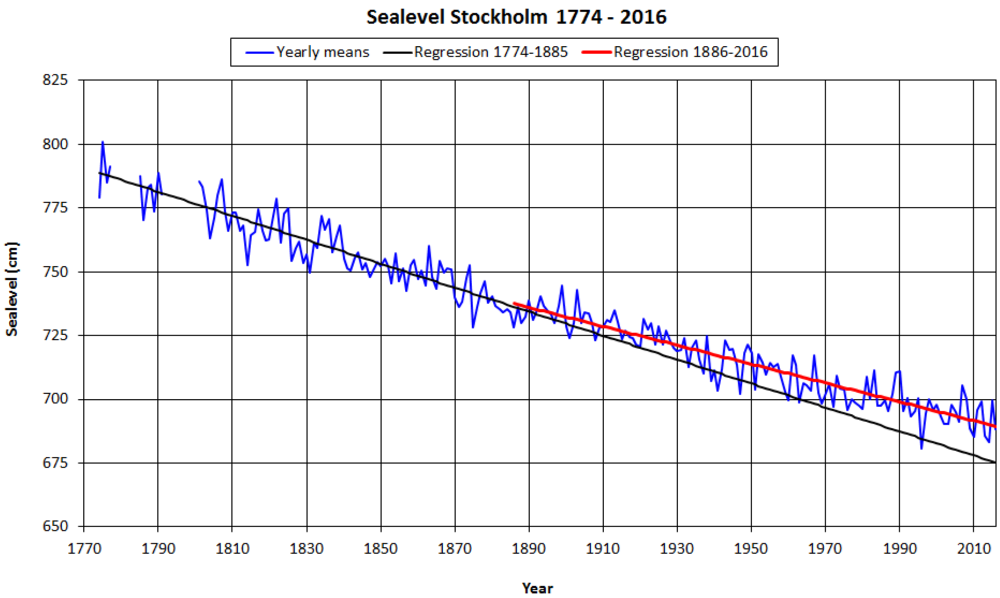

Figure 3. Annual mean sea levels in Stockholm since 1774, with the black regression line corresponding to the land uplift 1774-1885 and its extension into modern times. The increased sea level rise since the late 19th century appears as the deviation from the black regression line.

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. This mechanical equipment is nowadays used as a backup at SMHI for the digital recording equipment, mainly to prevent gaps in the time-series.

A new modernisation of the network was completed at SMHI at the end of 2005. A new data logger (Vaisala MAWS) was installed that is more capable of delivering near real time data. The data recorded by the measurement equipment is transferred to SMHI once an hour through the telephone line and stored in a database. From there, the data can be presented in real-time on websites and be distributed further to the users.

Quality controlled data are distributed to users via national and international exchange on a continuous basis. A software application connected to the database is used for validation and correction of the data. Gaps in the time series can be filled with data from paper charts or predictions. It is also possible to subtract a constant offset to the data. The original data and all manual readings are always stored in separate tables in the database.

In 2009, also the Swedish Maritime Administration (SMA) started to run sea level measurement in a more organized way at some locations around the Swedish coast. The number of stations has increased over the years and now SMA records the sea level at 36 locations, of which a few stations are co-located with SMHI stations. This is mainly due to different user needs how fast you may access real-time data. At present, 10-minute values from all stations are stored in the database but an updated 10-min running mean is available with only 30 seconds delay. At the stations operated by SMHI, even the maximum and minimum records every hour is acquired and stored in the database.

Since a couple of years, SMA and SMHI have a close cooperation on oceanographic observations. In the EU-finance FAMOS Odin-project (2017-2018), SMA and SMHI have decided to establish one common Swedish sea level network. The existing stations will be upgraded with new sensors and the communication to the stations will be improved. The target is to reach an accuracy of 1 cm and 1-minute values will be stored in the data base from all stations.

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 (radar and/or pressure sensors) and a logger installed at the stations. From these stations it is possible to re-collect data missing in real-time. Class 2-stations will have the same sensors, without a logger and without the possibility to recover data missing in real-time. Class 3- and 4-stations will be unchanged or 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. For Class 1-stations, an observer will visit the station every week and check the status of the station and validate real-time data. The long time series at SMHIs mareographs, starting in the late 19 century, will be continued. Summarized, there will be 53 upgraded Class 1- and 2- stations in the new Swedish sea level network and hopefully by the end of 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 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 two 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).

All sea level stations will be connected to the Swedish national reference datum RH2000, also abbreviated as the Baltic Sea Chart Datum 2000 (BSCD2000). The difference to the calculated Mean Sea Level (MSL) in the year of 2017 is about +15 cm in the central parts of the Baltic coast and -8 cm in the northern parts of the Swedish west coast.

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	0.1	2007
Skagsudde	63º 11' 26'' N	19º 00' 45'' E	1982	No	-	No
Spikarna	62º 21' 48'' N	17º 31' 52'' E	1968	No	-	No
Forsmark	60º 24' 31'' N	18º 12' 39'' E	1975	No	-	No
Stockholm	59º 19' 27'' N	18º 04' 54'' E	1889	1992A/B	15.3/3.4	No
Landsort Norra	58º 46' 08'' N	17º 51' 32'' E	2004	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	55º 33' 27'' N	14º 21' 28'' E	1982	No	-	No
Skanör	55º 25' 00'' N	12º 49' 46'' E	1992	2002B	1.8	No
Klagshamn	55º 31' 20'' N	12º 53' 37'' E	1929	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	57º 14' 59'' N	12º 06' 45'' E	1967	1991A	19.7	1993
Göteborg-Torshamnen	57º 41' 05'' N	11º 47' 26'' E	1967	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	0.05	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. 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

In 2013, SMHI have made all the oceanographic data available for free. From an INSPIRE-oriented web-site it is possible to download the long time series of data (hourly values): http://opendata-catalog.smhi.se/explore

In June 2017, 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 10-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, Copernicus, QUARTOD and others.

Programme	**Data host**	**Frequency**	**Resolution**	**Media**	**Notes**
PSMSL	NOC	Yearly	Month	Mail	All stations (24SMHI)
COPERNICUS	IFREMER	Daily	HiRes*	FTP	All stations (27SMHI, 36SMA)
GLOSS/NEAMTWS	VLIZ	Hourly	HiRes*	FTP	GLOSS stations (4SMHI)
BOOS/NOOS	SMHI	Hourly	Hour	FTP	All stations (27SMHI, 36SMA)
www.smhi.se	SMHI	Hourly	Hour	www	Real-time stations (24SMHI)
www.boos.org	DMI	Hourly	Hour	www	Real-time stations (24SMHI)

* 10-minute values and hourly maximum and minimum values. Minute-values are available for some periods, especially during severe storm periods.

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 level stations

The exchange of oceanographic data in the Baltic Sea is very well developed. Within the BOOS (Baltic Operational Oceanographic System, http://www.boos.org) community an easy FTP-box system have been developed for exchange of data between the different institutions on a routinely basis (usually every hour). The time resolution of the data is from 1 minute up to several hours, with the highest resolution for sea level data.

A work towards one common reference datum in the Baltic Sea, for sea level and nautical charts, has been going on for many years between BOOS and BSHC (Baltic Sea Hydrographic Commission). The work is coordinated by SMA. Reference datum for sea level stations located in the Baltic Sea are presented on the BOOS website: http://www.boos.org/wp-content/uploads/mwreg_boos.pdf

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. For the moment, the system consists of about 200 sea level stations (Figure 6): http://www.boos.org/boos-stations

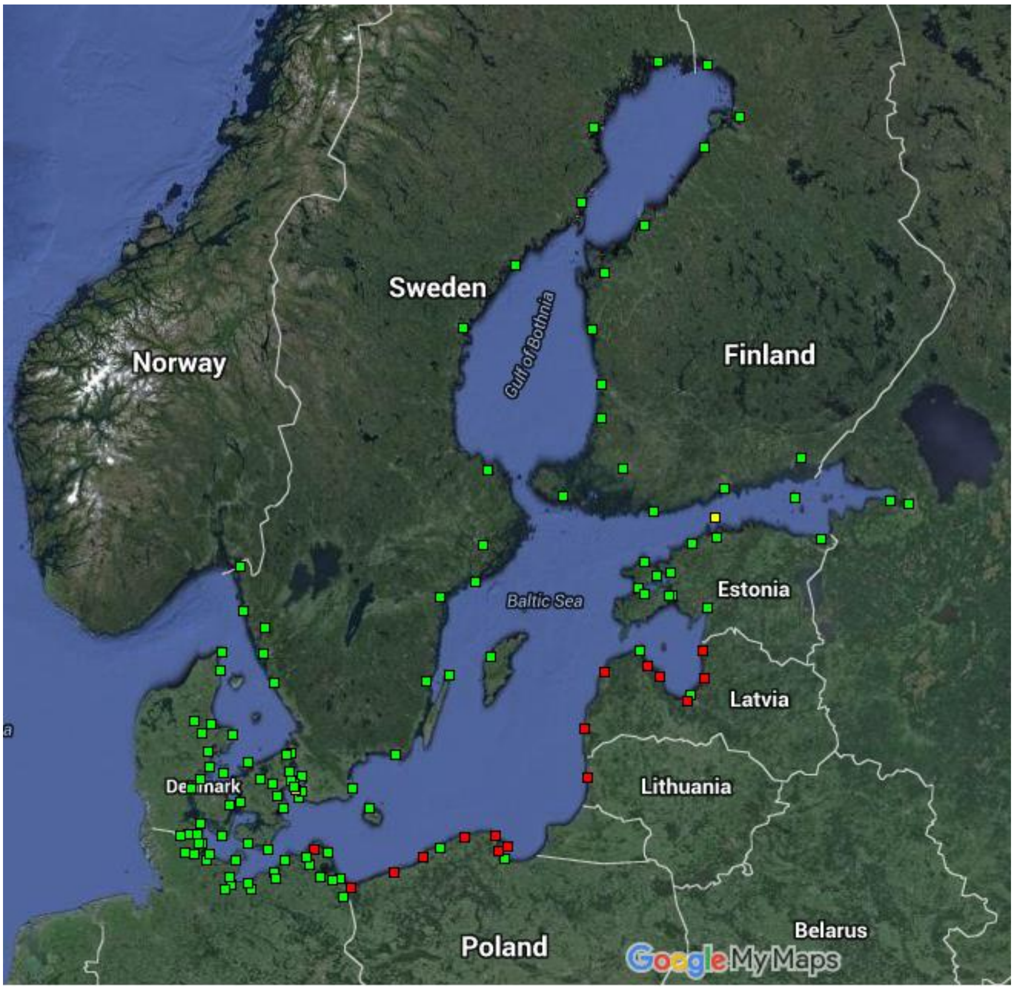

Figure 6. Sea level stations available through the BOOS Community. Stations marked in green are available in near real time. Stations marked in red are not available of different reasons.

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 7). A regression analysis indicates a sea level rise around 3 mm per year for the last 30 years and approximately 1.6 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 centimeters since 1886.

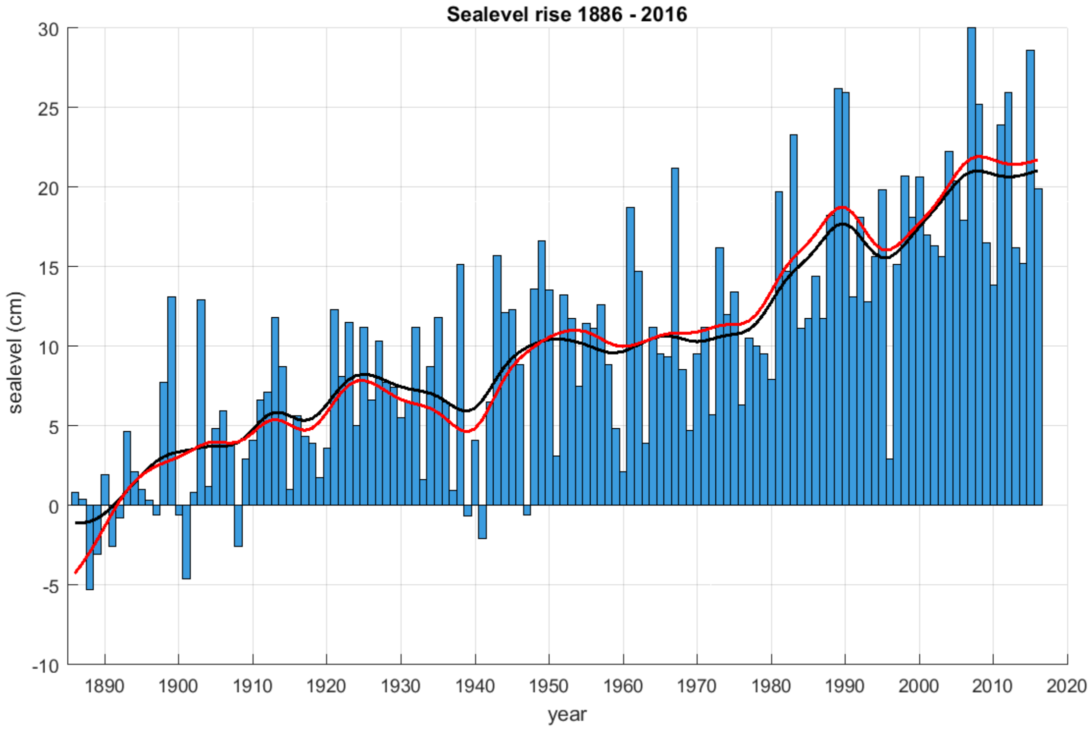

Figure 7. Sea levels corrected for the absolute land uplift (isostatic adjustment). Blue bars show the annual sea level averaged for 14 sea level records, compared to the 1886 level. The black and red line shows the gauss-filtered average and Stockholm sea level, respectively.

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 measuring sea level (Figure 9), 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.

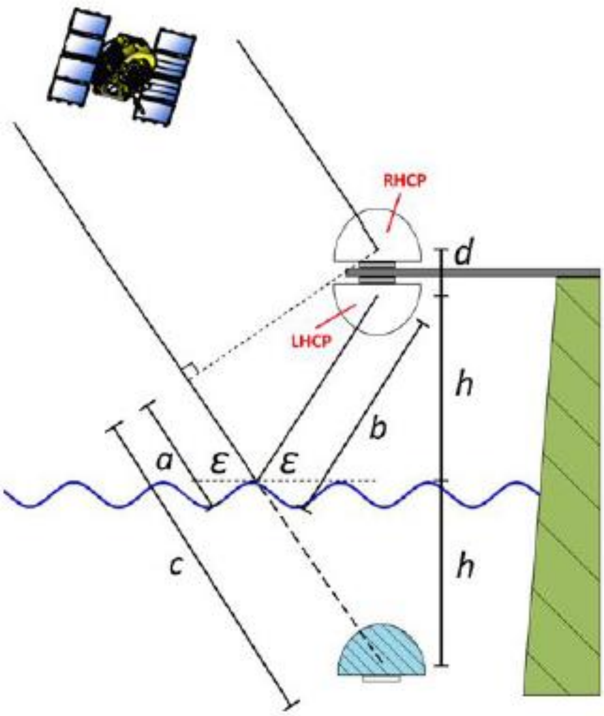

Figure 9. An upward- and downward looking GNSS-reflectometer

Temporary, mobile stations

Since 2011 have SMHI tested a new mobile system for sea level measurements, which is now operationalized. In 2014, the equipment were installed at three locations; Uddevalla, Arkö and Haparanda. Uddevalla and Haparanda indicates higher sea level during severe storm events, so it is very interesting to validate our sea level model at these locations. Uddevalla is located north of Göteborg in the Skagerack, Arkö at the entrance to the Bay of Bråviken and Haparanda, located at the northern most point of the Bay of Bothnia.

At the places we have pressure sensors, where sea level is adjusted for salinity and water temperature variations (also recorded). In Uddevalla we are also using a radar sensor, the same type as in Onsala (Figure 8). The stations are delivering high-resolution data every minute.

Figure 10. A mobile sea level station, which consist of a bubble-sensor (to the left) and radar sensor (to the right). During periods with ice conditions, the data from the radar sensor are neglected.

Appendix 1.

Swedish sea level stations owned and operated by the Swedish Maritime Administration (SMA) and Swedish Meteorological and Hydrological Institute (SMHI).

STATION	LATITUD	LONGITUD	START YEAR
KALIX KARLSBORG (SMA)	65° 47' 20''	23° 18' 12''	2009
HAPARANDA mobile (SMHI)	65° 46' 18''	23° 54' 11''	2014
KALIX STORÖ (SMHI)	65° 41' 49''	23° 05' 46''	1974
STRÖMÖREN (SMA)	65° 32' 59''	22° 14' 18''	2009
FURUÖGRUND (SMHI)	64° 54' 57''	21° 13' 50''	1916
GÅSÖREN (SMA)	64° 40' 43''	21° 14' 57''	2009
RATAN (SMHI)	63° 59' 10''	20° 53' 42''	1891
HOLMSUND (SMA)	63° 41' 45''	20° 20' 50''	2009
SKAGSUDDE (SMA)	63° 11' 26''	19° 00' 45''	2009
SKAGSUDDE (SMHI)	63° 11' 26''	19° 00' 45''	1982
SVANÖ (SMA)	62° 52' 50''	17° 52' 35''	2009
SPIKARNA (SMA)	62° 21' 48''	17° 31' 52''	2009
SPIKARNA (SMHI)	62° 21' 48''	17° 31' 52''	1968
LJUSNE ORRSKÄRSKAJEN (SMA)	61° 12' 25''	17° 08' 44''	2009
BÖNAN (SMA)	60° 44' 19''	17° 19' 07''	2009
FORSMARK (SMHI)	60° 24' 31''	18° 12' 39''	1975
LOUDDEN (SMA)	59° 20' 29''	18° 08' 14''	2009
STOCKHOLM (SMHI)	59° 19' 27''	18° 04' 55''	1889
NYNÄSHAMN (SMA)	58° 55' 03''	17° 58' 20''	2009
LANDSORT NORRA (SMHI)	58° 46' 08''	17° 51' 32''	2004
LANDSORT (SMA)	58° 44' 41''	17° 51' 54''	2009
E4 BRON SÖDERTÄLJE (SMA)	59° 11' 05''	17° 38' 34''	2009
VINTERKLASEN (SMA)	58° 39' 42''	17° 07' 29''	2009
JUTEN (SMA)	58° 38' 03''	16° 19' 29''	2009
MARVIKEN (SMHI)	58° 33' 13''	16° 50' 14''	1964
ARKÖ mobile (SMHI)	58° 29' 03''	16° 57' 38''	2015
VÄSTERVIK (SMA)	57° 44' 54''	16° 40' 31''	2009
VISBY (SMA)	57° 38' 21''	18° 17' 04''	2009
VISBY (SMHI)	57° 38' 21''	18° 17' 04''	1916
SLITE (SMA)	57° 42' 21''	18° 48' 36''	2009
SIMPEVARP (SKB)	57° 24' 37''	16° 40' 33''	2009
ÖLANDS NORRA UDDE (SMHI)	57° 21' 58''	17° 05' 50''	1851
OSKARSHAMN (SMHI)	57° 16' 30''	16° 28' 41''	1960
KALMAR (SMA)	56° 39' 32''	16° 22' 42''	2009
KUNGSHOLMSFORT (SMHI)	56° 06' 19''	15° 35' 22''	1886
KARLSHAMN (SMA)	56° 09' 15''	14° 49' 17''	2009
SIMRISHAMN (SMHI)	55° 33' 27''	14° 21' 28''	1982

STATION	LATITUD	LONGITUD	START YEAR
SKANÖR (SMHI)	55° 25' 00''	12° 49' 47''	1992
KLAGSHAMN (SMHI)	55° 31' 20''	12° 53' 37''	1929
FLINTEN 16 (SMA)	55° 33' 40''	12° 48' 34''	2009
FLINTEN 7 (SMA)	55° 35' 22''	12° 50' 40''	2009
MALMÖ HAMN (SMA)	55° 36' 49''	12° 59' 51''	2009
BARSEBÄCK (SMHI)	55° 45' 23''	12° 54' 12''	1937
HELSINGBORG (SMA)	56° 02' 41''	12° 41' 14''	2009
VIKEN (SMHI)	56° 08' 32''	12° 34' 45''	1976
HALMSTAD (SMA)	56° 38' 56''	12° 50' 09''	2009
FALKENBERG VA (SMA)	56° 53' 31''	12° 29' 22''	2009
RINGHALS (SMHI)	57° 14' 59''	12° 06' 45''	1967
ONSALA (CTH/SMHI)	57° 23' 31''	11° 55' 09''	2014
VINGA (SMA)	57° 37' 54''	11° 36' 32''	2009
TORSHAMNEN GBG HAMN (SMA)	57° 40' 50''	11° 47' 18''	2009
GBG-TORSHAMNEN (SMHI)	57° 41' 05''	11° 47' 26''	1967
KARET GBG HAMN (SMA)	57° 41' 16''	11° 52' 11''	2009
GÖTAÄLVBRON (SMA)	57° 42' 52''	11° 58' 03''	2009
MARSTRAND (SMA)	57° 53' 13''	11° 35' 37''	2009
STENUNGSUND (SMHI)	58° 05' 36''	11° 49' 57''	1962
UDDEVALLA mobile (SMHI)	58° 20' 51''	11° 53' 41''	2010
BROFJORDEN (SMA)	58° 20' 10''	11° 24' 17''	2009
SMÖGEN (SMHI)	58° 21' 13''	11° 13' 04''	1910
KUNGSVIK (SMHI)	58° 59' 48''	11° 07' 38''	1973