

MODERNISATION OF THE NORWEGIAN TIDE GAUGE NETWORK

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Abstract

The modernization of the Norwegian Tide Gauge Network using technologies of the 1980s is presented. Technical and organizational challenges are described in detail together with cost-estimates and possible future developments.

1. INTRODUCTION

The Norwegian Tide Gauge Network was completely modernized during the 1980s using the new technology available at the beginning of that decade. This transition to new technology was a major effort since we started virtually from scratch by completely specifying a prototype. In fact, the whole process was a combined technical and organizational challenge to our service. Looked upon in retrospect, it must be stated that all difficulties and problems were certainly not envisaged during the initial research and development phases. On the other hand, we now feel that the modernization was quite successful, i.e. that the general objectives outlined from the beginning were reached within the agreed time and budgets. Since this process may be of interest to other Hydrographic Services facing a similar challenge, we describe below the modernization, its prerequisites and the main results.

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2. HISTORY AND BACKGROUND

Accounts on the history of tidal observations along the Norwegian Coast are given in [15, 16, 5, 7, 1] and the reader should consult these references for more detailed information. Our objective here is to give a short and general description of the Norwegian tidal work at the beginning of the modernization process.

During the Second World War, the occupation forces were keen tidalists. They established 18 gauges which were transferred to The Norwegian Hydrographic Service (NHS) at the end of the war. The instruments (traditional float gauges with stilling wells) were manufactured by A. OTT. Nine of them were later transferred to The Norwegian Geographical Survey. Both institutions co-operated closely and exchanged observations and results freely. In 1958, NHS moved from Oslo to Stavanger where the institution has stayed since.

This situation continued from 1945 to 1980. Towards the end of that period, the German gauges became difficult to keep in continuous operation. Access to spare parts was difficult and frequent breakdowns covering long periods of time occurred. Some of these difficulties were caused by old and improperly designed stilling wells. The subsequent data reduction was cumbersome, time consuming and prone to errors. Especially timing errors caused by drifting mechanical clocks created a lot of problems. With sets of harmonic constants not tuned to study the tidal fine-structure, it may be difficult to discriminate between timing errors and inaccuracies in phase caused by poor harmonic constants when analysing oscillations in the residuals, i.e. differences between observed water levels and predicted tides.

Although the monitoring of tides along the Norwegian Coast was experiencing increasing difficulties towards 1980, it must be stated that the observation programme, and the reduction and analysis of observations together with the end results so obtained, was a sound basis for further development. Tide tables had, with some exceptions during the war, been regularly published, and mean sea levels together with extremes and other statistics had been given to national and international collaborating institutions covering a wide spectrum of applications. On the other hand, during the 1970s with a higher drive for information, the various customers experienced slow response to inquiries for access to observations, statistics, end results, etc. In addition, the consequences of the divided responsibility for tidal work between NHS and The Norwegian Geographical Survey were evident and cumbersome for the customers.

The first step to be taken towards a complete modernization of tidal work was the development of software for the digitization and subsequent processing of analogue tidal charts. This work was initiated in 1979. Software for the most important standard tidal work was operational during 1981. A number of manual processes were either automated or made easier using the new software. During the subsequent years nearly all tidal charts gathered by NHS were digitized, processed and archived. This work was completed in 1986 and the database then comprised about 250 years of data.

3. SPECIFICATION AND DEVELOPMENT WORK

During 1980-81, the first discussions on how to modernize the tidal network were initiated. A highly modular system with a modern digital tide gauge preferably without any direct physical contact with the sea was envisaged. Stilling wells should be avoided if possible. The observations (tidal and others) should be transferred to a central computer in the office using dialled communication on the ordinary telephone network. The most important items in the specification were:

- A computerized remote station with ports for analogue and digital sensors.
- A tide gauge without any direct contact with the sea.
- No stilling well.
- Connections between sensor(s)/gauges and remote station should be done by using standard cables. The potential use of VHF was defined as an option.
- Approximately continuous (i.e. small sampling interval) observation of water levels.
- Local presentation of water levels and barometric pressure. Water levels presented locally should be referred to Chart Datum.
- Battery backup for 24 hours.
- Communication with central computer in Stavanger using dialled connection on the ordinary telephone network.
- Interactive communication between remote station and central computer for setting/change of parameters.

A joint project was established by The Norwegian Geographical Survey, The Norwegian Polar Research Institute and The Norwegian Hydrographic Service. With this common project, all governmental institutions with responsibilities within this field were represented around the table. The interests of the Polar Research Institute were naturally concentrated on tidal observations in Arctic areas. The responsibility for project administration and funding was to be taken care of by NHS. From the very beginning of the project it was mutually agreed among the participants that NHS would assume responsibility for the national network (including all gauges) when the modernization process was completed. The Norwegian Geographical Survey retained the responsibility for the levelling of Tide Gauge Bench Marks (TGBM).

An important objective of the new network was good coverage of the entire coast (with a total length of about 2,600 km) as seen from a tidal point of view. This should, of course, be achieved by the lowest possible number of stations in order to

minimize the logistic burden and overall costs. An analysis (taking into consideration historical records etc.) showed that this could be obtained by 22 stations, see Table 1. The majority of them were stations with long historical timeseries. The station at Ny-Ålesund, Svalbard, was included after the modernization of the 22 stations was completed, see Section 5.

Table 1
Location and position of Environmental Data Stations

PORT	POSITION	
	Lat.	Long.
Viker	59°02'N	10°57'E
Oslo	59°54'N	10°44'E
Oscarsborg	59°41'N	10°37'E
Helgeroa	59°00'N	09°52'E
Tregde	58°00'N	07°34'E
Stavanger	58°58'N	05°44'E
Bergen	60°24'N	05°18'E
Måløy	61°56'N	05°07'E
Ålesund	62°28'N	06°10'E
Kristiansund	63°07'N	07°45'E
Heimsjø	63°26'N	09°07'E
Trondheim	63°26'N	10°26'E
Rørvik	64°52'N	11°15'E
Bodø	67°17'N	14°23'E
Kabelvåg	68°13'N	14°30'E
Narvik	68°26'N	17°25'E
Harstad	68°48'N	16°33'E
Andenes	69°19'N	16°09'E
Tromsø	69°39'N	18°58'E
Hammerfest	70°40'N	23°41'E
Honningsvåg	70°59'N	25°59'E
Vardø	70°20'N	31°06'E
Ny-Ålesund	78°56'N	11°57'E

Very soon it became clear that the tide gauge (i.e. the water level sensor) and Norway's difficult environmental conditions represented a real challenge to our project. In a preliminary survey of the market, an acoustic gauge produced by a Swedish manufacturer showed promising characteristics and specifications.

During the first half of 1982, the surveys of market and available technologies were completed and four Norwegian companies were invited to tender

for the delivery of one local station (in the following called Environmental Data Station - EDS) complete with sensors for barometric pressure and water level. This prototype station was expected to be the subject of thoroughly planned tests in order to reach a mature product which in turn could be the basis for subsequent ordinary production models. The prototype was to be delivered in May 1983. The Norwegian company A/S Scan-Matic of Kilsund, Arendal won the competition.

A figure showing the overall structure of the new system is given in Figure 1. The system as presented here may generally be described as a semi real time monitoring system with adjustment capabilities through interactive communication between the central computer and the remote station. The software for the EDS was to be developed and delivered by the manufacturer of the equipment.

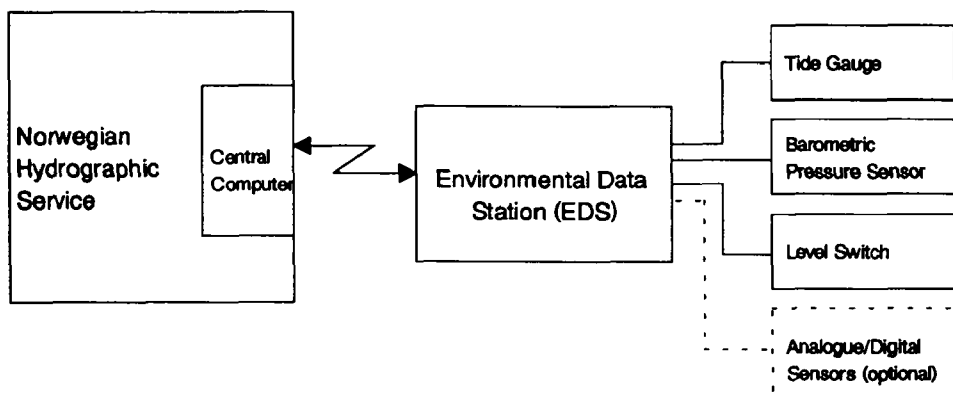


FIG. 1.- Overall structure of the new network.

The software of the central computer represented quite a challenge since software for applications like this is rather tricky and difficult to debug. In addition, it is important to avoid large telephone bills caused by malfunction of the software! Fortunately software developed for a similar purpose was brought to our attention. This software, written in FORTRAN, had been developed by electric power generating companies for hydrological monitoring. Mid-1983 a contract was written with the Norwegian research institution Elektrisitetsforsyningens forskningsinstitut (i.e. Norwegian Electric Power Research Institute) situated in Trondheim for refinements and adjustments of this software to suit our VAX 11/750 computer. This work was completed towards the end of 1983.

Parallel to these efforts it became clear that the general competence of the NHS in modern technologies had to be improved. Of particular importance in this respect were digital signal processing and other disciplines related to a digital environment. This competence was built up from about 1984 to 1986 through internal and external courses. Looked upon in retrospect, this part of the modernization was not given sufficient attention. The gap in competence caused some loss of efficiency during the specification phase. On the other hand, the Tidal Section of NHS at that time was small and the modernization process together with daily work and other responsibilities represented a substantial strain on such a small group of people.

4. PROTOTYPING AND LATER EXPERIENCES

The prototype EDS was delivered early in 1984 and was installed in the port of Stavanger, giving a rather convenient and easily accessible test-facility. The prototype was equipped with sensors for water level (i.e. an acoustic device) and barometric pressure. Very soon we encountered severe problems with the tide gauge. In spite of many proposals and promises from the manufacturer the situation continued to be difficult throughout the whole testing period. Several tests and separate investigations showed serious malfunctions and the project reached a critical stage. We finally concluded that the ultra-sonic sensor was an immature laboratory version not capable of reaching its specifications. Time was running out and we started a rather feverish survey for alternative tide gauges. We looked at pressure sensors but these were turned down due to the variations in salinity caused by fresh water run off from rivers and glaciers. Hence, the utilization of this principle would imply additional observations of other parameters in order to eliminate density as a source of error. This would in turn increase the complexity of the system making it significantly more vulnerable to various problems. We also looked at sensors based on micro-waves, lasers or infra-red light. To our best knowledge at that time we concluded that these instruments were either immature laboratory models or very expensive. Some of the instruments also had a high electric power consumption or were insufficiently robust for the harsh environment. We then decided that we would use well proven technology, i.e. the traditional, but modern, digital float gauge.

We worked with the prototype for about one year making all sorts of experiences. The debugging of the prototype was completed towards the beginning of 1985. It should be noted that this was indeed quite an effort due to the rather complex flow of data from the sensors via the EDS and telephone network to our central computer in Stavanger.

Early in 1985 negotiations for the delivery of four complete EDSs were initiated. A number of important modifications were included in the first four production models. They were installed in 1986 in the ports of Måløy, Ålesund, Kristiansund and Tromsø. In order to continuously evaluate the incoming observations, a lot of additional software was developed, debugged and implemented, see Section 8.

Surprisingly, the tide gauge gave us many problems during this stage of our project. The cause was very small tangential movements between the encoder-wheel and the thin wire connecting the float and the counterweight, see Figure 3. Through several versions of wire and encoder-wheel designs we experienced similar problems. This in turn presents itself as a false (i.e. caused by the instrument) and very slow drift (trend) in the observations. Even versions with small pins on the encoder-wheel showed similar problems. These problems continued until we, through contacts with tidal colleagues of the Canadian Hydrographic Service, became aware of a chain and corresponding wheel (i.e. sprocket) made by a US manufacturer. This well-proven solution to our problems was immediately adopted and installed at all stations and since then the problems have been non-existent.

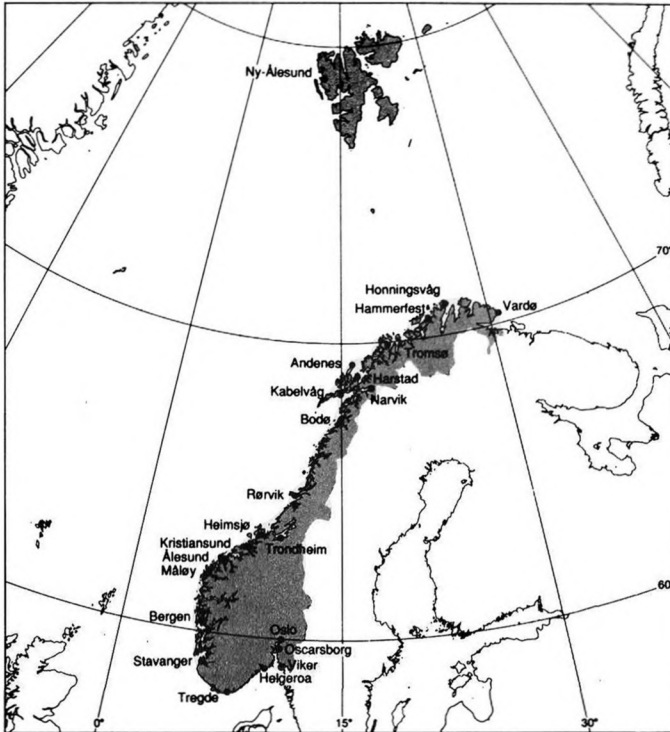


FIG. 2.- Norway with locations of the Environmental Data Stations.

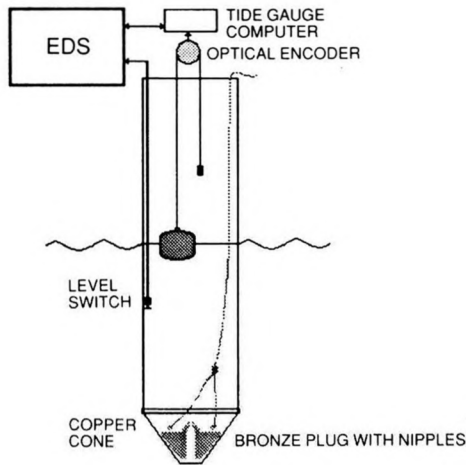


FIG. 3.- Stilling well with copper cone and bronze plug.

The well-known lesson to be learnt from this exercise was that even very small details of an observation system may be crucial to the overall characteristics of the system. Hence, every detail should be minutely evaluated. Even the smallest and most innocent change may have dramatic consequences.

The stilling wells necessary for realistic operation of traditional float gauges have been the cause of much trouble over the years. Initially we approached the design problem using the works given in [9, 10, 11]. These solutions soon proved to be difficult, being vulnerable to fouling and similar complications. In addition to being a problem as such, fouling may cause a substantial change in the characteristics of the stilling well which in turn may lead to changes in the overall signal processing characteristics of the system. This is of course a well known draw-back of stilling well systems. After some trial and error we feel that we now have a solution which is acceptable. A description of the stilling wells is given in Section 6.

5. INSTALLATION OF 23 ENVIRONMENTAL DATA STATIONS

Due to the various difficulties described above, no EDSs were ordered in 1986. The stations at Måløy, Ålesund, Kristiansund and Tromsø were debugged and modified. During this process a lot of minor but important shortcomings were eliminated. Nevertheless all new stations were in routine and daily operation.

The most important constraint with regard to the continuation of the subsequent modernization programme, was the size of the staff. Given the experiences of the previous years, we decided that planning, installation and testing of four EDSs each year was within the capacity of the staff and available budgets. The modernization was completed in 1991 when EDSs were installed in Oslo and Andenes. Table 1 shows geographical data of the EDSs and Figure 2 shows their positions along the coast.

Given the rather long time span of the process, a lot of practical experiences were gained and it was important to have these experiences implemented into the design of future EDS production versions. In addition, in order to keep the maintenance of the EDSs as simple as possible, it was convenient to stick to one design common to all stations. A fairly large effort was put into keeping the EDSs uniform. Whenever possible, changes on the new production versions were also implemented in the previously installed EDSs.

During 1991 and as a consequence of discussions between The Norwegian Polar Research Institute, The Geodesy Division (the latter, now together with NHS and other institutions, divisions within The Norwegian Mapping Authority) and NHS, it was decided to install an enhanced EDS at Ny-Ålesund, Svalbard. This site is of particular importance and interest due to the long timeseries (from 1976 and onwards) from this remote location far north. The difficult environmental conditions of this site caused by ice and low temperatures demanded a special and highly robust design. The stilling well at Ny-Ålesund is a steel tube of 60 cm diameter with a thickness of about 1 cm. The stilling well has a copper cone (see next section) and is welded to the steel front of the quay. This rigid construction is necessary to prevent destruction of the stilling well by heavy ice. In addition, the well has 220 V AC heating cables to avoid freezing of the water inside the well. The EDS communicates with the central computer as described above. To increase the robustness of this installation, a separate Aandereaa WLR 7 pressure gauge is

installed. The data from this gauge is gathered by a local PC whose data is accessed and dumped during the yearly inspection. It is also possible using a temporarily connected modem to transfer data to a central computer.

The EDS and ancillary equipment was installed at Ny-Ålesund during the summer giving a total of 23 EDSs in daily operation. During the winter 1992-93 no problems caused by the extreme environmental conditions of this site were seen.

For the majority of the EDSs a close co-operation with the local port authorities are established. Several of these offices have the EDS in house and are able to use the observations in their operations. In addition, their staff look after the equipment and may assist in various situations. Such assistance has on many occasions proved to be of great value.

6. DESCRIPTION OF STILLING WELLS

The stilling well is used as an analogue lowpass filter which attenuates the high frequency contribution of the surface waves, but leaves longer period variations unaffected. It also protects the equipment against wind, waves, extreme temperatures, salt spray, and daylight (which may cause marine fouling). We have tried to standardize the stilling wells, but the sites even now vary somewhat in design.

A typical stilling well consists of a polyethylene tube and a copper cone. The tube is fixed to the quay level and to the quay front or quay pillar. All materials are non-corrosive such as copper, sea water resistant steel and bronze.

The length of the tube is about 6 m and it has an internal diameter between 30 and 40 cm. Based on several recommendations [4, 14] the ratio between the inlet and well diameter should be 0.1. This is achieved with a copper cone and a bronze plug, see Figure 3. Bronze and copper are used to minimize corrosion and fouling. The plug has an inlet whose diameter is 6 cm. The inlet is adjusted with one or more nipples with threads inside and outside. In this way we are able to adjust the inlet if required and this may be done without using a diver.

Experience has taught us that the flow of water through the inlet may be easily obstructed due to marine fouling or by extraneous matter. The bronze plug makes maintenance and cleaning easy. The plug is simply attached to a rope and can be pulled up at any time without using a diver, see Figure 3. The conical shape of the plug fits the copper cone perfectly, so it will always be in the right position when loaded in the copper cone. Generally the cone and bronze plug are inspected annually.

The copper cone is mounted at the end of the tube. It is usually mounted on the tube before the tube is installed, but it is easily removed by a diver if necessary. A bracket with the tide gauge is mounted on a concrete block or on the concrete floor and it is not connected to the stilling well itself.

The level switch, see Section 7, is placed inside the well at the end of a thin copper tube whose diameter is about 1.5 cm. The cables from the level switch are located inside the 1.5 cm tube which gives good protection against damage caused by maintenance work, etc. The switch is situated at about mean sea level.

7. DESCRIPTION OF HARDWARE

The hardware of the EDS essentially consists of three different parts which are described in detail below.

7.1 The Environmental Data Station

The EDS is made for data acquisition, processing, storing and transmission to NHS's central VAX computer, see Figure 4. The main purpose is the observation of water levels, but other sensors, both analogue and digital, can be connected if required. The designation itself: Environmental Data Station, alludes to the possibility of using the station to measure other environmental parameters. A barometric pressure sensor and a water level switch are presently connected for NHS's own use.

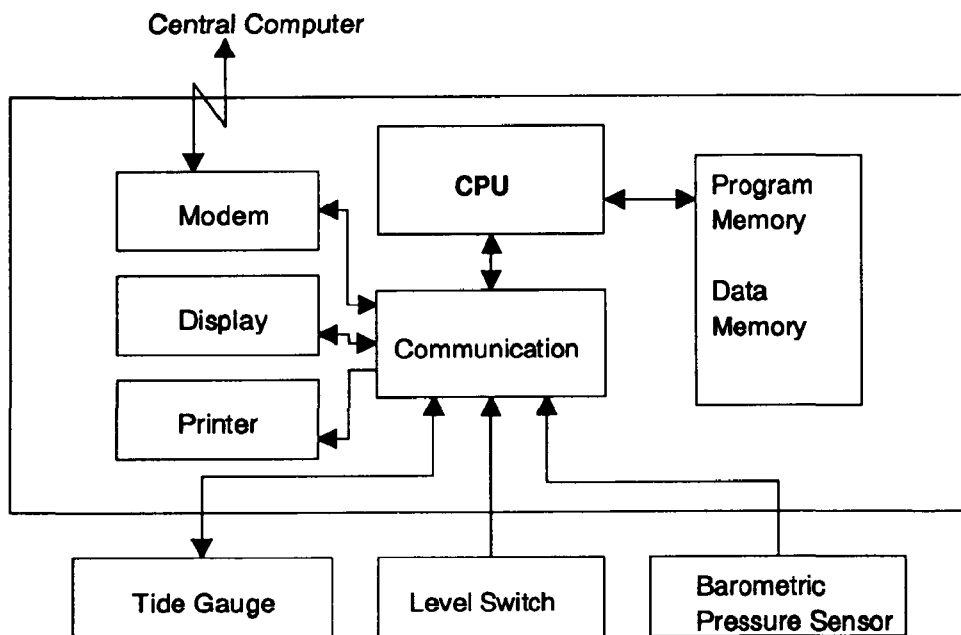


FIG. 4.- Block-diagram: Environmental Data Station.

The EDS can store data for seven days, but it is also possible to store data on a PC using a RS232 port. Other utilities are: password, display, local printer, synchronization between EDS clock and VAX clock, remote restart, remote level corrections, and setting of sampling interval.

The EDS is also equipped with battery backup in case of power failure. The battery backup should last for 24 hours, but the present power consumption has increased because of additional components since the station was designed. Today the battery backup lasts about 18 hours.

The station is galvanically separated from the 220 V AC power supply. This is done to minimize interrupts of the microprocessor caused by transients in the electric power supply which are likely to occur if there is a power failure.

The EDS is based on Intel's 8085 microprocessor. The electronics hardware is divided into 11 circuit boards. The CPU is separated from the memory, communications and sensor boards. This makes it easy to detect errors and to replace components. The program is stored on EPROMs and new versions of the EDS program can very easily be installed.

The EDS has a local display. Besides setting of parameters it can be used to get a local reading of each sensor. As a default it displays the time and the water level relative to Chart Datum. A local printer allows printouts of the last seven days of observations. This is very convenient for local use during the daily port operations. Setting of Chart Datum is done either at the EDS-display or remotely from the central computer. Calibration and definition of tide gauge zero is done using a temporary display connected directly to the tide gauge. The tide gauge has its own display for local setting of parameters and for calibration, see Section 10. The display shows the water level relative to the tide gauge zero.

Communication with NHS's central computer and the tide gauge (and other sensors if required) are other important tasks for the EDS. The station communicates with NHS's central computer via a modem connected to the ordinary telephone network. It supports full duplex, and it is possible to change parameters both in the EDS as well as in the water level gauge.

7.2 The tide gauge

The tide gauge is a digital, modern float gauge. It consists of a dedicated 8085 processor, a traditional float, chain and counterweight system and an optical encoder. The processor does not store any observations, but transmits the observations to the EDS. The processor communicates via a current loop connection, except for the station in Bergen which communicates via modem. This is done to reduce noise influence which occurred because the long cable was picking up noise from a trolley-bus cable. It is also possible to use a VHF link if the distance between the EDS and the tide gauge is large.

When the water level changes, the float and chain turn a wheel which rotates a Gray coded disk inside the encoder. The water level is then given by the angular position of the wheel. The position is represented by a digital code which is directly read by the processor.

The accuracy and resolution of a single 15 s water level observation are about 1 cm and 1.5 mm respectively. Since an average of 241 15 s observations is used for the 10 minute observations, the final accuracy of the 10 minute observations is about 1.5 mm.

7.3 The level switch

The level switch is a tiny float which switches a current loop when the water level passes the level where the switch is mounted. The computer registers the time when the level switch turns on or off. This level is well known, and can be compared with the tide gauge observation at the same time. The level switch has been very important in order to detect several problems, such as the "trend" problem mentioned in Section 4 and for daily quality control.

8. DESCRIPTION OF SOFTWARE

The software is rather complex and is the result of a more or less continuous stream of improvements over several years. The description is divided into appropriate subsections for the convenience of the reader.

8.1 EDS software

The EDS collects observations every second from the tide gauge, but only every 15th value is saved. Alarms will be given if more than two out of the 15 values are missing. The 15 s values are filtered with a digital lowpass filter (FIR-filter) and then decimated. The result is 10 minute samples (or another chosen sampling interval between 15 s and 1 hour). The 10 minute water level samples are transmitted, together with the instantaneous, hourly barometric pressure values and the observations from the level switch, to the central computer. The 15 s values (the *raw data*) may also be transmitted to the central computer. The EDS has memory sufficient for 7 days of 10 minute values. The data is transmitted in hexadecimal ASCII code, and the transmission rate is 300 baud. The transmission protocol contains three main parts; the identifying part, the data part and the Cyclic Redundancy Check (CRC). The software for the EDSs is written in the programming language PL/M by Scan-Matic A/S. The transmission protocol is designed by Scan-Matic A/S.

8.2 Data communication and transmission

The communication between the EDS and the central computer is designed as a question/answer procedure with obvious similarities to human telephone calls! The central computer calls up the EDS and asks for a status report. The status report contains the time, number of sensors, sampling code, alarm code, reference level and a synopsis of any power failures. A CRC follows at the end. The central computer may now ask for transmission of data, or for a change of the parameters in the EDS.

Parameters which can be altered are the EDS clock, the sampling codes and the reference level. A full restart may also be performed. A password must be given to be able to modify the parameters. The software for the communication and data collection parts is written in FORTRAN by the Electric Power Research Institute.

8.3 Software for the central computer

The communication with the remote stations may be done either on user request (i.e. interactively) or automatically through a hibernating batch job. The batch job starts at given intervals, typically once every night. If communication with any of the remote stations fails, these stations will be redialled after a given time interval. Information about how the communication proceeded and information about the parameters are written to a log file. Messages on this log file will then tell us if we reached all stations, and the duration of each call. Any differences between the clocks in the EDSs and the central computer will be flagged and automatically corrected if they are between 4 and 13 seconds. The last three periods with power failures are reported.

After complete transmission of the 10 minute water level observations to the central computer and their subsequent conversion to physical values, the observations are automatically compared with tidal predictions. The registrations from the level switch are also available. Alarms are given if the observations and predictions differ more than a predefined threshold. Alarms are also given if the heights obtained by the level switch data differ too much from the previously known switch level or if some of these data is missing. These heights are obtained by interpolation of the water level observations at the instants when the level switch indicated that the water passed the switch level.

Plotting routines make it possible to present the observations graphically on a screen or a plotter. The water level observations may be plotted as 10 minute values or as hourly values. The plot may include observations, predictions and residuals (see Figure 6). The timescale is user selectable. It is also possible to plot the barometric pressure, the level switch registrations, or just the residuals, see Figure 7 and 8.

If the inspection of the data reveals errors in the observed heights that we want to correct, there are routines to take care of these corrections. In cases where only a few hours (less than six) of observations are missing or contaminated by errors, it is possible to replace the missing observations with "adjusted" predictions. Meteorological contributions are added to the predictions by interpolation between the meteorological contributions to the water levels before and after the gap. It is also possible, of course to delete one or more of the observations.

All changes to the observations, as described above, are written to a file, so that it is possible to reconstruct the original data series.

The 10 minute values may be converted to hourly values by using a digital lowpass filter. The implemented filter is a Butterworth filter of order 4 with a cutoff period of three hours. The filter has a cascaded implementation, and will not give any phase shift.

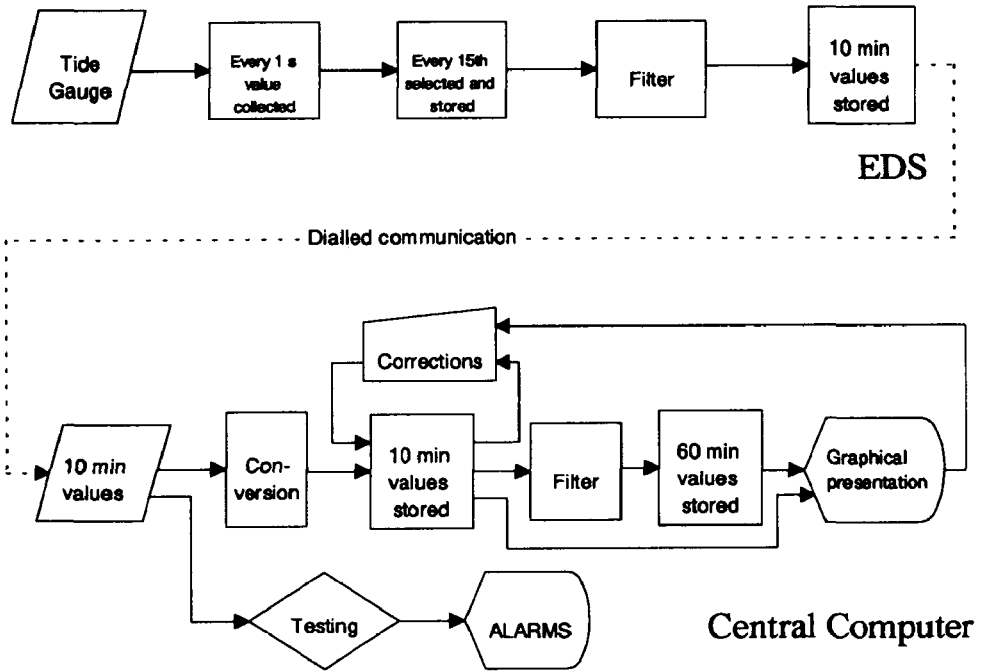


FIG. 5.- Outline of data flow for the water level observations.

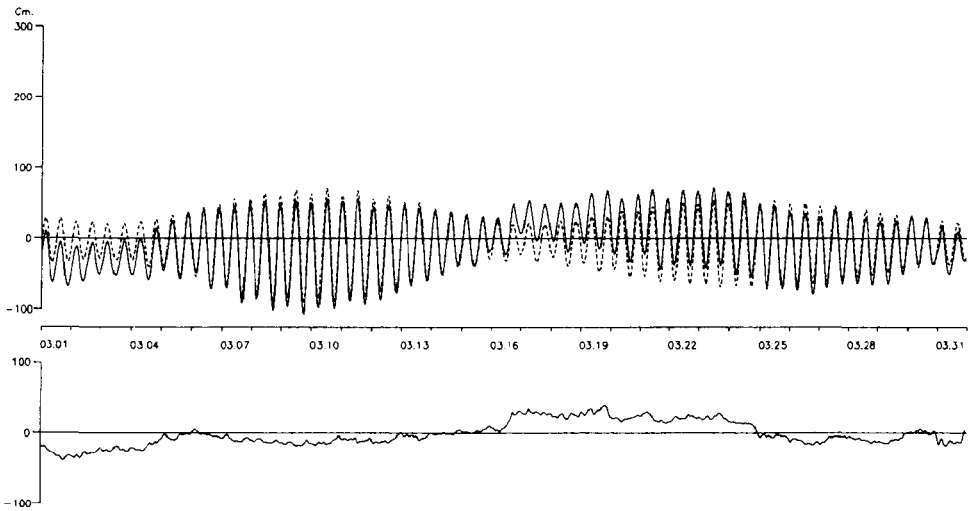


FIG. 6.- Observed water levels, predicted tides and residuals for the port of Bergen, March 1993.

The software is written in FORTRAN, and runs on VAX machines under the operating system VMS. The software for processing, analyses and graphical presentation is written by NHS. An outline of the dataflow is shown in Figure 5.

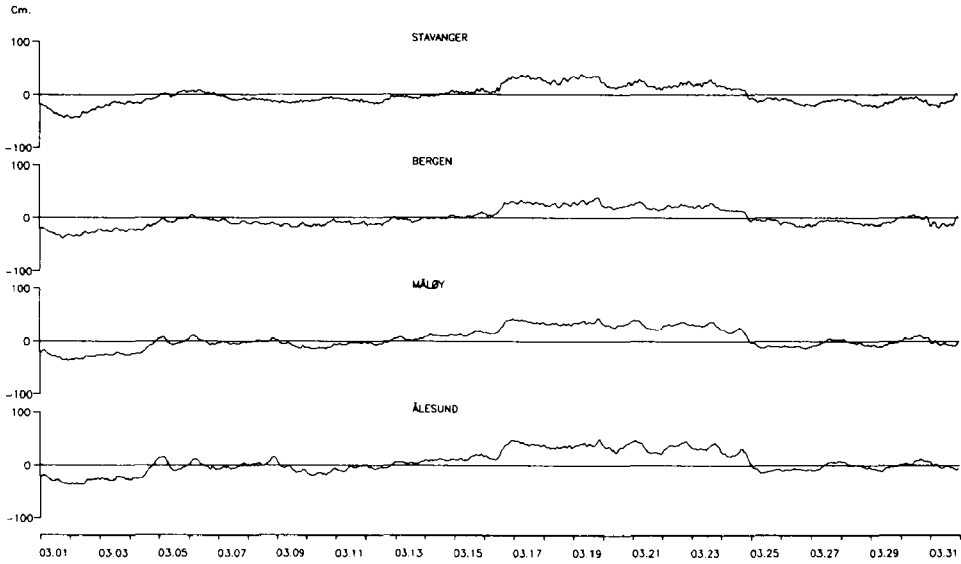


FIG. 7.- Residuals for the ports of Stavanger, Bergen, Måløy and Ålesund, March 1993.

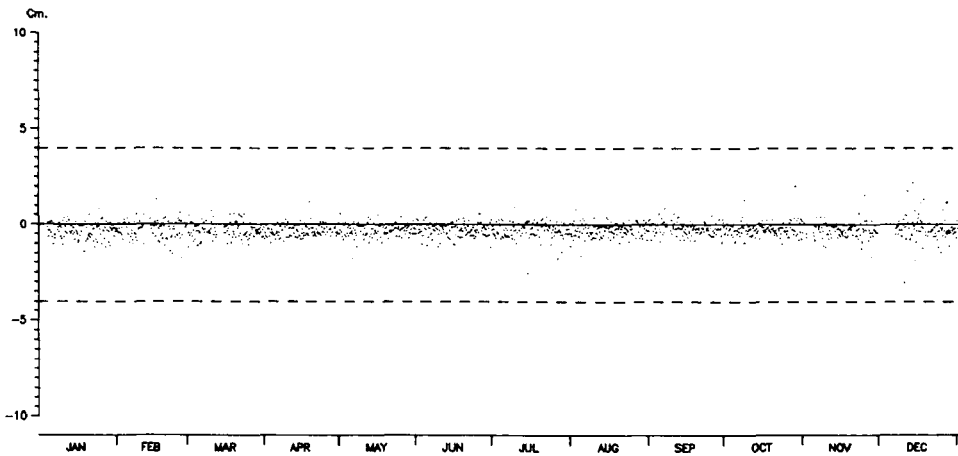


FIG. 8.- Plot showing data from the level switch for Bergen 1992.

9. DAILY OPERATION OF THE NETWORK AND QUALITY CONTROL

Because of the close co-operation with The Norwegian Meteorological Institute on the national storm surge warning service (to be described in Section 12), the network is subjected to a close monitoring schedule. The EDSs are generally

dialled every night when the load on the telephone network is low. The low transmission rate together with the automatic communication procedures (cyclic redundancy checks, redialling and queue procedures) give stable and reliable communication between the EDSs and the central computer.

Immediately after the completion of communication with all 23 EDSs, the observations (water levels and barometric pressures) are automatically converted to physical values easily available for inspection and evaluation of data quality. Further, data from the level switch described in Section 7 are available for inspection.

Graphical presentation is the key to a thorough inspection and control of the observations, i.e. 10 minute samples from 23 tide gauges together with hourly values of barometric pressures. Figure 6 shows a typical display used for the daily inspection. In order to compare residuals from neighbouring ports, a common presentation may be done as shown in Figure 7. The data from the level switch is presented as given in Figure 8. The level switch data is used mainly for supervising the stability of tide gauge zero.

With these tools at hand, malfunctions are generally easily detected and identified by experienced personnel. Over the years, a number of different errors have been detected, identified and thoroughly understood. The personnel responsible for the operation of the network attend weekly meetings where the operation during the previous and coming week is reviewed. It is important to have the correct blend of competence within a group like this in order to secure an efficient handling of all sorts of problems which occur more or less regularly. Another important matter is that the experiences so obtained should, after due analysis, be used for modifications, improvements, etc. of the technology and operating routines. It is clearly seen that the stable operation of the network relies heavily on good organizational and administrative routines together with tight routines for continuous quality control. For the year 1992 the data capture was 98.6% for the entire network.

10. CALIBRATION AND CONTROL LEVELLING

Given that the modernization should imply a substantial improvement of the data quality, the question of calibration and elimination of systematic errors has been taken very seriously using improved methods and technology. Systematic errors are difficult enemies of all water level observation systems and should be minimized as far as possible if the observations are used as input for studies of vertical datum, mean sea level variations and possible global changes in mean sea level caused by the greenhouse effect.

The basic imperative for water level observations is to have a unique and well defined tide gauge zero, see [8, 12, 6, 3, 13]. Further, the tide gauge zero should have a known and closely monitored relation to a Tide Gauge Bench Mark (TGBM). The TGBM should be a stable bench mark situated in solid rock and should not be exposed to local geological movements. Several supplemental bench marks with known relations to TGBM are also recommended and implemented in our practice.

Recent international recommendations state that the TGBM should be known in a global co-ordinate system which may be achieved by using satellite technologies (i.e. GPS), see [2].

Generally it is impossible to have the TGBM close to the tide gauge. The gauge is mounted on a bracket (made of sea water resistant steel) which represents a very stable platform for the gauge. The bracket has what we call a "reference pin" whose relation to TGBM is known by precise levelling. This relation is supervised by annual precise levelling. Tide gauge zero is (by definition) a given distance below TGBM and from this follows the distance between the reference pin and tide gauge zero.

Calibration of the tide gauge is done by installing a temporary levelling staff inside the stilling well. The zero of this staff is mounted at the level of the defined tide gauge zero and this is achieved by temporarily fixing the staff to the reference pin by a simple vice. A small video camera is lowered into the stilling well together with a 220 V AC lamp. A monitor is placed just outside the stilling well. The water level relative to the defined tide gauge zero may now be read off. The gauge is calibrated by making its readings equal to the observations on the staff. This procedure is repeated several times with good stability of the readings as the desired end result. We have seen over the years that this calibration procedure gives a tide gauge zero accurate to within a few millimeters.

At some of our installations the counterweight for the float gauge may run partially or completely into water. The error contribution from this effect has been analysed in detail and the necessary corrections are known. The observations are only slightly influenced by this effect and may if necessary be adjusted during a later data reduction by using a mathematical model, provided that the counterweight's position is known at the time of calibration. We prefer to do the calibration when the counterweight is completely in the air.

Using the procedure described above, all 23 EDSs are inspected and calibrated once every year. The documentation routines are fairly strict and all work reports, support documents etc. are properly archived. Strict routines in the office and during the field work are essential to achieve the high overall quality of the observations.

The potential problem of tangential motion between chain and encoder wheel (see Section 4) is effectively monitored using the observations from the level switch. As an additional tool, small marks on the chain and encoder wheel are used by the local operator to check if any tangential movement between chain and sprocket has taken place. This is of particular importance during the early phase of a suspected movement since a "one-tooth" change of their relative position corresponds to an apparent change in the level switch of about 7 mm. During periods with heavy weather this small change is not easily detected in the plots. The local operator is under such circumstances asked by NHS to inspect the mutual relation between the marks.

Since the barometric pressures are used mainly as a supplementary parameter when analysing the residuals, the calibration of the pressure gauges is taken more leisurely. The instruments are supervised by inter comparison of

measurements from different ports and by simple visual inspection of the data. From time to time we also gather data from the Meteorological Institute to check the observations.

The annual precise levelling is done by The Geodesy Division. Their field work is done through the summer months and the results are reported some months later.

The stilling well represents a rather tricky calibration problem which may be difficult to deal with. For a few of the EDSs we have performed simultaneous readings inside and outside the stilling well. The overall system characteristics of the wells are documented in broad terms by this procedure. The stability of the characteristics may however change due to marine fouling or other causes. After some time the changes may be detected by the presence of unusual oscillations in the residual curve or by some strange change in the level switch data. Crucial factors here are of course the quality of the harmonic constants used for the predictions and the general weather at the time. Continuous harmonic analysis of the observations may resolve this problem since a significant change of the characteristics of the stilling well should lead to a change in the phases and amplitudes of the constituents, see Section 13.

11. INVESTMENT, MAINTENANCE AND OPERATION COSTS

The overall costs of the entire network are somewhat difficult to assess. Part of the reason is the rather long period of time used for the modernization from its beginning to its completion in 1991. In addition, a varying number of NHS personnel have been working on the project. Further to this, contributions (i.e. mainly man-hours) from the co-operating institutions should be added.

NOK 300,000 (USD 43,000) may be given as a round standard figure for the cost of one complete EDS equipped as described above. This includes the stilling well and a small hut for the protection of the equipment. A typical size of the hut is about four square meters. The huts are connected to a 220 V AC power supply and are heated in cold weather. Many of the EDSs are situated in the harbour master's office with the sensors located some distance away transmitting their signals through cable to the EDS. In cases like this, the costs are of course lower. The cost of the EDS hardware is about two-thirds of the cost given above.

The costs of the central unit may be broken down into hardware and software costs. The hardware consists of a VAX/VMS workstation, dialling equipment, modem and peripheral units. The total cost of this equipment (including network devices in the NHS office building) is about NOK 750,000 (USD 110,000). The total value of the software for the central unit is more difficult to assess. A rough idea of the amount of software involved for a stable, reliable and user-friendly operation of the network may be given by stating that about 35,000 lines of FORTRAN code go into the software. Knowing that this software is rather difficult and that debugging is very time-consuming when compared to general software, it is evident that the costs are substantial. Again as a rough figure, about 6-7 man-years

would probably be necessary for the specification, development, debugging and implementation.

The maintenance costs for the next few years should be rather low. The overall quality of the network is satisfactory and we do not expect major expenses. The software of the EDSs is however outside the direct control of NHS, and we envisage a situation where the software must be upgraded. Although partly dependent on the manufacturer, we do not expect this situation to occur during the next few years.

Assuming daily communication with all EDSs, the average annual communication costs about NOK 60,000 (USD 8,500). About 50% of these costs are fixed charges which are independent of the dialling rate. The costs may be reduced if the stations are dialled less frequently. The communication costs may be further reduced if the transmission speed is increased.

The operating costs in terms of man-years are highly dependent on the actual situation at the institution responsible for the operation. In our practice we would say that about 2-3 man-years are necessary for a stable operation including contributions to the national storm surge warning service.

12. CONTRIBUTIONS TO NATIONAL STORM SURGE WARNING SERVICE

During the years around 1985, NHS co-operated with The Norwegian Meteorological Institute on verification and improvement of the numerical models used by The Meteorological Institute. In 1987 a major storm surge struck the Norwegian South-East coast which caused a lot of damage. This event together with a later algae bloom triggered a new programme under the Ministry of Environment. The programme is intended to establish better methods and exploit existing technology and infrastructure to improve the surveillance of environmental conditions in Norwegian waters. A storm surge warning service should be an important part of this. In 1990, the then existing tide gauge network of NHS was transferred from a MicroVax to a VAX/VMS workstation which allowed for smoother and simpler operation of the network. Water level observations have been regularly transmitted to The Meteorological Institute since April 1991. This is generally done by 1100 hours every day after due quality control by NHS. If necessary, observations are gathered from the network more often and transmitted to The Meteorological Institute. In storm surge situations a very close co-operation is established with strict co-ordination of information to the public and to the media.

At The Meteorological Institute the observations are used for supervision and adjustments of estimates derived from their numerical model. The adjustments (if any) are done subjectively, no automatic (objective) assimilation is (as of 1993) in routine operational use.

The co-operation has proven to be very useful during these few years and has on several occasions contributed to a substantial reduction of losses caused by

storm surges. Due to serious budget cuts and an ongoing evaluation, it is not clear that this programme will continue.

13. FUTURE DEVELOPMENTS

Some possible improvements have been mentioned above. The characteristics of stilling wells should be better documented through simultaneous measurements of water levels inside and outside the stilling well. Using modern laser technology, this may be done in a fairly straightforward way. In principle it should be done for all 23 stilling wells.

The surveillance of the data quality should be improved. We believe that steps in this direction are possible by using a sliding harmonic analysis in combination with stochastic models. Some research is necessary to see if this leads to significant improvements.

The original requirement for a tide gauge without any direct physical contact with the sea should not be forgotten. Nowadays there are new sensors on the market which may realize this dream. On the other hand, the costs may be high (multiplied by 23!) and no improvements will take place before the existing gauges show signs of wear and tear.

The communication costs may be reduced by increasing the baud rate. The present baud rate is very low indeed, and may be significantly increased, probably without subsequent communication instabilities. The Norwegian telephone network with its digital telephone exchanges is of very high quality offering better service and stability now than around 1980 when the network was designed. On the other hand, the change would be a major modification requiring changes in software, communication protocols and new modems. This will be done as part of a future general update and revision of the network and is some years ahead.

Finally the question of improvements to the EDS software must be mentioned. Although this software is very stable, one should keep in mind that it was developed at the beginning of the 1980s and improvements and better capabilities are possible. On the other hand, given cheap PCs with efficient software for communication, one should perhaps look to this technology for the next generation of tide gauge network.

We conclude this section by stating that the operation of a modern tidal network is a continuous development process where the routine operation is done parallel to running improvements and development work.

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