Title   *Efficient, Safe and Sustainable Traffic at Sea*

Acronym   *EfficienSea*

Document No. D_WP4_4_4

Document Access: Public

Design and deployment of an AtoN remote monitoring centre and IT infrastructure for providing e-Navigation service

Contract No. 013

DOCUMENT STATUS

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Document History

Revision	Date	Organisation	Initials	Revised pages	Short description of changes

Contents

1. AtoN Remote Monitoring

1.1 Introduction

Due to the high availability requirements imposed on provision of light signalling service within the marine navigation safety infrastructure, the responsible authorities need continuous awareness of the status of equipment operating at the lighted visual aid to navigation (AtoN) sites to be able to guarantee timely repairs and condition based preventive maintenance. Based on navigational risk assessment to determine critical AtoN sites, a typical solution for maintaining adequate AtoN state and technical (engineering) situation awareness at the operations centre is implementing a remote control and monitoring system (RCMS) of AtoN site equipment using wireless technologies available in the region, often utilizing public cellular networks (GSM) for transmission of information from the fielded systems to a remote control and monitoring centre (RCMC).

Cybernetica AS has set the goal of developing such solution further to bring added value to the classical AtoN remote monitoring, utilizing the equipment, the monitoring centre software components and the communication links established for transmission of scarce state reports and expectedly rare failure alarms for introducing the e-Navigation service elements for provision of improved situation awareness both to the authorities responsible for AtoN operation, and to the mariners: forwarding of status messages received from navigational buoys to the Automatic Identification System (AIS) network for broadcasting as Monitored Synthetic AIS AtoN reports, gathering buoy heel angle information for more sophisticated visibility range analysis, and even estimating the sea states in the future. The Cybernetica solution is based on application of GPS-capable ekta™ Telematics Field Controller (TelFiCon or simply Telficon) units employing GSM/GPRS based communication that provide acceptable availability and latency (transfer delay) levels, feeding the information from remote sites (AtoN outstations) into a single monitoring centre over the public networks utilizing the reliable TCP/IP protocol. At the monitoring centre, several software components are at work on the received data to provide decoding, analysis, logging, serving the informational content to authorized users, and forwarding it to other networks as necessary. Recording of all the relevant information in an AtoN database and creating systematic situation reports helps to keep track of the events potentially leading to failures, to avoid configuration errors, and to perform AtoN maintenance in most efficient way. While the original intent of creating such RCMS was to develop an information system extending beyond the mere event status recording tasks when it was started over fifteen years ago, only the developments in sensor and communications technologies, networks, and costs have made such more sophisticated systems feasible. This document provides an overview of the principles, equipment and software used to achieve the set goal.

1.2 Remote AtoN Site Equipment

The AtoN sites are fitted with navigation lights for provision of the primary functionality of AtoN service to the mariners, controlled by either a single or duplicated (redundant) flasher unit and powered either by primary batteries, solar, wind or utility power in combination with rechargeable batteries and corresponding regulator/chargers. An optional monitoring, positioning and communications module typically employed for system health and performance monitoring at critical AtoN sites is tasked with checking AtoN operation, integrity, position, and technical state. It initiates a communications session with the remote monitoring centre to send a system status message at regular reporting intervals, or an error/warning message upon detection of either any monitored parameter exceeding a set threshold for measurements directly performed by the monitoring module, or a position outside the allowed area in case of GPS position monitoring

activated. It also interfaces the site local area network (LAN) to the remote monitoring centre, forwarding the error and warning messages originating from site equipment to the centre.

Figure 1. AtoN site equipment: a LED lantern, a flasher, a Telficon E9262, and an ice buoy lantern E8921 integrating the same Telficon and flasher board with a LED array and GSM/GPS antenna.

Due to the fact that significant part of Estonian waters is located only about 7º south of the Arctic Circle, environmental conditions during the winter can be rather harsh, with occasional solid ice formation on fairways and air temperatures falling below -25ºC. Since passenger and cargo traffic with neighbouring countries and the Estonian islands (partly replaced by setting up ice bridges for road vehicles when possible) is upheld even during the winter, requirements to reliability and power efficiency of AtoN equipment used are high. Amount of solar radiation that could be obtained from integrated photovoltaic panels on buoys is not sufficient for most of the navigation season; therefore primary batteries are used to power floating AtoN systems, resulting in strict limitations to the power consumption of the onboard equipment. A good example of a robust but capable floating AtoN system is an ice buoy lantern E8921 manufactured by Cybernetica, providing monitoring and synthetic AIS AtoN operation with GPS position monitoring in typical configurations (AIS M21 in every 3 min) at 7.2Wh per day spent for communications; light signalling doubles or triples the energy consumption depending on the nominal range and flashing character used.

In this paper, mainly floating AtoN sites that are remotely monitored using a Telficon unit (currently, model numbers E9261 and E9262) are discussed. Monitoring and measurement mission parameters of a Telficon are described in detail in paragraph 2.

1.3 Monitoring Centre Configuration

The Remote Control and Monitoring Centre implementation developed at Cybernetica is documented under product number E752. It consists of several hardware and software configuration items:

- A dedicated server computer based on X86 hardware and running a Debian GNU/Linux operating system

- A monitoring front end software component for communication with remote AtoN sites, formatting and forwarding of pre-formatted synthetic AIS AtoN reports: PaSS (requires a Sun Java Runtime Environment (JRE), ver. 6 or higher)

- A PostgreSQL based database application for storing AtoN and event information: GAB

- An Apache based web server application providing online access to AtoN monitoring and configuration information by Internet browser software: GVL

- Software components for data analysis, alarm generation, reporting, interfacing, RCMC health monitoring and diagnostics, etc

The software has been designed to enable implementation of a redundant server configuration in the future.

Another software component that may be located outside the RCMS server but logically belongs to the e-Navigation service infrastructure is the Cybernetica AIS Router. It is operating close to the AIS server segment, receiving the contents of synthetic AIS AtoN reports from PaSS, finalizing the formatting of these into proper AIS AtoN messages, and routing the results to the relevant AIS base stations.

1.4 Handling of Monitoring Data

In a traditional AtoN remote monitoring application, the central station (system server) either polls the remote stations regularly, or waits for the remote stations (clients) to initiate the communications. In case of using the cost effective GSM/GPRS based connectionless TCP/IP communications, typically only a remote AtoN site (a Telficon) can initiate a communications session with the monitoring centre server due to the specifics of the GSM service provider network. Should a need arise for communicating with a remote site earlier than the next scheduled reporting time, a following feature is foreseen: it is possible to force a Telficon into initiating a communications session with the monitoring centre server by simply calling its GSM phone number.

While the main function of the Cybernetica AtoN RCMC is still waiting for regular status, position and error reports, the scope of information available from a Telficon extends beyond simple system status monitoring. Data received from the Telficon units installed at remote AtoN sites belongs to one of the four categories below, and is subject to corresponding handling by the server software component PaSS:

A. Messages with navigation safety critical content: AtoN site equipment failure/error or warning messages, „Buoy off station", "Critical heel angle", collision alert, synthetic AIS AtoN status report – these messages receive priority treatment and result in immediate alarm generation or forwarding. All such messages are time stamped by Telficon and saved to the database upon receipt, with the exception of regular status reports from the buoys that are subject to synthetic AIS AtoN reporting.

B. Operational status information: regular status reports at pre-configured time interval from AtoN sites other than the buoys subject to synthetic AIS AtoN reporting, containing power supply voltage, temperature, GSM field strength, coordinates, flasher status report, etc. These messages are saved to the database when certain configuration conditions are met (significant status changes, etc), and used as input information for daily automated situation reports.

C. Information requested from a Telficon by the RCMC during a communications session: status reports from and configuration settings of the AtoN site equipment connected to a Telficon over the RS485 interface based LAN, parameters not included in regular status reports (heel angle and communications statistics), etc. This information is saved to corresponding locations of the database.

D. Acceleration measurement information: this information is currently saved in binary files for further processing by external applications, formatted according to Cybernetica conventions. Evaluation of feasibility of developing an application for online sea state estimation is a work under progress.

Requesting additional information from a Telficon is accomplished by creating a corresponding communications scenario for a specific AtoN site by the means of the RCMC software. Once the Telficon initiates a communications session, it discovers and executes the created scenario, uploading requested information and downloading new settings when instructed so. Information exchange between a Telficon and the RCMC is discussed in more detail in section 2.

1.5 Synthetic AIS AtoN Reports Generated by the AtoN Remote Monitoring System

With the support built into the shore side information processing and transmission infrastructure, the Telficon modules installed on navigational buoys can be used as status data sources for broadcasting of synthetic AIS AtoN messages by the means of the AIS shore network. In addition to cost savings both on hardware and on energy for power supplied, this kind of arrangement offers benefits to the responsible authorities by enabling full control over the AIS AtoN broadcasting: it can be configured online with ease, enabled/disabled individually, or limited to broadcasting of off station/failure messages. Synthetic AIS AtoN functionality of Cybernetica AtoN monitoring solution is described in Sections 2 and 4.

2. Communications, Positioning and Measurement Module ekta™ Telficon E926X for AtoN Integration into e-Navigation Infrastructure

2.1 Telficon: a Telematics Field Controller for AtoN Monitoring

The E926X Telficon products are designed and manufactured at Cybernetica AS specifically for AtoN remote monitoring applications, sharing common software/hardware architecture with similar products designed for e-Police and railway applications. A Telficon unit integrates a programmable 8-bit microcontroller with a standard GPS receiver, a GSM/GPRS modem and a solid state 3-axial acceleration sensor on the circuit board level. With the firmware tailored to operate at lowest achievable power consumption levels, it is responsible for implementing GPS positioning, time synchronization, communication and measurement functions at the remote AtoN sites, allowing limited control of AtoN mission parameters from the monitoring centre over public GSM-900/1800 GPRS based packet switching TCP/IP networks. In case of ekta™ brand of LED buoy lanterns manufactured by Cybernetica AS, the Telficon unit is typically mechanically integrated with the lantern. It is fitted with an RS485 interface for wiring together a local area network of up to 16 equipment units installed at the remote AtoN site (redundant flashers and power supplies, etc) that can utilize the proprietary A-Bus protocol used by ekta™ AtoN products, creating a gateway for these devices to the RCMC for sending alarms, monitoring, firmware re-configuration and updating.

A Telficon is typically configured at the factory for the AtoN monitoring mission in accordance with user requirements. It can later be re-configured either using a personal computer equipped with the maintenance software Lanserv+ and a suitable interface adapter module (E8152), or over the air from the RCMC server software. Furthermore, since the end of the year 2009 and firmware version 2.0, the Telficon product features Firmware-Over-The-Air (FOTA) capability allowing replacing the whole firmware of a fielded Telficon unit from the RCMC to improve or change the functionality within the limitations of the hardware. This remarkable feature brings significant cost efficiency and reduced environmental footprint to AtoN monitoring system operation, considering multi-seasonal buoys and costly visits of a 60m buoy tender with fuel consumption of 200 l/h to 500 l/h (up to EUR 500 per hour for fuel costs only) that were necessary for retrieval of the buoy for re-programming beyond the capability offered by the RCMC in the past. The method used for transfer and activation of new firmware is applied in error tolerant way, guaranteeing that the Telficon will not be rendered inoperable or commence erroneous operation either after an unsuccessful remote update, or in case of unlikely transmission errors, always resuming operation with a previous firmware version in case when the integrity checking of received new firmware version fails.

A Telficon can be configured for operation at the remote AtoN site with one of the following mission profiles:

A. Standard AtoN monitoring (either fixed or floating)

B. Standard AtoN monitoring (either fixed or floating) with synthetic AIS AtoN reports

C. Floating AtoN monitoring with collision detection

D. Floating AtoN monitoring with heel angle statistics and critical heel angle detection

E. Floating AtoN monitoring with acceleration measurement and transmission

These profiles are not strict or menu-selectable; they are provided here for guidance and can actually be applied in almost any combination by corresponding RCMC software settings. The only profile not recommended for mixing with synthetic AIS AtoN reporting is the acceleration measurement. The only difference between profiles A and B is in the reporting frequency, with AIS reports being sent to the RCMC at fixed time intervals, down to once every 60 seconds when necessary, while in case of standard AtoN monitoring as few as only two regular event triggered messages may be sent to the RCMC per day ("Light on" and "Light off", generated by a flasher module as a result of ambient light measurement).

In case of any mission profile, a Telficon performs the following repetitive tasks at a pre-configured time interval to check the system integrity and to discover potential malfunctions or deviations:

- Polling the AtoN equipment connected to the site LAN for status information to detect failed or missing devices

- Requesting a position fix and time synchronization from the GPS receiver to check that the position is within the alarm (watch) circle of the buoy, and to update the clock

- Performing the measurement of power supply voltage and external voltages at the analog to digital converter (ADC) inputs, including the temperature from an onboard temperature sensor.

Depending on selected mission parameters, the following additional actions can be performed:

- Synchronization of the clocks of external AtoN equipment based on GPS time

- Measurement and analysis of acceleration to detect collisions

- Measurement and analysis of acceleration to detect a critical heel angle

- Measurement and analysis of acceleration for heel angle statistics

- Measurement and buffering of raw acceleration data for transmission to the RCMC

After performing the pre-programmed polls and measurements, a Telficon shall analyze the results in accordance with its mission profile, proceeding as follows:

- Initiates a communications session with the RCMC for sending an error message (alarm status report) if any abnormal conditions were detected;

- Initiates a communications session with the RCMC for sending a regular status message (report) if the concluded poll was the last one in the number of polls given as an interval for sending regular status reports;

- Goes back to sleep mode for saving energy, to be waked up either by any event reports from external equipment connected to site LAN, or by internal clock upon arrival of the next polling time.

When a need arises for sending a status message to the RCMC, a Telficon uses a compact proprietary 32-byte binary status message containing the following data items:

- UTC timestamp with time zone offset specified by RCMC settings

- Power supply voltage level

- Temperature inside the Telficon enclosure (at the onboard temperature sensor)

- Last known position and time of the last GPS position fix

- Status of the last known position: accuracy (GPS or DGPS), inside or outside of the designated area (alarm circle radius); in case of missing position fix, the probable reason (waiting time exceeded or missing coordinates in GPS receiver's NMEA sentence)

- Content of two last error messages and time of sending

- GSM signal field strength

- State of Telficon's two digital inputs (passive or active)

- Additional status bits marking error or warning states (checksum error of firmware or configuration settings discovered, "critical" or "submersion" heel angle exceeded, etc)

In addition to the above standard status information, a Telficon maintains records and statistics that must be queried by specific scenarios set up at the RCMC software.

Each equipment unit connected to a Telficon has its own 32-byte standard status message that is forwarded to the RCMC during a communications session without any local analysis. Content of such status messages depends on the type of equipment and must be anticipated by the RCMC for correct recording in the system database.

In case of an acceleration measurement mission, the measurement information is sent to the RCMC over a separate TCP/IP connection (session), coded in packages of dedicated format, not within status messages.

2.2 Telficon as a Synthetic AIS AtoN Data Source

When a Telficon unit installed onboard a buoy is tasked with a synthetic AIS AtoN reporting mission, it is simply configured to send its status reports with time interval suitable for AIS network in the area. Typical reporting interval currently in use in Estonia is 3 minutes, with the limiting factor for reducing the interval down to 1 minute being excessive power consumption of the communication circuitry. For example, at the 3 minute AIS reporting interval, average daily power consumption of an ice buoy lantern E8921.W in an application as a 3.8 NM safe water buoy with LFI W 10s flash (2+8=10 s), is 7.2 Wh for communication only, totaling to 20 Wh per day with the LED array (50 cd to 150 cd) operated at the luminous intensity of 51 cd. In

case of a traditional AtoN monitoring mission, the power consumption for communication will decrease to 2.2 Wh/day or even 1.5 Wh/day when reporting intervals of 20 minutes or 4 hours are applied, correspondingly.

Transcoding of the AtoN status information received from a Telficon into a standard M21 message and routing of this message into the AIS broadcasting network is performed by two software components working at the server side as described in sections 3 and 4.

2.3 Onboard Buoy Heel Angle Calculation and Statistics Functionality

Contemporary buoy lanterns generally utilize LED technology that is reliable and power efficient, allowing designing products with narrow vertical divergence angle to spare energy. This may result in reduced nominal range of the light signal in two opposite sectors already at small heel angles of the buoy carrying a LED lantern, with significant range reduction at moderate angles, paired with parasitic light signal modulation due to buoy sway that distorts the flashing pattern seen by the mariner. Heel angle monitoring and statistics capability introduced in Telficon enables analysis of the dynamic behaviour of a buoy deployed in a specific location, allowing to determine field proven vertical divergence angle requirements for the lantern mounted on this buoy that are sufficient to guarantee required visibility range of the light signal in conditions dominating at this location.
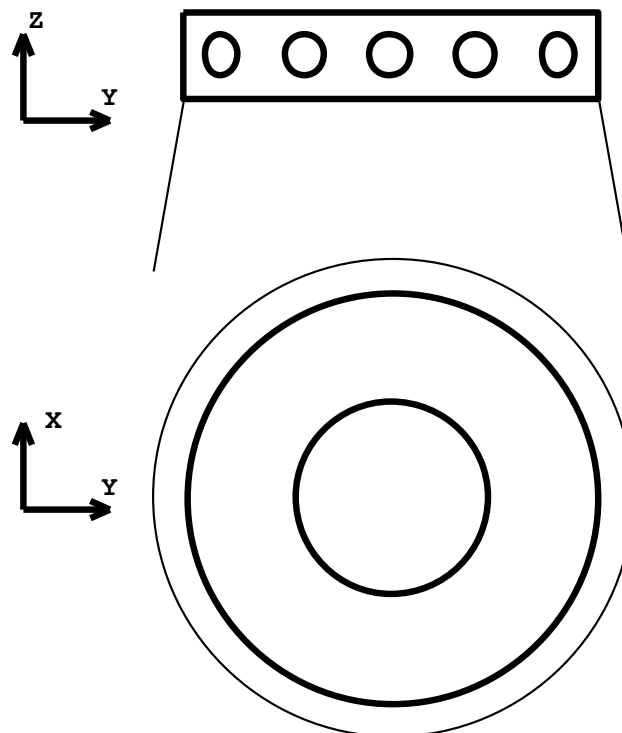
Figure 2. Telficon E9261's acceleration sensor axis directions when integrated with the Ice Buoy Lantern E8921. With the buoy standing upright as expected at calm seas, the sensor output voltages correspond to the following g values: X=0g; Y=0g; Z=1g.

When installed onboard a navigational buoy, the Telficon products allow to record buoy movements by the means of registering acceleration values in three axes of the buoy, sampling the outputs of a 3-axial solid state acceleration sensor mounted on the E926X circuit board. This feature was originally introduced for

determining heel angle statistics for a buoy hosting a Telficon by sending the raw acceleration measurement values to the remote control and monitoring centre for processing. The latest generation of Telficon products are capable of performing limited local calculations to establish the buoy heel angle and to keep average angle statistics for pre-programmed time periods, to send warning messages to the RCMC upon detection of critical heel angles exceeding the pre-set values significantly reducing the visibility range (or forecasting imminent submersion of an ice buoy), as well as detecting excessive lateral accelerations presumably resulting from a collision with another floating object and reporting such events to the monitoring centre.

The algorithm used for heel angle calculation is described in detail in paragraph 2.4, including the decoding of meta-variables received at the server side. A Telficon can be configured to sample the acceleration sensor outputs with the interval of 20 ms to 5 s, while the maximum buffer size for averaging is 8388608 measurements, resulting in a maximum of 46.6 hours window when sampling at 20 ms. The base sampling interval for all activities relevant to acceleration measurement is 20 ms, and the measurement intervals used for heel angle calculation, statistics and online transmission can be configured as equal to or multiple of the base sampling interval. It is recommended to select the time window for average heel angle calculations from the range of 10 minutes to 24 h, in accordance with the reporting interval used, so that the averaging process does not loose information between communication sessions. While one average value is being calculated starting from cleaning the buffer, a timestamped value of the preceding averaging period is available for downloading up to the end of the current averaging period when it is replaced by the new value. It is expected that Telficon based heel angle statistics analysis is arranged in a way permitted by the Telficon's mission with timely requests for average values during regular reporting sessions, and further analysis is performed at the RCMC.

2.4 The Buoy Heel Angle Calculation Algorithm

2.4.1 Introduction

This section provides information about the signal processing principles employed for obtaining heel angle information from navigational buoys fitted with an AtoN Telematics Field Controller of the Telficon family manufactured by Cybernetica AS. The inclination angle calculation is based on buoy acceleration measurements performed by a 3-axial solid state accelerometer (MEMS g-sensor) with the maximum range of ±3g, integrated with a Telficon module.

2.4.2 Mathematical Background

Calculation of the inclination angle based on digitized real-time acceleration data can be performed by using simple trigonometric functions like sine or tangent. For systems that have hardware floating point support, the most elegant and easiest way would be to use tangent. In 8-bit embedded systems where all numbers have quite small range, the only feasible option is to use the sine function. 8-bit systems cannot use tangent because tangent have infinite value when the angle is 90 degrees, and it is very inefficient to use fixed point variables to store such values. When using the sine function for angle calculation, it is necessary to use an additional operation; this is not a problem in all systems with sufficient available computational power. This additional calculation makes all data processing a little more time consuming and may introduce small inaccuracies, making this approach not suitable for raw acceleration data processing on the server side.

It is possible to simplify the rest of calculations by finding the length of the vector in X-Y plane and using it as a single value describing the horizontal plane. This simplification is possible due to the absence of directional data in the horizontal plane of the buoy.

Length (magnitude) of the horizontal acceleration vector:

$$a_{xy} = \sqrt{x^2 + y^2} \tag{1}$$

Where:

x and y –   Acceleration values from X and Y axis outputs of the sensor

Sine function also needs the hypotenuse:

$$h = \sqrt{a_{xy}^2 + z^2} \tag{2}$$

Where:

a_{xy} –   Length of the horizontal acceleration vector

z –   Acceleration value from the Z axis output of the sensor

The inclination angle (buoy heel angle) can be found using the following formula (angle α is usually given in radians):

$$\alpha = \arcsin\left(\frac{a_{xy}}{h}\right) \tag{3}$$

2.4.3 Angle Calculation in Dynamic Environment

In real marine environment, the acceleration values obtained from the acceleration sensor are changing continuously which can cause some error in short term calculations. However, it is possible to perform a long term calculation that averages all input data and thus will eliminate most errors caused by the constantly changing acceleration. Averaging is possible because buoy movement is mostly symmetrical to all axes and averaging provides a central value without short term excessive acceleration peaks.

2.4.4 Algorithm Realization in Telficon Firmware

The most important limitation at using the inclination angle calculation algorithm directly in Telficon firmware is the absence of square root, floating point and trigonometric functions. These functions can only be used on the server side. Inclination angle calculation algorithm for Telficon is based on the following simplification that results in a meta-variable that is directly proportional to the inclination angle, allowing taking actions at detecting certain threshold angles when necessary.

First, the squares of catheti and hypotenuse are calculated:

$$a_{xy}^2 = x^2 + y^2 \tag{4}$$

$$h^2 = a_{xy}^2 + z^2 \tag{5}$$

The inclination angle meta-variable is calculated as follows:

$$\theta = \frac{\left(a_{xy}^2 \cdot c\right)}{h^2} \tag{6}$$

Where:

c — Constant 2^{16}

The result of formula 6 is a value that holds enough information to unambiguously determine the inclination angle of the buoy from the vertical axis. It can be averaged locally, or forwarded to the server side inside corresponding messages of the Telficon for use by other systems. Processing necessary for decoding this value is described in paragraph 2.4.6.

Due to the limitations of Telficon hardware it is possible to use only fixed point values; therefore, all values shall be in 16 bit range (0...65535).

Worst case accuracy δ is calculated as follows:

$$\theta = c \cdot \sin(\alpha) \qquad (7)$$

$$\delta = \left| \alpha - \arcsin\left(\frac{\theta}{c}\right) \right| \qquad (8)$$

, where the variable θ is <u>rounded down to a nearest integer</u>.

Worst case accuracy can then be found by inserting angle values between 0º and 90º into formulas 6 and 7, resulting in heel angle calculation errors as shown in detail on graphs in Figures 1, 2, and 3.
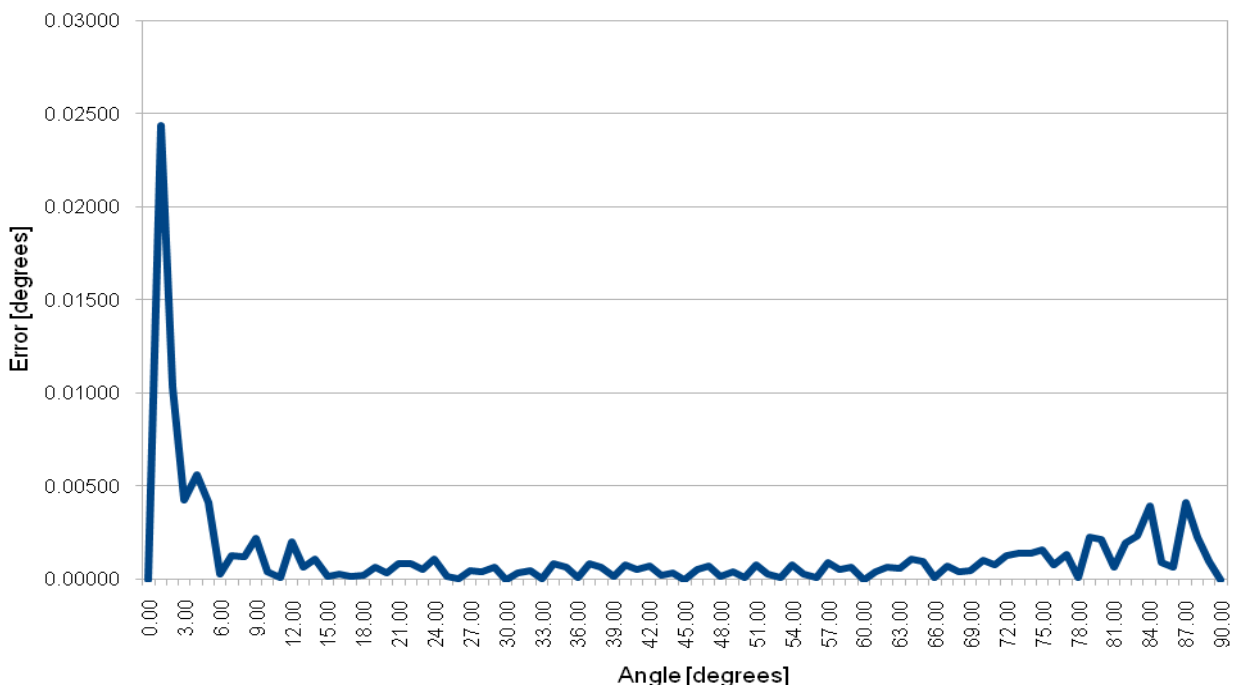

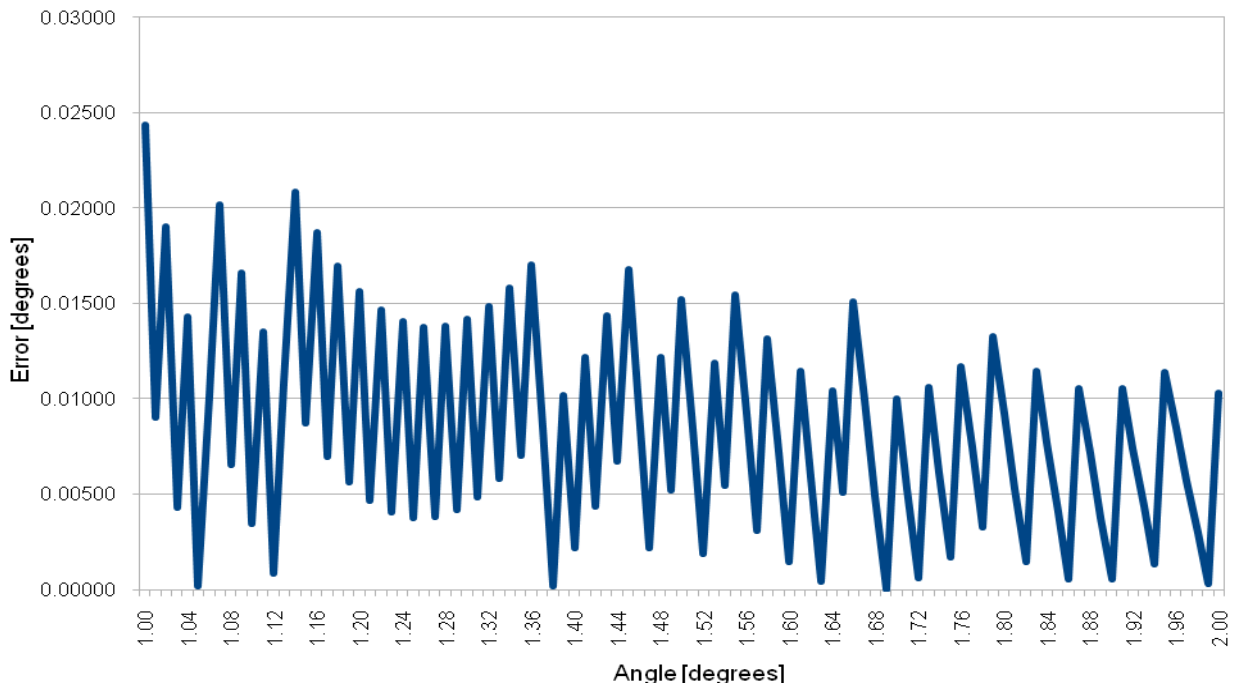Figure 3. Heel angle calculation errors over the full range of 0º to 90º

Figure 4. Heel angle calculation errors in the range of 1º to 2º
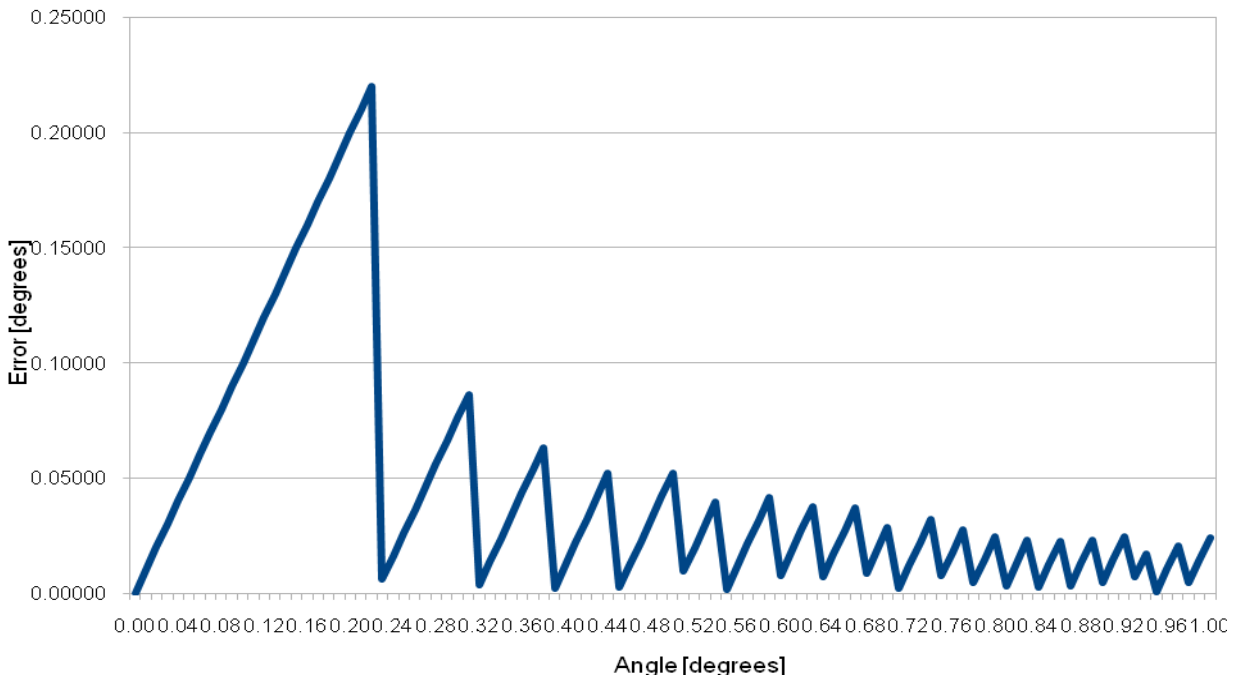

Figure 5. Heel angle calculation errors in the range of 0º to 1º

Resultantly, the worst case computational accuracy at determining the heel angle of a Telficon is 0.220° in the range of 0° to 1° degrees, 0.024° in the range of 1° to 2° degrees, and 0.010° in the range of 2° to 90°.

2.4.5 Averaging Algorithm Implementation in Telficon

Implementation of the average inclination algorithm in Telficon firmware is accomplished as follows. First, the average square of the catheti and the hypotenuse is calculated:

$$\overline{a_{xy}}^2 = \left(\frac{1}{n}\sum_{i=1}^{n} x_i\right)^2 + \left(\frac{1}{n}\sum_{i=1}^{n} y_i\right)^2 \tag{9}$$

$$\overline{h}^2 = \overline{a_{xy}}^2 + \left(\frac{1}{n}\sum_{i=1}^{n} z_i\right)^2 \tag{10}$$

The average inclination angle over the averaging period is calculated as shown in formula 11:

$$\theta = \frac{\overline{a_{xy}}^2 \cdot c}{\overline{h}^2} = \frac{\left(\left(\frac{1}{n}\sum_{i=1}^{n} x_i\right)^2 + \left(\frac{1}{n}\sum_{i=1}^{n} y_i\right)^2\right) \cdot c}{\left(\frac{1}{n}\sum_{i=1}^{n} x_i\right)^2 + \left(\frac{1}{n}\sum_{i=1}^{n} y_i\right)^2 + \left(\frac{1}{n}\sum_{i=1}^{n} z_i\right)^2} =$$

$$= \frac{\left(\left(\sum_{i=1}^{n} x_i\right)^2 + \left(\sum_{i=1}^{n} y_i\right)^2\right) \cdot c \cdot \left(\frac{1}{n}\right)^2}{\left(\left(\sum_{i=1}^{n} x_i\right)^2 + \left(\sum_{i=1}^{n} y_i\right)^2 + \left(\sum_{i=1}^{n} z_i\right)^2\right) \cdot \left(\frac{1}{n}\right)^2} = \frac{\left(\left(\sum_{i=1}^{n} x_i\right)^2 + \left(\sum_{i=1}^{n} y_i\right)^2\right) \cdot c}{\left(\left(\sum_{i=1}^{n} x_i\right)^2 + \left(\sum_{i=1}^{n} y_i\right)^2 + \left(\sum_{i=1}^{n} z_i\right)^2\right)} \cdot \frac{\left(\frac{1}{n}\right)^2}{\left(\frac{1}{n}\right)^2} = \tag{11}$$

$$= \frac{\left(\left(\sum_{i=1}^{n} x_i\right)^2 + \left(\sum_{i=1}^{n} y_i\right)^2\right) \cdot c}{\left(\sum_{i=1}^{n} x_i\right)^2 + \left(\sum_{i=1}^{n} y_i\right)^2 + \left(\sum_{i=1}^{n} z_i\right)^2}$$

As seen in formula 11, angle averaging can be accomplished without division, simplifying the calculations.

2.4.6 Decoding of Angle Data on the Server Side

Decoding of instantaneous or average angle values from the meta-variables received from a Telficon on the server side is accomplished as follows (the angle α is given in radians):

$$\alpha = arcsin\left(\frac{\sqrt{\theta}}{c}\right) \tag{12}$$

Where:

θ –   Coded angle meta-variable received from a Telficon

c –   A constant 2^{16}

To calculate the buoy heel angle from the vertical axis in degrees, the following further operation is required:

$$\alpha_{deg} = \alpha \cdot \frac{180}{\pi} \tag{13}$$

NOTE: The buoy heel angle algorithm described in the paragraphs 4 and 5 is implemented in Telficon firmware starting with version 2.1 (926T1021)

2.5 Critical Heel Angle Warning Functionality

To utilize the calculated heel angle values for immediate estimation of the effect of buoy movement and posture on the visibility range of the buoys light signal, two threshold values are foreseen for monitoring:

- „Critical heel angle" for triggering a warning on reduction of the visibility range below specification published for the mariners due to excessive heel angle; a typical threshold value can be in the range of 10 to 15 degrees (depending on the vertical divergence of the lantern used), with a filtering (averaging) window of 5 to 10 minutes to suppress occasional peaks that are expectedly rare but may occur due to noise

- „Near submersion heel angle" for triggering a warning on imminent submersion of a buoy due to probable ice pressure forcing the buoy to nearly horizontal angle; typical threshold value can be in the range of 30 to 40 degrees (depending on the vertical divergence of the lantern used), with a filtering (averaging) window of 3 to 5 minutes

For studying the dynamic behaviour of a buoy, the user can set any angle value of interest as critical for gathering the statistics (counts of the configured angle value being exceeded)..

A submersion scenario with the buoy heeling significantly due to ice pressure from one direction is considered as most probable. Nevertheless, a scenario with the ice buoy being dragged away from the position upright and sinking due to the anchor being lifted into deeper waters is possible; it is possible to predict this in case of acceleration measurement showing a stable posture of the buoy.

Enabling of the warning report generation is accomplished by the RCMC centre software within the angle limits of 1 to 89 degrees and filtering limits of 1 to 65536 measurements. Acceleration sensor output sampling interval is from 20 ms (base interval) to 5 s; it can be configured individually for heel angle measurement function.

2.6 Collision Detection and Warning Functionality

A Telficon can be tasked with collision detection mission, based on monitoring of the output values of the onboard 3-axial acceleration sensor. When collision detection is activated, the base sensor output sampling interval must be set to the shortest available (20 ms) for the Telficon to be able to detect fast changes in acceleration. Configurable parameters include the sampling interval, acceleration threshold for a collision event, filtering (averaging) time and immediate reporting requirement.

Once a Telficon detects a collision event while immediate reporting is enabled, it initiates a communications session with the RCMC to send a collision warning message. A corresponding data bit will be set in the status message showing that a collision event has been detected; when immediate reporting was not required, the RCMC will receive this information during the next scheduled status reporting session.

The last collision event with a timestamp and total number of collisions detected are maintained inside a Telficon, accessible from the RCMC by a corresponding communications scenario.

2.7 Acceleration Measurement and Online Transmission Functionality

A Telficon can be set up for a buoy acceleration measurement mission with online data transmission to the RCMC, enabling collection of buoy movement data on the server side for analysis of buoy dynamics and sea state. Configuration of such mission can be accomplished only from the RCMC by setting up a scenario to be downloaded and executed by a Telficon during a communications session. The measurement can be configured to last either until the next communications session (regular or alarm status report), or for a duration of set number of LAN poll intervals. Correspondingly, this allows setting up a measurement arrangement either with continuous or fragmentary data acquisition as necessary – for example, transmitting acceleration data for 10 minutes twice an hour.

In case of acceleration measurement mission, the outputs of the onboard 3-axial acceleration sensor are sampled with a set interval (from 20 ms to 5 s); measurement values are buffered (63 samples from each axis, 252 bytes total). Once the buffer is full, it is dispatched to the RCMC within a TCP/IP packet. While it would be possible to transmit each measurement immediately inside a single TCP/IP packet, considering the non time critical application, it is not feasible due to higher communication costs resulting from the packet overhead.

2.8 Description of the Data Acquisition Algorithm

The measurements by the ADC of Telficon's microprocessor are not taken with simultaneous sampling: a finite time interval typically less than 0.3 ms passes between the values are read from the multiplexed input channels connected to the analog outputs of the acceleration sensor, except during the first samples and in case of unexpected interrupts from site LAN when this delay may be slightly higher. From the point of view of Telficon's missions, this time shift is insignificant for measurement of voltages and temperature, and can be considered short enough for ignoring it during acceleration measurement due to the limited bandwidth of the analog output signals of the solid state acceleration sensor.

With acceleration measurement activated (for any function), the measurement values are obtained from the ADC with the set base interval (20 ms by default) in the following order:

- X axis output voltage

- Y axis output voltage

- Z axis output voltage

3. AtoN remote monitoring centre software „GPRS Keskus" for provision of e-Navigation service infrastructure elements

3.1 Introduction to the GPRS RCMC

The new remote control and monitoring centre software solution developed at Cybernetica AS and commissioned in 2009 at the Estonian Maritime Administration had a working project title „GPRS Keskus" („GPRS RCMC") due to the main distinguishing feature: implementation of connectionless packet switching and the TCP/IP protocol for communication with equipment at the remote AtoN sites over the GSM/GPRS mobile data link instead of former use of dedicated GSM data connection. Nevertheless, the RCMC software is not GSM/GPRS specific and can be considered future proof, allowing to work with AtoN monitoring equipment utilizing the ekta™ proprietary protocols over any media supporting the TCP/IP protocol. When such needs arise, replacement of the GSM/GPRS modems in the upgraded Telficon products with new radio link submodules (modems) is a foreseen path, possibly requiring minimum firmware and product form factor changes. The protocols utilized for data transfer within AtoN LAN (A-Bus) as well as between the RCMC and AtoN sites are kept confidential for preserving the security and integrity of the system. Other significant differences compared to the previous generation were migration to the Linux operating system instead of MS Windows, a web-based multi-user interface instead of dedicated client software, utilization of the PostgreSQL database instead of Paradox, and introduction of support for new features of the Telficons (FOTA upload, buoy heel angle measurement, critical heel angle alarms, etc).

Daily operation of the AtoN monitoring is performed using a set of HTML/JavaScript based webpages served to the users by the GVL software component of the RCMC for system status display and equipment configuration. A simple text-based structured table showing coloured blocks with AtoN numbers inside was chosen for the main situation status screen over a chart based graphical display due to the interface efficiency - capability of providing a clear technical overview of AtoN operational situation, uncluttered by irrelevant details, and the speed of navigating between different screens (Figure 6). Nevertheless, an interface is provided for displaying the AtoNs on the marine chart background using external web-based application. The user interface of RCMC software is currently provided in the Estonian language.

The operational status display of an AtoN site reflects information from at least two remote equipment units: a Telficon, and a flasher (two in redundant configurations). The coloured blocks presenting the status of each remote AtoN site have two coloured indicators: a frame and a fill, with the frame colour representing position status (on station / off station / unknown) and the fill colour representing navigation light status (normal / malfunction / unknown). In addition, the colour of the AtoN number shows whether the light is on or off, with strike through style on gray background telling that information on this AtoN site is not available.

Figure 6. Screenshot of the AtoN operational situation status overview page of the GPRS RCMC

The main screen presents colour coded operational status of all registered AtoN sites subject to remote monitoring by region, including third party AtoNs that are reporting to the maritime authority. The whole software solution is described in corresponding manuals and online help windows.

Figure 7. AtoN status display blocks on the GPRS RCMC operational situation status overview screen. A white number depicts an AtoN site with navigation light currently ON, and a black number with the light off. A black border depicts unknown position of the AtoN, while red and green indicate "Off station" and "On station", respectively. Crossed blocks indicate failed communication sessions during a calendar day in status history.

The current RCMS is foreseen for monitoring of and handling message streams from up to 200 AtoN sites in the current software/hardware configuration, with expected upscaling capability to thousands of remote sites when necessary.

3.2 AtoN Monitoring Mission Configuration

Depending on the primary AtoN monitoring mission objective, a Telficon can be set up either for regular AtoN status monitoring with lowest achievable power consumption and communications costs, or for extended monitoring with additional mission objectives like heel angle statistics and monitoring, collision detection, acceleration measurement and synthetic AIS AtoN reporting as described in paragraph 2.1. Specifics of a mission are defined using various configuration settings available via RCMC equipment configuration pages.

Typical operational settings of a Telficon also depend on the type of AtoN site where it is installed.

Recommended settings for monitoring of a buoy subject to synthetic AIS AtoN reporting:

- The GPS receiver's power is set to „constantly on" to guarantee immediate position fixes, improved positioning precision and lesser amount of position jumps

- The GPS poll period is set to 1minute

- The GPS position fix delay time is set to 5 s

- The „Off station" / „Missing coordinates" alarm is set to 3 to 4 consecutive cases

- The regular reporting interval is selected within the range of 3 to 6 minutes (preferably 3 minutes, but beware the implications on communications costs and power consumption)

- The flasher is configured not to report the „Light On" / „Light Off" events (regular reporting is frequent enough).

In case of a floating AtoN that is not subject to synthetic AIS AtoN reporting, the GPS receiver's power is selected based on criticality of the AtoN site, density of vessel traffic in the region, allowable latency of detecting off station situations, and available resources (energy, communications costs).

Recommended settings for monitoring of a regular buoy system:

- The GPS receiver's power is set to „constantly on" to guarantee immediate position fixes

- The GPS poll period is set to 2 or 3 minutes depending on navigational significance of the AtoN and whether the watch circle of the buoy is smaller or larger

- The GPS position fix delay time is set to 5 s

- The „Off station" / „Missing coordinates" alarm is set to 3 to 4 consecutive cases

- The regular reporting interval is set to 15 or 20 minutes

- The flasher is configured to report the „Light On" / „Light Off" events

Recommended settings for monitoring of a regular buoy system in „economy mode":

- The GPS receiver's power is set to „trickle mode" to guarantee lowest power consumption

- The GPS poll period is set to 5 to 15 minutes depending on whether the watch circle of the buoy is small, medium, or large

- The GPS position fix delay time is set to 40 s

- The „Off station" / „Missing coordinates" alarm is set to 3 consecutive cases

- The regular reporting interval is set to 30 to 240 minutes

- The flasher is configured to report the „Light On" / „Light Off" events

It is important to note that in the „economy monitoring mode" with long reporting intervals, it may take hours for the RCMC to discover missing reports. The criteria of missing communications warning should be set in the range of 2.5 to 3.5 reporting intervals. Also, once such buoy has drifted off station, it is recommendable to execute a scenario setting the reporting interval equal to the GPS position poll interval to keep track of the buoy movement and warn the mariners when necessary.

Recommended settings for monitoring of a fixed AtoN system:

- Presence of a GPS receiver on a fixed AtoN depends on the need of GPS synchronization (leading lights, etc). When present, GPS power is set to „trickle mode" to guarantee lowest power consumption; in case of utility power, „constantly on" is recommended

- The GPS poll period is set to 6 minutes, while the watch circle parameter is set to at least 500 m to avoid irrelevant alarms

- The GPS position fix delay time is set to 40 s

- Position alarm is disabled

- The regular reporting interval is set to 30 to 120 minutes

- The flasher is configured to report the „Light On" / „Light Off" events

When a GPS receiver is not used, the system must be correspondingly configured. In such cases the server performs synchronisation of Telficon clock over the network. Remaining mission parameters of a Telficon are configured based on monitoring or measurement requirements.

3.3 Reception and Handling of Status and Warning Messages from AtoN Sites

The Telficon units residing at the AtoN sites initiate TCP/IP communication sessions to the pre-configured IP socket (IP address and port number) listened by the PaSS software component residing on the RCMC server according to regular reporting intervals, or upon detection of any reportable events (equipment malfunctions, parameter out of range warnings, etc). The configuration settings file of PaSS allows to select one of five levels for logging of raw data received from the Telficons at remote AtoN sites, with the most detailed setting resulting in logging of every data byte received, to the least detailed setting of logging only the hardware and software errors reported.

The PaSS software component extracts detailed site and device specific parameters from the binary data, determining the category of the incoming status report – whether it is a regular status report, warning, or error report. The results are compared to the last known status of the equipment, with the results recorded in the corresponding locations of the AtoN database when necessary. All irregular status reports (errors and warnings) are saved to the database in full. Typically, detailed results of regular status reports are not saved to the database, only the time of last session and the corresponding session counter are updated. All received information is saved when significant changes in status report content are discovered, when the existing information is outdated according to the criteria set for a particular AtoN, or when a communications breakup existed prior to receiving a status report.

The data items received are processed to obtain the current operational status of the AtoN site, and to take actions when necessary: immediate dispatching of information to the maintenance personnel, logging of alarms to the database, etc. The situation status page of the user interface shall be updated with the results of this analysis.

3.4 Reception and Handling of Navigation-Related Messages from AtoN Sites

Upon receiving a message with the content reporting significant navigation-related events at the AtoN site like GPS coordinates outside the watch circle of a buoy or failure of the light signal, the following actions are taken:

- The maintenance personnel responsible for the AtoN site are notified about the event by e-mail, including an SMS text message delivered to their mobile phones (e-mail by SMS)

- The status report is saved to the database in full

- The operational status of the AtoN is correspondingly changed.

After checking the received information, the operator may decide to request additional information from the AtoN site, selecting a suitable scenario or setting up a new one for retrieving such information, activating it, and placing a call to the GSM number of the corresponding AtoN to force the Telficon into a new communications session resulting in uploading of updated information.

3.5 Transcoding of Synthetic AtoN AIS Messages

The PaSS software component performs immediate transcoding of relevant data received from a Telficon onboard a buoy subject to synthetic AIS AtoN broadcasting into a proprietary $PCYBA sentence, and forwards it over the TCP/IP network to the AIS Router software component residing at the IP address provided in the configuration file. For the information to be relevant at the time of AIS radio broadcasting, total time delay introduced by the chain Telficon -> GSM/GPRS network -> TCP/IP ground network -> PaSS -> AIS Router -> AIS network -> AIS base station must be less than 60 s. Expectedly, time delay from Telficon to AIS Router remains below 20 s for 99% of time.

The $PCYBA intermediate data sentence with content necessary for formatting of an AIS AtoN message M21 is developed at Cybernetica AS in NMEA 0183 style. It consists of the comma separated fields carrying the information on AtoN position, status, etc, for example:

$PCYBA,100107,090533,162,992761005,05937.7217,N,02504.3470,E,A,1,29,227,0,20,Aksi   N   buoy,0, 001.001.01.01,1,Wrong Location*1F

Based on the error status description embedded in this sentence, the AIS Router is able to prepare and broadcast corresponding AIS messages M12 and M14 when necessary. The off position indicator (OPI) will be set after measured position difference (a distance from the assigned position) analysis performed by the PaSS software. Typically, the criteria for setting OPI to 1 is defined as K*r, where K>1 to create a larger drift tolerance before activating broadcasting of off position warnings over the AIS network; K values between 1.2 and 1.5 are recommended.

The protocol is described in the following document: „Packet-oriented NMEA-$PCYBA protocol description", Document number N-B76250-2, © Cybernetica AS, 2007 (in Estonian).

3.6 Reception and Handling of Critical Heel Angle Warning Messages from AtoN Sites

„Critical" and „near submersion" heel angle warning messages are sent to the RCMC by a Telficon when the heel angle monitoring functionality is activated, the corresponding thresholds are exceeded, and the reporting is activated. Upon receipt of such messages, the PaSS software component records the status in the database, notifies the maintenance personnel assigned to relevant group by e-mail or SMS message, but does not change the AtoN status to „malfunction".

3.7 Reception and Handling of Collision Warning Messages from AtoN Sites

Collision warning messages are sent to the RCMC by a Telficon when the impact monitoring functionality is activated, corresponding acceleration threshold is exceeded, and the reporting is activated. Upon receipt of such messages, the PaSS software component records the event in the database and notifies the maintenance personnel assigned to relevant group by SMS message for immediate identification of the cause of collision.

3.8 Reception and Handling of Average Heel Angle Data from AtoN Sites

To receive heel angle statistics from a Telficon installed on a buoy, first the corresponding functionality of the Telficon must be activated with necessary averaging window configured; then a scenario must be prepared at the RCMC for requesting the heel angle statistics meta-variable during the status reporting communications sessions. This meta-variable is converted into the angle value in degrees and stored in the AtoN database where these values are accessible for further analysis. Preparation of the arrangement for calculation of average heel angles of a buoy over a given period and inclusion of the results in automated reports is work in progress.

For example, when hourly averages of buoy heel angle are of interest, it is recommended to set both the averaging interval and the reporting interval of the Telficon to one hour. In case of a buoy subject to synthetic AIS AtoN reporting, the scenario would retrieve average heel angle meta-variable during every reporting session; in such cases it is recommended to shorten the averaging to match the reporting interval.

3.9 Reception and Handling of Acceleration Data from AtoN Sites

To receive acceleration data from a Telficon installed on a buoy, first the corresponding functionality of the Telficon must be activated with necessary sampling interval and measurement period length configured (number of poll periods or full time between status reports), and then a scenario must be prepared at the RCMC for activating the online transmission of acceleration data. In this case the RCMC will not close the communications session but will wait for the acceleration data packets to arrive. Acceleration measurement will be interrupted when it is time to send a regular status report, or an error report. If the acceleration

measurement scenario has not been removed in the meantime, the system assumes acceleration data reception when the status message is processed.

The RCMC shall record the received data into binary files with names formed with identification of the data source (Telficon's serial number), date and time of beginning of the measurement session. Acceleration data are not saved to the database; the files created are intended for analysis by external software applications. Integration of online acceleration data analysis for sea state estimation is subject to a further feasibility study.

3.10 Estimation of AtoN Performance and Analysis of Service Availability

The PaSS software component of the RCMC gathers statistics on several aspects of AtoN operation including availability. Currently, the automated daily report includes the following system performance data items:

- Percentage of time when the light was on when required (%)

- Percentage of time when a buoy was located inside the watch circle (%)

- Percentage of communication sessions initiated and concluded according to expectations (%)

- Percentage of time when the communications were consistent – a missing report is discovered within the time of 3 to 5 planned intervals, but the analysis is done from the first miss (%)

- Percentage of successful synthetic AIS AtoN message transmissions to the AIS Router (%)

- Percentage of synthetic AIS AtoN messages transmitted to the AIS Router with transmission delays exceeding the 30 s maximum allowable delay (%).

In addition, other information relevant to system availability estimation is gathered: AtoN site power supply voltages under load (in flash) and without load (during eclipse), average time delay from getting the GPS fix to sending out the AIS sentence, etc.

Introduction of automated reports with performance statistics for longer time periods is currently under consideration.

3.11 Web-Based Interface for Institutional and Public Access

Online access to the RCMC is possible only through user authentication. Existing RCMC software enables configuration of user groups with different levels access rights, allowing providing access to the system to third parties who operate AtoN sites with compatible equipment. For this kind of access, all AtoN sites belonging to such 3'rd party user are arranged into a single AtoN group (region) and all necessary rights for configuration and management of these AtoNs is provided to such user, with the exception of system and account administration. Open public access directly to RCMC is not permitted; a specific subset of webpages is created for online Database of Aids to Navigation.

Tests have shown that GSM/GPRS communications between a Telficon deployed at a significant physical distance from the RCMC can be rather stable even for acceleration measurements; therefore it is expected to be feasible to use the centre for buoy movement and heel angle analysis by third parties when permitted by the Estonian Maritime Administration.

3.12 Integration with Legacy and External Systems

A large amount of AtoN sites of the Estonian Maritime Administration is still monitored by the previous generation of GSM communications controllers that are unable to use the GSM/GPRS data communications. Operational and static parameters of these AtoN sites are maintained in a Paradox database that is also used in the common process of management of AtoN deployment and configuration. Integration of the RCMC with this existing AtoN database is accomplished to the level where the static settings of AtoN sites subject to GSM/GPRS based monitoring in the new AtoN database are synchronised once every night with the old Paradox database.

A work in progress is integration of the RCMC database with an external chart server, allowing presenting the navigational information of subject AtoN's on the background of an electronic navigation chart (ENC) right within the GVL user interface. The following information is presented on the chart, provided that it does exist in the RCMC database:

- Static status information of all AtoN sites: designated position of the anchor (station), radius of the deployment circle, watch circle, and alarm circle. The anchor symbol is displayed when a buoy is currently deployed.

- Water depth at the buoy station

- Track history of a selected buoy over a given time period. Position symbols are shown in accordance with position status as reported by the corresponding Telficon: on station (normal, inside the alarm circle), off station (filtered (averaged) position outside the alarm circle), or a single position detected outside the alarm circle (off-station alarm not activated yet)

- Buoy movement vectors showing the direction of drifting between the positions fixed

Periodic refresh of the information in the database of the chart server is monitored by a software tool used for system monitoring – Nagios.
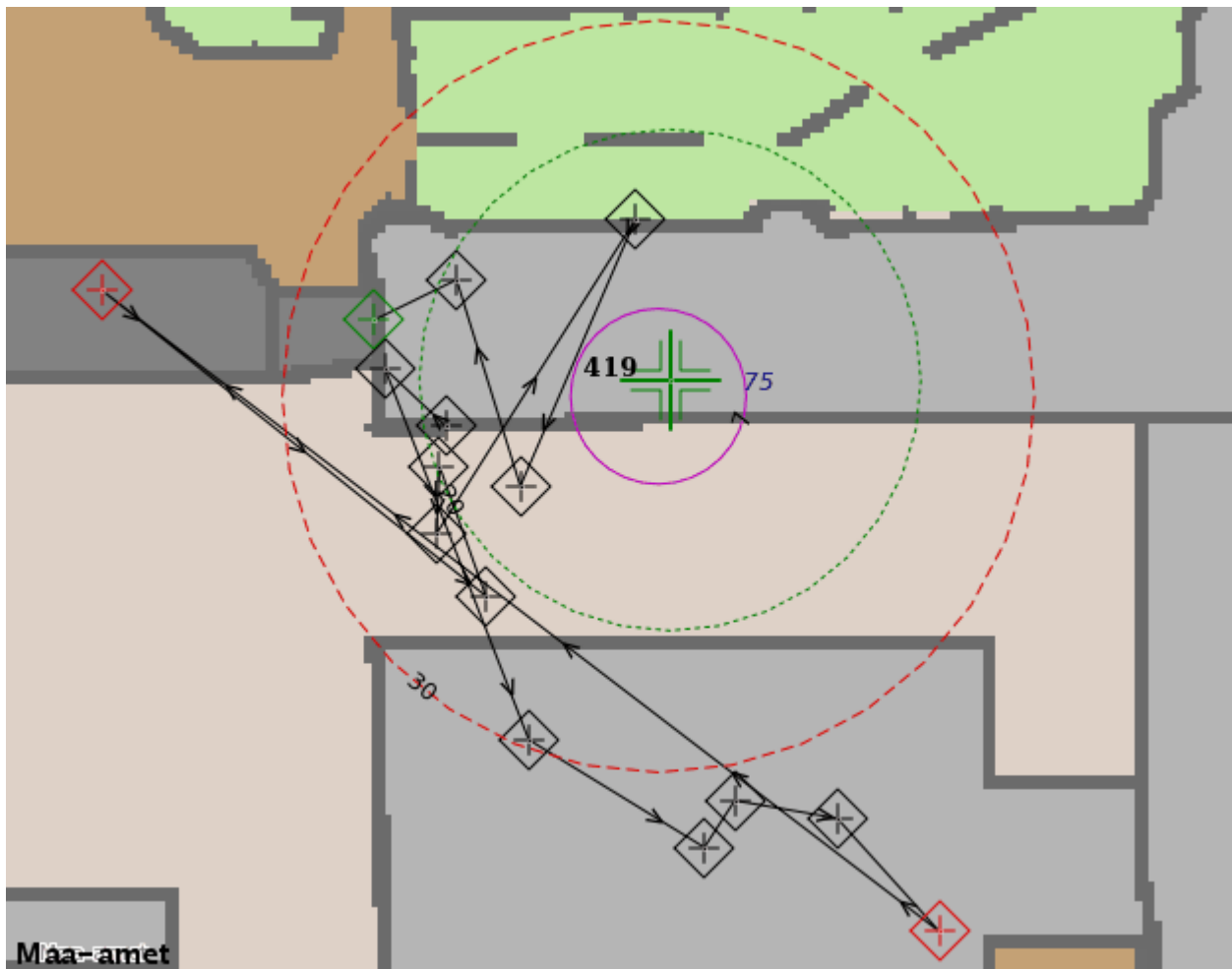
Figure 8. Floating AtoN (buoy) station information and track history displayed on ENC background

The status of other software and hardware components operating at the RCMC is also monitored by an external application Nagios for detection and logging of server side failures. Implementation of a redundant system with automated failover is under consideration.

4. AIS Infrastructure Used for AtoN Status Report and Safety Related Message Broadcast

4.1 AIS Message Routing and Broadcasting

The AIS Router is a software component responsible for formatting of the $PCYBA sentence content received from PaSS into proper M21 synthetic AIS AtoN messages, and routing these messages to the relevant AIS base stations in the AIS shore infrastructure for broadcasting. It typically resides in the AIS/VTS segment of the navigation safety infrastructure and has timely information about location and status of all AIS base stations as well as of the AIS traffic in the network, allowing substituting a neighbour base station for broadcasting instead of a malfunctioning base station where necessary.

In addition to message M21 formation, the AIS Router can be set up for generating safety related AIS messages M12 and M14 in case of detecting AtoN malfunction indicators in the $PCYBA sentence. No feedback is given in such cases to the RCMC which currently operates merely as a source of $PCYBA sentences, logging and analyzing only its own output sentence stream.

The AIS Router operation is described in the document „AIS Router - a module for routing AtoN-specific AIS messages M8, M12, M14, and M21", Document number: Y-399-28, © Cybernetica AS, 2009.

4.2 AIS Channel Load Produced by Synthetic AIS AtoN Messages

The current RCMC / AIS Router implementation enables full control of the synthetic AIS AtoN message broadcasting at two key points in the system: the RCMC, and the location where the AIS Router resides (either RCMC or the AIS/VTS centre). It is possible to adjust the reporting frequency as necessary to maintain a reasonable AIS channel load without the expense of travelling to a buoy to shut down a dedicated AIS AtoN transponder when such needs arise.

The minimum target load used specified for software engineering was transmission of the synthetic messages from at least 200 AtoN sites, up to one report per minute from each.