



## MICROCOMPASS FOR SAFE SEA NAVIGATION

**Marcin Życzkowski**

*Gdańsk University of Technology  
Faculty of Ocean Engineering and Ship Technology  
Department of Marine Mechatronics  
tel. (+48 58) 347-20-57  
e-mail: [marzyczk@pg.gda.pl](mailto:marzyczk@pg.gda.pl)*

### **Abstract**

*This paper presents the results of design microcompass for safe sea navigation where navigation, electronic, programming knowledge was joined to make more safe sea navigation. In first part of article presents navigation tools which using in practise. Article underlines that mostly satellite system is used to make navigation, but recommends traditional navigation method like alternative to determinate position in case of breakdown or any accident which reduce reliability of satellite system.*

*Next part of article introduces declination and deviation compass knowledge. Article underlines what problem should be considered during design microcompass for safe sea navigation. Article presents project on diagram of intermodule communication, describes main functions and requirements and main aim which is alternative tool to a GPS system. In article in next part presents transform technique of raw data form magnetometer and next step which is calibration process. Result of microcompass test is comparison with conventional magnetic compass which is presented in article. Last part of article introduce to expansion opportunities.*

**Keywords:** *navigation, electronic, compass, programming, magnetometer*

### **Introduction**

The main purpose of navigation is to keep to a voyage schedule. The most efficient method for meeting this goal is to navigate along a route specified on a map. Such a route comprises multiple waypoints whose positions are marked on the map, and which systematically bring the ship closer to its destination. A straight line is determined between adjacent waypoints that is the voyage direction. Figure 1 below shows a route with waypoints (WP).

A person in charge of navigation – the navigator – must not only possess a map, but also tools enabling the determination of the ship's position and direction. This rule has been applied for hundreds of years and the method for efficient navigation has not changed yet. The most common method for determining a ship's position is to read data from the GPS. After two positions are read, direction is also determined. When all the waypoints of the planned route are input into the GPS receiver memory, we are dealing with semi-automatic navigation. The receiver informs the navigator of the approaching waypoints and suggests a change of course. It must be noted, however, that the American military satellite system, GPS, is not autonomous and as a result of political decisions it may be switched off or access to it may be restricted. The latter took place during military actions in the Persian Gulf in the nineties, when the GPS signal in this area was limited. That is why a magnetic compass and a map are required for sea navigation and each ship approved for sea navigation by the international

IMO regulations shall be equipped with them.

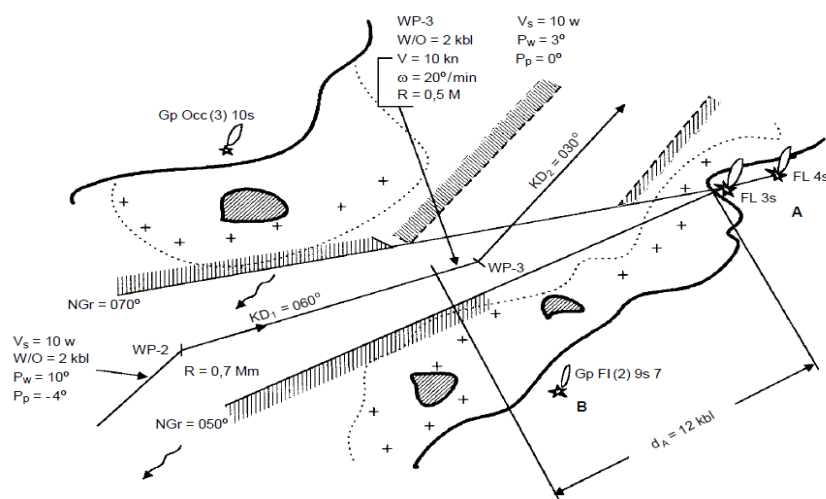


Fig. 1. Route on a navigation map

A magnetic compass is a basic navigation tool whose principle of operation has not changed for hundreds of years. This principle involves the determination of direction on the basis of analysing the impact of the Earth's magnetic field. The first mention of a magnetic needle used for navigation, floating in a container of water, was found in a Chinese book – Zhu Yu Pingzhou Ke Tan from 1117. In our part of the world the first mention of a magnetic needle and its use in navigation was found in De naturis rerum by Alexander Neckam, wrote around 1190 in Paris. A device measuring the Earth's magnetic field called the magnetometer was invented in 1833 by a German mathematician and physicist, Carl Friedrich Gauss. The determination of direction using the magnetic field is not perfect, however, in view of its independence and wide availability to navigators it is treated as equal to the GPS satellite system. Furthermore, a navigator performing continuous navigation with the map is able to approximately locate the ship's position without the GPS. A map and a magnetic compass are sufficient for safe open-sea navigation. In inshore navigation, position and direction are controlled using visual and radar observations on the basis of an up-to-date map of the navigation area.

This article presents a concept of a design and construction of a microcompass for the purposes of navigation safety. The advantage of the compass is its simplicity and low cost of construction and operation.

## Direction measurement

Direction measurement is the deviation of the compass needle from a given reference surface at a given angle (Figure 2). Which instrument or method we will be using for direction measurement depends on the name and the value of direction. There is a true, magnetic, compass and gyro direction, each assigned a different value.

The reference plane for a true direction is the plane of the geographic meridian of the observer that determines North and South. Therefore, all geographic meridians on the Earth determine the direction N-S. This method assumes that Earth is a sphere and the axis crossing the centre of the Earth determines geographic poles  $P_n$  and  $P_s$ . In the case of a magnetic direction, the great circle crossing the magnetic north pole and the magnetic south pole is the reference plane. The Earth is a giant, natural magnet. Geomagnetism is directly related with the structure of the Earth and its rotations. The Earth magnetic field is caused by vortical electric currents flowing in its core. This field may be compared to a magnetic dipole field inside the Earth.

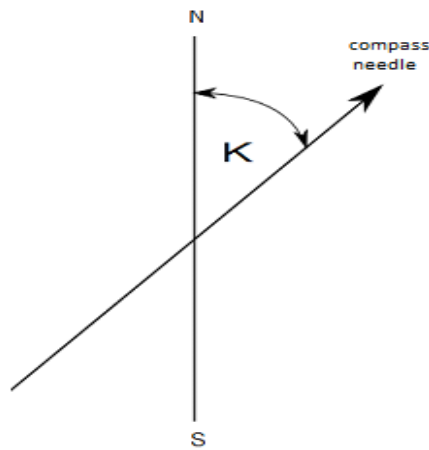


Fig. 2. Direction measurement

The extended axis of a symbolic dipole (substitute magnet) crosses the surface of the Earth, giving rise to magnetic poles: MN – north and MS – south. The axis connecting both poles is inclined to the Earth rotation axis by approximately 11.5° (Figure 2). The difference between true direction TD, and magnetic direction MD is called declination,  $TD = MD + d$ .

A compass direction is different from a magnetic direction by the deviation that is related with ferromagnetic elements of which a ship is made and the direct vicinity of the external compass. Deviation on a ship is not very dynamic, and does not require frequent corrections during the compass operation. In the proposed mobile microcompass such a deviation correction would change depending on the changing level of the battery supplying the microcompass and its current location. In this case the formula accounting for deviation is  $MD = CD + \delta$ , where  $\delta$  is deviation and CD is compass direction.

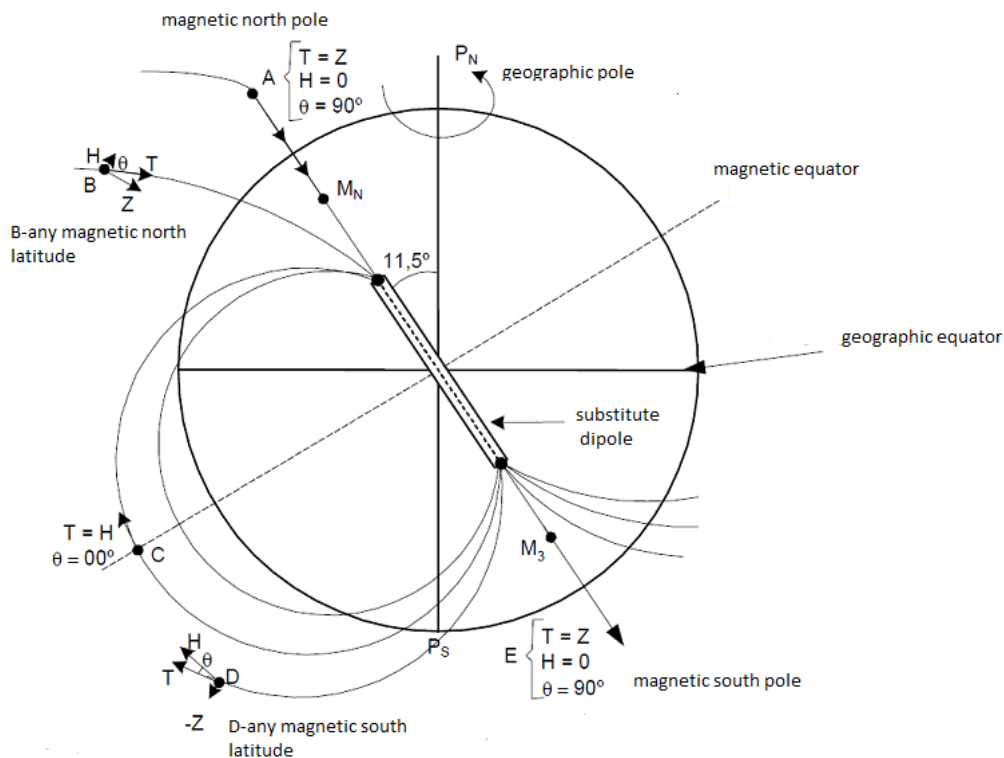


Fig. 3. Geomagnetism [ 1 ]

A gyro direction is determined by a device tracking the Earth's rotations. The process of determining the reference plane, i.e. the true meridian, is relatively time consuming and sensitive to additional external interferences, as well as burdened with a correction called tgc (total gyrocompass correction). The dependence of true direction TD on GD is  $GD = TD + tgc$ .

Table1 summarizes the methods for determining directions in sea navigation.

*Tab. 1 Methods for determining directions in navigation*

Direction	Designation	Correction	Calculations	Application and description
true	TD	None	TD	Theoretical, assumes that the Earth is a sphere. The primary direction in navigation. Navigation maps and the GPS system both specify this direction.
magnetic	MD	Declination	$TD=MD + d$	Magnetic compass, the main tool for determining directions, using geomagnetism, correction results from varying distribution of geomagnetism impact
compass	CD	Deviation	$TD=CD+d+ \delta$	Magnetic compass, accounts for corrections resulting from ferromagnetic interferences of the observer's surroundings
gyro	GD	Gyrocompass correction	$GD=TD+tgc$	Gyrocompass. Device using the Earth's rotations, correction results from the device imperfections

### Microcompass design

The proposed digital microcompass operates on the basis of the Earth's magnetic field measurement, however, it also considers necessary corrections and presents a true direction. Declination that arises from varying distribution of the geomagnetism impact, as well as deviation that arises from ferromagnetic interferences in the observer's surroundings were both considered while programming the compass. In the long term of the compass operation, deviation and declination corrections would be input from various geographical positions or the current battery level in the form of an online database, and as a correction input by external devices. The navigator may find the information on declination in navigation documentation (a navigation map, etc.), and information on deviation – in the ship's documentation (a deviation table for a given ship). External devices cooperating with the microcompass are gyrocompass, or the navigator. It may also cooperate with the GPS, however, in such a case it is no longer an autonomous device. Figure 4 shows a logical design of the microcompass, with relevant modules performing certain functions and certain tasks. The primary element of the microcompass is a microcontroller supplied from a proper voltage source, that combines all other modules. Raw data will be taken from the magnetometer. The data is useless without proper software and calibration. That is why raw data are transferred into the programming module. After data are transformed and calibrated, they are sent to the microcontroller as a true direction. While operating the microcompass it is possible to input correction updates from external devices. The desired result will be displayed. Its format depends on particular requirements, it may be programmed and displayed in a complete mode, point mode or other.

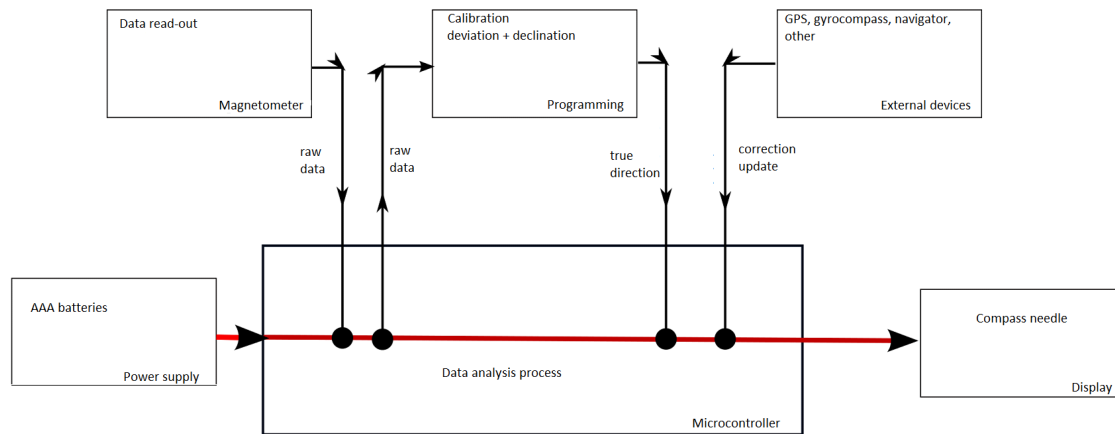


Fig. 4. Diagram of intermodule communication in the microcompass

The design assumptions for the microcompass are given in table 2:

Tab. 2 Design assumptions

<p><b>Aim:</b> To create a tool for the navigator that would constitute an alternative to a GPS system as regards direction measurement, in view of a possible lack of the GPS signal</p>
<p><b>Functions:</b> - to make a conventional magnetic compass more attractive to the user through mobility, semi-automatic updates, clear display - equipped with the possibility to connect with other tools in view of correction updates - equipped with the possibility to add other modules that would perform other functions</p>
<p><b>Requirements:</b> Energy savings – the microcompass is built in such a manner that it consumes little electric energy while performing the basic functions of a compass Low production cost – the microcompass is built using widely available and inexpensive electronic and navigation components</p>

The centre of the designed system, through which all data pass, is the microprocessor. Its task is to control the entire process: collection of information from the magnetometer, proper data transformation, calibration, correction update and display of the compass indication in a clear manner. For the purposes of the current design, an ATMEL AVR processor by ATMEL was selected: megaAVR – Atmega 8. Its characteristics include the possibility of supply with voltage between 4.5 and 5.5 V, 28 pins, speed of up to 16 MHz, power consumption at 4 MHz – 3.6 mA. Microsoft Visual Studio based ATMEL STUDIO AVR software is available in Atmel series that enables the development of a programme, its compilation, as well as initiation of the processor operation. Processors may be programmed in several languages, including C++, in which the programme for this particular microcompass was written.

Another designed element was the display. The initial design assumed the use of a relevant number of LEDs for displaying information. This, however, posed difficulties in constructing the system. In order to increase simplicity, as well as the accuracy of data presentation, a display was used instead. The two most common solutions are alphanumerical or a graphical display. Ultimately, an alphanumerical, single-line display without backlight was chosen, displaying up to 16 characters in one line. The main reason behind this was power consumption and the fact that the presentation of elements other than characters was not necessary. What was also important was the fact that displays based on the HD44780 controller are well documented and many libraries are available for their operation using the ATMEL AVR processor.

A proper programmer was necessary for the construction of the microprocessor. The most common programmer for AVR processors was used – USBasp. The programmer is connected to a USB interface and it provides for not only the programming of the processor,

but also the supply of the system with 500 mA power fed from the computer USB port. It is not equipped with a debugging function, but considering the simplicity of the programme, it was decided that only functional testing will be used. It is worth noting that the programmer is able to programme many AVT processors, including ATtiny2313 and ATmega8.

A device reading raw data – LSM303DLHC by Pololu – was used as a magnetometer. It has complete documentation and manufacturer's support as regards the system operation. Its characteristics are: supply voltage of 2.5 – 5.5 V, power consumption of 10 mA, output data I<sup>2</sup>C – magnetometer and accelerometer, measuring range for accelerometer: ±2G, ±4G, ±8G, ±11 G, for magnetometer: ±1.3, ±1.9, ±2.5, ±4.0, ±4.7, ±5.6, ±8.1 gauss, dimensions – 13 x 23 x 3 mm, pins arrangement: VDD – output 3.3 V, VIN – power supply, GND – ground, SCL – clock line I<sup>2</sup>C, SDA – data line I<sup>2</sup>C, DRD-Y – magnetometer readiness indication, INT1, INT2 – configurable interruptions.

The system power supply should enable both long term operation of the device and its easy replacement and regeneration. The required voltage of +5 V had to be as easily achievable as possible, i.e. preferably without using additional voltage increase or decrease systems that are always associated with costs due to lost energy and often the generation of additional heat. Therefore, battery supply was selected (AAA battery). The advantage of the battery is that it is lightweight, small, low-cost and has the capacity of 900-1155 mAh. This selection is in accordance with the design requirements (Table 2).

Having selected the components, all that is left is to develop a programme in Atmel Studio using available libraries that facilitate communication between the modules (Figure 5). Table 4 shows types of intermodule communication, libraries used and functions responsible for communication, as well as tasks performed and the course of intermodule communication process:

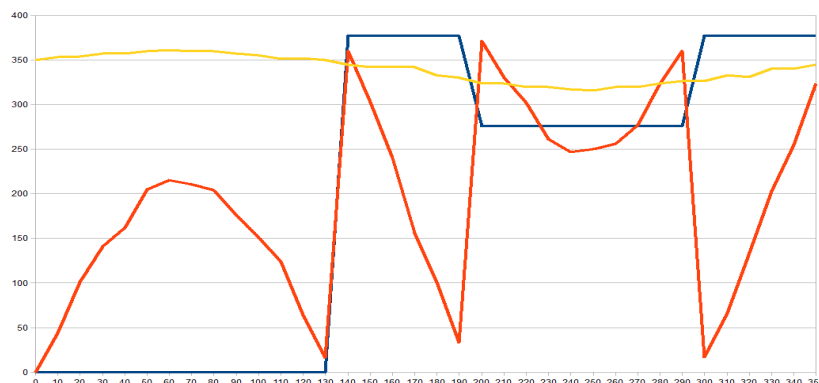
Tab. 4 Intermodule communication

Type	Tasks	Libraries used	Performed functions	Comments
Magnetometer – Microprocessor	- making raw data from the magnetometer available to the microprocessor through i2c	Library of I2C bus #include "i2cmaster.h" Library of control: #include <delay.h>	1)i2c_init()- Initiates I2C interface 3)i2c_stop()- Stops communication on i2c 2)i2c_write(compass address)- Writes into compass register 4)i2c_start_wait(compass address+1)- Switches the compass into writing mode and awaits writing, when + 0 is read-out 5)i2c_start(compass address +1) - Switches the compass into writing mode, when + 0 is read-out 6) i2c_rep_start(compass address + 1)- Again, switches the compass into writing mode, when + 0 is read-out 7)i2c_readAck(void )- Collects data from the compass and demands other data 8)i2c_readNak (void)- Collects data from the compass and ends reception 9)delay_ms(5000) – delays	i2c bus: Control process – i2c initiation + switching of the compass into writing mode + selection of a register responsible for data transmission + input into the register of the value that stimulates the compass to send data + receipt of data in the form of 8 bits to the board and awaiting other data (repeated three times) + receipt of 8 bits and reception completion. Data are included in the character table.

			transmission	
Microprocessor + Programming	<ul style="list-style-type: none"> <li>- conversion of the character table into magnetometer vector variables</li> <li>- calculation of direction using vector variables</li> <li>- conversion of degrees into points</li> <li>- calculation of compass deviation</li> <li>- data transmission onto the display</li> <li>- compass calibration</li> </ul>	Auxiliary libraries: <pre>#include &lt;math.h&gt; #include &lt;stdio.h&gt; #include &lt;string.h&gt;</pre>	<pre>1)int przelicz(int x, int y) - Converts the collected magnetometer data into degrees 2)char * rumby(int deg)- Converts degrees into points 3)void odchylenie_gora_dol(int k) - Displays information on incorrect deviation of the compass</pre>	A link in the form of a programmer is necessary for this type of communication – for this design Usbasp was used. The microcompass may be programmed when the new programme code is entered into the microcontroller using the link.
Microprocessor – External External	Corrections updates	Libraries of external devices control	Depends on the capacity of external devices	One PORTD input in the microcontroller is intended for additional signals from external devices
Microprocessor - display	Display of a message received from the microprocessor	Display control library <pre>#include "lcd.h"</pre>	<pre>1)lcd_init(LCD_DISP_ON)- Initiates the display 2)lcd_clrscr()- Display clear command 3)lcd_puts("char")- Transmission of text onto the display</pre>	Total process control by the microprocessor

### Functional tests

Thanks to the use of I<sup>2</sup>C interface and a proper library for its operation, data flow can always be monitored on the display. In order to evaluate the correctness of operation, results generated by the microcompass without a correction, with reference to the GPS, were analysed. Such raw data from the magnetometer are shown in Diagram 1.



Diag. 1 Data from the magnetometer without transformation

Apart from the monitoring of raw data, the manufacturer also provided information on the necessary data transformation. The magnetometer provides three 16-bit variables. X and Y

are used for determining the direction, while Z is the information on the device deflection. Data in the form as in Diagram 1 are raw and useless – in order to be able to determine the direction using those data, they must be subjected to a relevant transformation. In accordance with documentation, LSM303DLHC requires additional calculations of  $\Delta X = (\min(X1) + \max(X1))/2$ ,  $\Delta Y = (\min(Y1) + \max(Y1))/2$ , where  $\min(X1) = -290$ ,  $\max(X1) = 220$ ,  $\Delta X = -35$ ,  $\min(Y1) = -460$ ,  $\max(Y1) = 120$ ,  $\Delta Y = -170$ . The transformation is shown in Table 5. The transformation of data collected from the magnetometer is shown in Diagram 2.

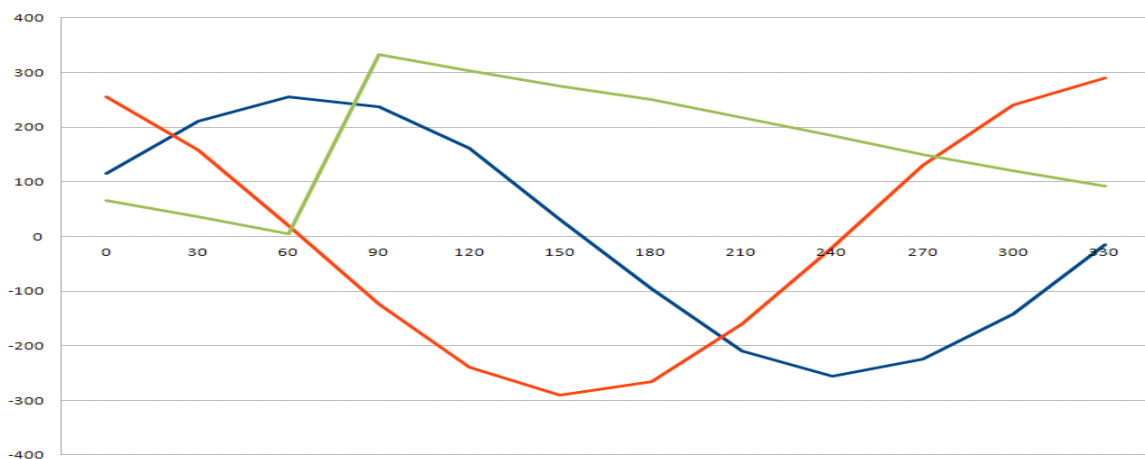
Tab. 6 Transformation in line with the documentation of magnetometer LSM303DLHC

Directions	X1 before trans.	Y1 before trans.	X=X1- ΔX after trans.	Y= Y1- ΔY after trans.	Direction In accordance with the formula from Table 7
0	81	86	116	256	65.6
30	176	-12	211	158	36.8
60	220	-150	255	20	4.5
90	203	-294	238	-124	332.5
120	126	-409	161	-239	304.0
150	-4	-460	31	-290	276.1
180	-130	-436	-95	-266	250.3
210	-244	-330	-209	-160	217.4
240	-290	-190	-255	-20	184.5
270	-260	-40	-225	130	150.0
300	-177	70	-142	240	120.6
330	-50	120	-15	290	93.0

Tab. 8 Transformation of data collected from the magnetometer

L.p.	Data X	Data Y	Direction
1	X > 0	Y >= 0	arctan(Y/X)
2	X < 0		180 + arctan(Y/X)
3	X > 0	Y < 0	360 + arctan(Y/X)

The results of the transformation are given in Diagram 2 below:



Diag. 2 Data obtained from the magnetometer following transformation

The red and blue lines are two sinusoids used as arguments for the mathematical function – tangens. The green line is the determined direction that does not coincide with 0 due to the lack of calibration with the true North, however, it may be observed that it is displaced by a constant. The green line should start with 360, then drop to 0, and rapidly



increase to 360. Due to abrupt measurements, the line looks broken, while in fact it is a continuous function. Calibration was performed during programming, so that 0 coincides with the true North. The declination and deviation correction is 65.6.

In order to evaluate the microcompass operation quality, a comparative method was used, where the microcompass operation was compared with a conventional magnetic compass. Table 9 below contains measurements from four different locations.

*Tab. 9 Differences in measurements using a conventional magnetic compass CC, and the compass from the project, PC*

CC	PC Measurement 1 Gdańsk University of Technology	PC Measurement 2 Beach, Gdańsk Jelitkowo	PC Measurement 3 Beach, Gdańsk Brzeżno	PC Measurement 4 Gdańsk University of Technology	Average Average KP	Difference
[°]	[°]	[°]	[°]	[°]	[°]	[°]
0	355	356	355	7	358.25	1.75
90	94	88	96	96	93.5	-3.5
180	210	180	187	187	191	-11
270	256	269	273	268	266.5	3.5
					Average deviation	4.9

As results from table 9, deviations remain within permissible limits. The result of the comparison with a conventional compass is  $\pm 5^\circ$ . The microcompass was programmed considering corrections, i.e. it indicates a direction close to the true direction. A conventional magnetic compass indicates a compass direction. Declination in the area where the tests were performed is approximately  $+ 5^\circ$  (areas of beaches in Gdańsk Brzeżno and Gdańsk Jelitkowo, as well as the Gdańsk University of Technology). Deviations may be omitted due to the lack of ferromagnetic elements in a needle compass). Therefore, measurements may be deemed satisfactory.

### **Expansion opportunities**

The microcompass was proposed in accordance with the design assumptions given in Table 2 (aim, delivered functionality and requirements). Further development is still possible. It is possible to introduce an automatic declination and deviation correction using the indications of a GPS receiver or another external device (such as a gyrocompass) or a navigator. This would result in a more precise measurement that would be comparable to a GPS receiver. Another idea is to create a database of declination corrections. Up-to-date declination corrections would be saved into the database with the record of the current position and time from the GPS. After approaching the position in which the declination correction was saved, the microcompass would be able to download this correction. An external device may be used for this functionality, so that the performance and economy of the microcompass operation are not compromised. This function may only be activated when demanded by the microcompass, as a "check correction from the declination corrections database" function. Another idea is to use a marine magnetic compass mechanism that reacts in case of ship listing and enables operation even in difficult sea conditions. The microcompass may also calibrate its horizontal and vertical deflection on the basis of a read-out from the accelerometer, however, this requires additional calculations and the replacement of the current microcontroller with a different one with larger memory, which in turn increases power consumption and data reading interferences. Currently, the microcompass provides information on incorrect placement and suggests a change with + and -. Another solution is to design a common interface for the GPS system and the microcompass that

would continuously provide information on differences in direction reading. Such a solution would reduce power consumption by the microcompass (it would not be equipped with a display), as well as provide the navigator with additional information. Another development step would be to use Wi-Fi technology that would enable the installation of a mobile repeater that repeats read-out from the microcompass, for example in a hand watch or a mobile phone. As a result, continuous direction control by the navigator would be possible even after his watch is over.

The design is based on a modular structure that makes it possible to add new elements, expanding the system with new functions and tasks. For example, an information module that could provide warnings on the change of course, due to an approaching danger or due to a deviation from the route planned on the map. This in turn would provide for the centralization of the navigator's information and increase in navigation safety.

## REFERENCES

1. Mirosław Jurdziński "Podstawy nawigacji morskiej", Fundacja Rozwoju WSM w Gdyni, 2002, Gdynia
2. Franciszek Wróbel "Vademecum oficera wachtowego", Trademar w Gdyni, 2013, Gdynia
3. Paweł Borkowski "Mikrokontrolery PIC w praktycznych zastosowaniach", Helion, 2009, Gliwice
4. Cezary Specht "System GPS.", Wydawnictwo Bernardinum w Pelplinie, 2007, Pelplin
5. Jacek Januszewski "System GPS i inne systemy satelitarne w nawigacji morskiej", Akademia Morska w Gdyni, 2008
6. Jacobson Cliff "Mapa. Kompas. GPS", Eremis, 2007
7. Tomasz Francuz "Język C dla mikrokontrolerów AVR. Od podstaw do zaawansowanych aplikacji", Helion, 2010, Gliwice
8. Kardaś Mirosław "Mikrokontrolery AVR język C, podstawy programowania", Atnel 2013, Szczecin
9. Kardaś Mirosław "Język C Pasja programowania mikrokontrolerów 8-bitowych", Atnel 2012, Szczecin
10. Wolfgang Trampert "AVR-RISC Mikrocontroller", Franzis, 2002, Germany
11. <http://magnetic-declination.com/>
12. <http://www.gps.gov/applications/marine/>
13. <http://inventors.about.com/od/cstartinventions/a/Compass.htm>
14. <http://www.compassadjustment.com/>
15. <http://www.visualmicro.com/page/Arduino-for-Atmel-Studio.aspx>
16. <http://www.physicalgeography.net/fundamentals/6h.html>
17. <http://www.microchip.com/ParamChartSearch/chart.aspx?branchID=1009&mid=10&lang=en&pageId=74>
18. <http://www.microchip.com/ParamChartSearch/Chart.aspx?branchID=211>
19. [http://www.atmel.com/images/atmel-2486-8-bit-avr-microcontroller-atmega8\\_1\\_datasheet.pdf](http://www.atmel.com/images/atmel-2486-8-bit-avr-microcontroller-atmega8_1_datasheet.pdf)