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Communication

Soft and hard iron compensation for the compasses of an operational towed hydrophone array without sensor motion by a Helmholtz coil.

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Abstract: Usually, towed hydrophone arrays are instrumented with a set of compasses. Data from these sensors are utilized while beamforming the acoustic signal for target bearing estimation. However, elements of the hydrophone array mounted in the neighborhood of a compass can affect the Earth's magnetic field detection. The effects depend upon the kind of elements present in the platform hosting the compass. If the disturbances are constant in time, they can be compensated for by means of a magnetic calibration. This process is commonly known as soft and hard iron compensation. In this paper, a solution is presented to carry out the magnetic calibration of a COTS (Commercial Off The Shelf) digital compass without unattainable sensor motion. This approach is particularly suited in applications where a physical rotation of the platform that hosts the sensor is unfeasible. In our case, the platform consists in an assembled and operational towed hydrophone array. A standard calibration process relies on physical rotation of the platform and thus on the use of the geomagnetic field as a reference during the compensation. As a variation on this approach, we provide to the sensor an artificial reference magnetic field to simulate the unfeasible physical rotation. We obtain this by using a tri-axial Helmholtz coil, which enables programmability of the reference magnetic field and assures the required field uniformity. In our work, the simulated geomagnetic field is characterized in terms of its uncertainty. The analysis indicates that our method and experimental set-up represent a suitably accurate approach for the soft and hard iron compensation of the compasses equipped in the hydrophone array under test.

Keywords: Magnetic Instruments, Digital compass, Soft and Hard iron compensation, Helmholtz coil, Towed hydrophone array.

1. Introduction

The towed hydrophone array (THA) consists essentially of a line of hydrophones mounted inside a flexible hose that is towed by a submerged or surface vessel. Some of the advantages of such arrays are a large aperture at low frequency of operation and the reduction of susceptibility to vessel noise [1]. However, the assumption that the hydrophones lie in a straight line behind the towing vessel cannot always be made. The correct computation of Magnetic North direction is usually the only information available for signal processing on the received acoustic waves [2]. Thus, non-acoustic sensors such a digital compass containing a triaxial magnetometer and a triaxial accelerometer are used in the array to provide heading information.

In a digital compass, the accelerometer measures the gravitational vector and the magnetometer measures the Earth's magnetic field vector. The latter means that the compass behavior can be influenced by any object mounted near the sensor that can affect the Earth's magnetic field.

This effect depends on the system under test, but as long as the distortions are stationary in time and space, they can be taken into account through a magnetic calibration.

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This process is commonly known as soft and hard iron compensation. The words hard and soft refer to the magnetic properties of the material generating the distortion, particularly to the strength of the magnetic field needed to align the magnetic domains.

It is important to note that the calibration of magnetometers with Helmholtz coil is a well-known technique, very often adopted by manufacturers [3] and has the aim of intrinsically calibrating a magnetometer [4][5] However, it is a process at a different level from the proposed soft & hard iron compensation, which calibrates the magnetometer with respect to external disturbances of a platform on which the sensor is mounted. The software programs of commercial compasses are designed so that the calibration process is achieved with a physical rotation, while in this work an innovative technique has been developed to perform the calibration with the coil without moving the array of hydrophones that have large dimensions (several meters). The work therefore adopts a known method but with an application development different from that envisaged by the compass manufacturers.

Hard magnetic materials have a wide hysteresis loop, so they have a high residual magnetization and cannot be easily demagnetized. In our application, this means that they can maintain their magnetic induction regardless of the presence of an external magnetic field in the range of earth's field [6]. Soft magnetic materials are characterized by a narrow hysteresis loop and therefore they can be easily magnetized and demagnetized [7]. In this case, the magnitude and direction of the induced field changes according to the magnitude and direction of the external magnetic field. Consequently, the two groups have a different effect on the outputs of the magnetometers. The usual calibration procedure relies on physical rotations of the compass and the host platform in the Earth's magnetic field to obtain an estimation of soft and hard iron distortions superimposed on the Earth's field. Indeed, by mapping the magnetometer outputs, the errors caused by these disturbances can be calculated with numerical techniques and removed adjusting the digital compass outputs. The process assumes that varying the orientation of the sensor in a non-disturbed geomagnetic field, all measured values of magnetic field would ideally lay on an axis-centered sphere. Whereas in presence of soft and hard iron distortions they lay on a shifted ellipsoid. Calibration software derives a function to fit the measured ellipsoid to the reference sphere and it uses this function to create a set of magnetometer calibration parameters [8][9].

2. Soft and Hard Iron compensation simulating towed hydrophone array motion

To carry out a soft and hard iron compensation that considers all the THA distortions, during the calibration the compass must be installed as in its operative configuration. According to compass manufacturers procedure, users would then have to rotate the platform including the sensor in a place where the Earth's magnetic field is undisturbed. In principle this means that physical rotations of the fully assembled and operational (i.e. powered on) array should be carried out, since a current carrying conductor has the same effect of a hard iron distortion on the compass. The above-mentioned operation is not feasible when one must manage arrays that are tens of meters in length. Therefore, our approach is to generate an artificial reference magnetic field as a stimulus for the compensation. Indeed, by placing the segment of the array containing the compass inside a tri-axial Helmholtz coil (HHC) and generating a rotation in the space of a uniform magnetic field, the physical rotation may be simulated. The main design requirements for our application are:

1) To generate a magnetic field sufficiently homogeneous inside a region. This region shall be large enough to contain the segment of the hydrophone array;
2) To be able to produce a magnetic field in any direction;
3) To be reprogrammable through a PC since the field produced by the laboratory setup depends upon the location;
4) To generate a magnetic induction comparable with the Earth's magnetic flux density (i.e. about 50 μT).

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To account for the first two requirements, a tri-axial Helmholtz Coil (Model: HHC Spin-Coil series 7-9-11-XYZ by Micro Magnetics) has been used. Moreover, bipolar power supplies are necessary to make the current flow in the two directions. To make the system easy to configure three digitally controlled power supplies (Model: EASY-DRIVER 0112 by CAEN ELS) have been selected to drive the coils. The power supplies are controlled with MATLAB Instrument Control Toolbox using a TCP/IP protocol. The complete description of the main components of the calibration system is shown in Fig.1.

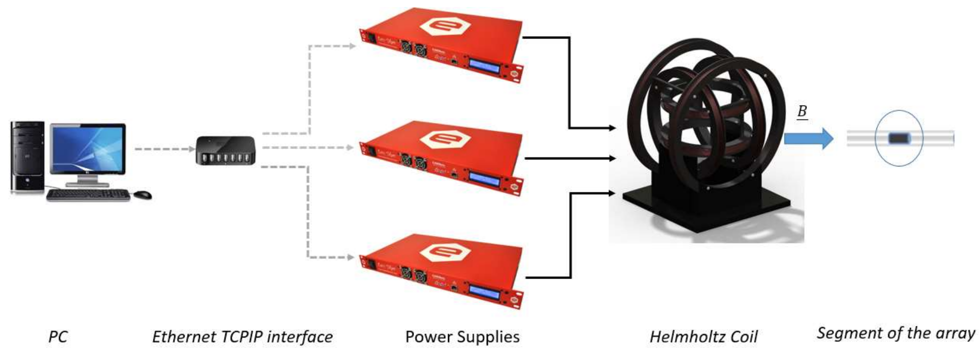

Figure 1. Main components and connections of the experimental set-up.

Our approach aims to simulate the rotation of the host platform and the sensor while continuing to use the magnetic calibration's software provided with the compass. In this regard, it must be pointed out that a digital compass is a 6-axis device that integrates a 3-axis magnetometer and a 3-axis accelerometer. The device incorporates an accelerometer to obtain tilt information: i.e., to detect the roll and pitch angles between the sensor's reference frame and the local horizontal plane defined perpendicular to the gravity vector. Whereas magnetometers sense the Earth's magnetic field to measure heading angle, that is the relative angle between Magnetic North, and the projection of the longitudinal axis of the sensor into the local horizontal plane [10]. Due to this computation and given that the calibration's software uses accelerometer data, the only rotation that one can simulate is the one around the vertical axis (aligned with gravity) as the outputs of the accelerometers are expected to remain constant in any case. Therefore, aligning our set-up to a North-East- Down (NED) frame, the HHC must be able to perform a rotation of the horizontal components of the Earth's field whilst maintaining the vertical component constant (see Fig. 2).

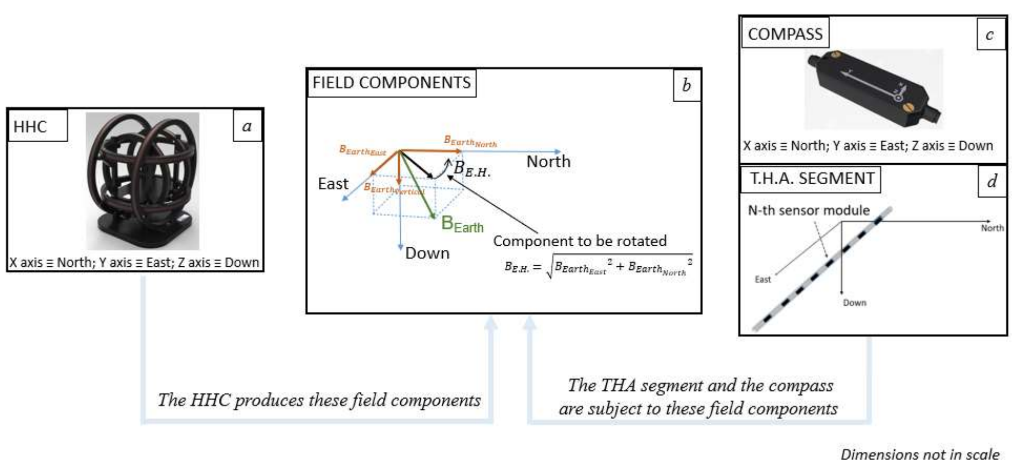

Figure 2. Set-up alignments.

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3. Experimental procedure

With the aim of generating an artificial field which simulates the rotation of the THA around the vertical axis, a two-step procedure has been developed. Firstly, there is the "System calibration" step that it is carried out with an auxiliary 3-Axis Magnetoresistive Milligauss Meter (model MR3 by AlphaLab) positioned at the center of the HHC with the hypothesis of no axis misalignment. This meter has much better specifications than magnetometers used in the digital compasses used in the THA. Secondly there is the "Compass calibration" step with the THA segment including the compass inside the HHC.

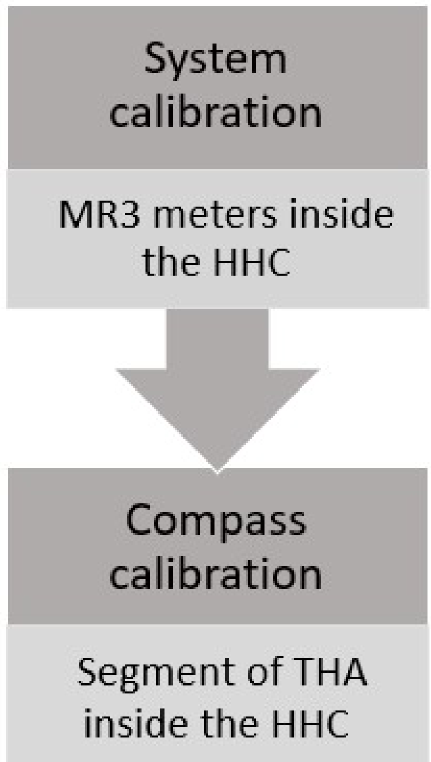

Fig. 3. The two-step procedure needed to calibrate our set-up.

The first step is performed through a test rotation and magnetic field measurements taken with the MR3 meter. It is devised to get rid of possible systematic error sources of our experimental system, to measure the local background field and to verify the effect of the background field. Indeed, the background field is not to be affected by the change in the field generated by the HHC. This eventually means that the effect of the background field should be limited to the hard iron type, since a soft iron would give different perturbations in the first and second steps. So, background field compensation as well as care in positioning the coils in a suitable environment, where there are no magnetically soft material surrounding the HHC, are the main tasks of this activity.

In the test rotation we drive the system to generate the desired calibration values of magnetic field. We define the desired components (B_{Earth_East},B_{Earth_North},$B_{Earth\_Vertical}$)according to our location, through the model provided by the International Geomagnetic Reference Field (IGRF). Driving X (North) and Y(East) coils with a current with harmonic time dependence produces the rotation of the vector around the vertical.

$$B_{x_d}(t_i) = B_{E.H.} * (cos\omega t_i) \quad (1)$$

$$B_{y_d}(t_i) = B_{E.H.} * (sin\omega t_i) \quad (2)$$

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$$B_{z_d}(t_i) = B_{Earth_{Vertical}} \quad (3)$$

Where $B_{E.H.}$ is defined in Fig.2 and ω is the angular frequency of the artificial rotation of the magnetic field vector. Actually, the sinusoidal waveform is obtained with a sequence of steps. The number of the steps should be chosen in such a way that the settling time of the system is considered, the amplitude of the steps is minimized and the value can be recorded by the MR3 meter. We find out that sending commands to power supplies with an interval of 0,5 s and a period of 60 s is a suitable trade-off.

A set of parameters are extracted from the measurements $B_{x,y,z_{MR3_i}}$ taken with the Milligauss meter during the test rotation. These parameters are needed to overcome the background field, check that there is no soft iron effect in the background and calibrate the system. This is obtained by measuring the eccentricity through SF_x and SF_y and the offset of the test rotation:

$$SF_x = \frac{2B_{E.H.}}{max\left(B_{x_{MR3_i}}\right) - min\left(B_{x_{MR3_i}}\right)} \quad (4)$$

$$SF_y = \frac{2B_{E.H.}}{max\left(B| \; |y_{MR3_i}\right) - min\left(B_{y_{MR3_i}}\right)} \quad (5)$$

$$B_{Off_x} = \frac{\sum_{i=1}^{N} B_{x_{MR3_i}}}{N} \quad (6)$$

$$B_{Off_y} = \frac{\sum_{i=1}^{N} B_{y_{MR3_i}}}{N} \quad (7)$$

$$B_{Off_z} = \frac{\sum_{i=1}^{N} B_{z_{MR\;i}}}{N} - B_{z_d} \quad (8)$$

With the aid of the previous steps, we can now perform the rotation of the field, which simulates a physical rotation in a uniform "Earth Field". To make this we require from the coils the field components expressed by the following equations:

$$B_{x_c}(t_i) = SF_x * \left(B| \; |E.H.* (cos\omega t_i) - B_{Off_x}\right) \quad (9)$$

$$B_{y_c}(t_i) = SF_y * \left(B_{E.H.} * (sin\omega t_i) - B_{Off_y}\right) \quad (10)$$

$$B_{z_c}(t_i) = B_{Earth_{Vertical}} - B_{Off_z} \quad (11)$$

During both steps, the input currents I that are requested to the power supplies are computed through:

$$I_{x,y,z}(t_i) = \frac{B_{x,y,z}(t_i)}{k_{x,y,z}} \quad (12)$$

where k is the coil-constant provided by the HHC manufacturer.

The accuracy limit of the procedure is given by the auxiliary magnetometer that has been used as a reference. The influence of this parameter is discussed in the next section.

4. Discussion on the artificially generated magnetic field

As a variation on the standard calibration, which relies on a real geomagnetic field, we expose the sensor to an artificial field. Although the artificial field has a small degree of non-uniformity, in the soft and hard iron compensation the important requirement is that the modulus of the stimulus used as a reference be constant during the calibration, the actual value is less important. The reference vectors we provide for the compass cal-

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ibration step are affected by an uncertainty deriving from the measurements taken with the MR3 meter for the system calibration. Such uncertainty is tolerable if small enough to allow the assessment of compliance of the compass to be compensated within its specifications. In this regard, it is worth noting that the manufacturer's procedure for soft and hard iron compensation is intended to take place directly in the Earth's magnetic field. Therefore, the compass datasheet does not report specifications required for the field used as a stimulus during compensation. In our case, we will evaluate the uncertainty of the components B_{x_c}, B_{y_c} as acceptable, as long as it induces a heading error lower than the accuracy of the sensor to be calibrated. As reported in Fig. 4, the worst-case situation is when B_{x_c}, B_{y_c} are subject to the maximum value of the uncertainties with opposite sign. This is equivalent to summing to the desired vector an orthogonal vector, with magnitude equal to the vector addition of the uncertainties (Fig. 5):

$$\left|\underline{u_{tot}}\right| = \sqrt{u_{B_{x_c}}^2 + u_{B_{y_c}}^2} \tag{13}$$

Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

Then, the assessment of the uncertainties on B_{x_c}, B_{y_c} allows evaluation of the maximum heading error ψ_e of our system through the scalar product between the two resulting vectors $\underline{B_{E.H.}}$ and $\underline{B_{E.H.}} + \underline{u_{tot}}$:

$$cos\psi_e = \frac{\underline{B_{E.H.}} \cdot \left(\underline{B_{E.H.}} + \underline{u_{tot}}\right)}{\left|\left(\underline{B_{E.H.}} + \underline{u_{tot}}\right)\right| \left|\underline{B_{E.H.}}\right|} \tag{14}$$

For simplicity's sake, calculus is not reported here and we only state that the overall results turn out to be suited for soft and hard iron compensation of compass with a heading accuracy of 1°, which is typical for the COTS compasses that are mounted on the THA.

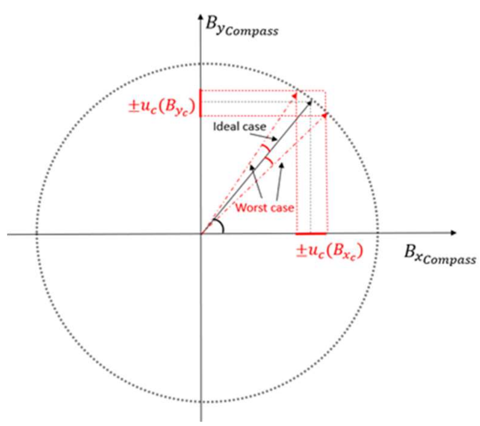

Fig. 4. Maximum heading error during the compass calibration step

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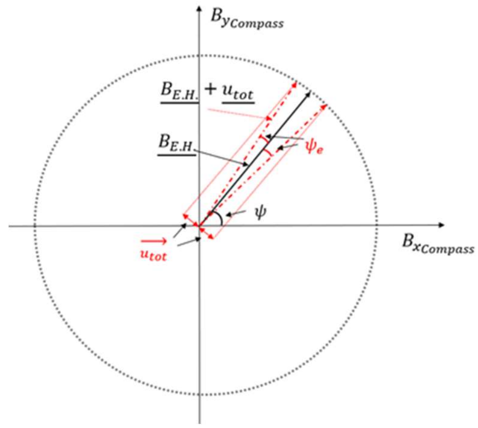

Fig. 5. Maximum heading error during the compass calibration step

5. Conclusions

This work led to the definition of a procedure and an experimental set-up to perform the soft and hard iron compensation on the compasses mounted in a towed hydrophone array. The novelty of this work lies in a calibration procedure that does not rely on an unfeasible sensor motion, It permits keeping the array assembled and operational whilst calibrating the compasses. This has the benefit of considering all the interference event though this is not foreseen by the compass manufacturer. sources that arise when the array is being operated in the field; factors which cannot be considered if the compass is calibrated prior to mounting in the THA.

Author Contributions: Conceptualization, T.L. and L.T.; methodology, T.L.; software, T.L.; validation, T.L.; formal analysis, L.C., C.C.; investigation, T.L.; resources, L.T.; data curation, L.C., C.C.; writing—original draft preparation, T.L.; writing—review and editing,T.L,L.T,C.C.,L.C; visualization, T.L.; supervision, L.C,C.C.; project administration, L.T.; funding acquisition, L.T.. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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