

Springer Series in Measurement Science and Technology

Pasquale Daponte
Giovanni Battista Rossi
Vincenzo Piscopo *Editors*

Measurement for the Sea

Supporting the Marine Environment
and the Blue Economy

 Springer

Springer Series in Measurement Science and Technology

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Homme libre, toujours tu chériras la mer!
C. Baudelaire, Les Fleurs du Mal, 1857

Preface

In the history of mankind, the sea has always played a key role as a privileged medium for communication, commerce and contact among civilities. It constitutes an essential ecosystem and an invaluable reservoir and source of foods for all living beings. Therefore, its health is a real challenge for the survival of humanity since it is one of the most important environmental components targeted by the global warming. Measuring and monitoring techniques are key tools for supporting the marine environment and the Blue Economy. In this perspective, a series of annual international events, labelled MetroSea (Metrology for the Sea, <http://www.metrosea.org/>) started in 2017. Their increasing success inspired this book that provides an anthology of tutorials dealing with a representative selection of topics, in this fascinating investigation area, with the aim of reaching a broad readership.

The book deals firstly with hydrography and measurements for meteorology and oceanography. Typical metrological issues, such as calibration and traceability, are also considered for both physical and chemical quantities. Then key techniques, such as underwater acoustic investigation, remote sensing in satellite oceanography, sea-waves and sea-level measurements, and sea-monitoring network, are treated. Marine geology and the monitoring of cetaceans are presented, and finally economical and legal aspects of standardisation with reference to ISO containers are discussed.

Such an unparalleled wide vision of measurement for the sea may be of interest for people involved in sea-related activities as well as for persons that have a cultural interest in the marine natural and human environment and have some scientific or technical background.

Envisaged readership includes:

- students of different University levels, attending courses related to the sea, from different perspectives (science, engineering, economics, etc.), to provide them an overview of the “measurement” issue, of its importance and potentials
- professionals and researchers involved in sea-related activities, interested in having a look at the entire panorama of measurements for the sea, for achieving a better knowledge of the “world” in which they operate

- people generically interested in the sea, including those that practise sea-related sports or leisure activities, those that like to cruise or to spend holidays on the sea, or are interested in the cultural environment related to the sea or in the potentials of the Blue Economy, and just have some mathematical/physical background

To reach such a wide readership, the subjects are presented in a tutorial fashion, featuring a multidisciplinary approach, with a special focus on measurement.

Benevento, Italy
Genoa, Italy
Naples, Italy
April 2021

Pasquale Daponte
Giovanni Battista Rossi
Vincenzo Piscopo

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He has organised some national or international meetings in the field of Electronic Measurements and European co-operation; he was General Chairman of the IEEE Instrumentation and Measurement Technical Conference for 2006 and Technical Programme Co-Chair for I2MTC 2015. He was a co-founder of the IEEE International Symposium on Medical Measurements and Applications (MeMeA); now, he is the Chair of the MeMeA Steering Committee, memea2018.ieee-ims.org.

He is also the co-founder of the IEEE Workshop on Metrology for the Sea (www.metrosea.org) as well as of several other series of international workshops in various emerging application areas of Metrology.

He is involved in some European projects.

He has published more than 320 scientific papers in journals and at national and international conferences on the following subjects: Measurements and Drones, ADC and DAC Modelling and Testing, Digital Signal Processing, Distributed Measurement Systems.

He received in 1987, the award for the researches on the digital signal processing of the ultrasounds in echo-ophthalmology from the Italian Society of Ophthalmology in 2009, the IEEE Fellowship in 2009, the Laurea Honoris Causa in Electrical Engineering from Technical University "Gheorghe Asachi" of Iasi

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Giovanni Battista Rossi obtained the Diploma in classical humanities in 1974 from Liceo Classico Giuseppe Mazzini, Genoa, and received the Laurea degree (with first-class honours) in mechanical engineering from the University of Genoa, Italy, in 1981.

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He has been chairman of Technical Committee 7 (Measurement Science) of the International Measurement Confederation (IMEKO) from 2012 to 2018 and has co-chaired international scientific events; he was the Italian vice-representative of the General Council of IMEKO from 2011 to 2015. He is currently a member of the Technical and Scientific Board of the Sea Study Centre of the University of Genoa.

Vincenzo Piscopo is Associate Professor of “Ship constructions and marine plants” at the University of Naples “Parthenope”, Department of Science and Technology, since 28th December 2020, where he was also Assistant Professor (RTDb) since 28th December 2017 and Research Fellow (RTDa) since 4th January 2016. He also worked at the same University as postdoctoral researcher from 1st October 2012 up to 30th April 2015. At the end of December 2009, he obtained the Ph.D. in Aerospace, Naval and Quality Engineering at the University of Naples “Federico II”, where he also earned cum laude the master’s and bachelor’s degrees in Naval Engineering in July 2006 and July 2004, respectively. He is currently

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The main research activities involve ships and marine structures, with particular reference to: (1) non-uniform torsion, buckling and ultimate strength analysis of ships and platings affected by pitting corrosion wastage, (2) mooring design and selection for floating offshore wind turbine, (3) dynamics of offshore structures, (4) design of wave energy converters, and (5) sea spectrum reconstruction based on ship motion analysis.

Chapter 1

Hydrography: From Marine Data to Information



Nicola Marco Pizzeghello and Luigi Sinapi

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Abstract Hydrography is the branch of applied sciences, which deals with the measurement and description of the physical features of oceans, seas, coastal areas, lakes, and rivers. It focuses on measurement itself, and no longer on the use of measurement, as the data-centric approach has become the foundation for the marine knowledge. “Map once and use many times” has become a general rule for all hydrographic surveyors. Collect data using standards and evaluating their quality are not just necessary to safety of navigation products but to all marine applications. The chapter explores why hydrography is useful for the sustainable use of the sea, what are the core hydrographic data, and how they are collected and processed using the international standards, which the International Hydrographic Organization has been updating since 1968. Finally, it focuses on marine knowledge starting from hydrographic data used for creating hydrographic and cartographic products and marine spatial data infrastructures.

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1.1 Hydrography: An Applied Science

Defining a certain subject often means having a close view of its connection with other matters. In the case of “Hydrography” the same definition includes its diffusion and use, so that it can be exploited as a common element for different fields of application.

The word hydrography can be divided into two parts: the first, *hydro*, which refers to water, and the suffix *-graphy*, which refers to writing. Hydrography measures and draws the marine environment: today through software, computers, and hydrographers, in the past through pencils, sheets, and always hydrographers. The way of operating has changed over time, but the foundation of the discipline has remained the same, especially for the attention to the hydrographic measurement.

Clarified that hydrography has a quantitative rather than descriptive-qualitative scope, the *International Hydrographic Organization (IHO)*¹ defines it as follows:

“Hydrography is the branch of applied sciences which deals with the measurement and description of the physical features of oceans, seas, coastal areas, lakes, and rivers, as well as with the prediction of their change over time, for the primary purpose of safety of navigation and in support of all other marine activities, including economic development, security and defense, scientific research, and environmental protection”.²

Wikipedia, the free encyclopedia, reports the same definition: it is an expression of the level of sharing that the IHO definition of hydrography has now reached.

The *International Federation of Hydrographic Societies (IFHS)*³ defines hydrography as follows:

“Hydrography is the measurement of various physical characteristics of the oceans (or other waters) such as bottom depth, currents, and waves. Although hydrographic surveys were traditionally carried out in order to produce navigation charts, nowadays such surveys are used in many applications from the oil and gas industry, to leisure activities and the fishing industry”.⁴

The contents of the IHO and IFHS definitions are similar, and they show the convergence of the use of hydrographic data to a wide range of applications.

Let us analyze step by step the definition given by the IHO.

“Hydrography is a branch of applied sciences....omissis”: it is a very elegant way to express the idea that the discipline does not have its own independent and exclusive field, but rather it acts as a bridge between pure sciences (mathematics,

¹The International Hydrographic Organization is an intergovernmental consultative and technical organization that was established in 1921 to support safety of navigation and the protection of the marine environment (from IHO website, www.iho.int).

²From publication S-32 “Hydrographic Dictionary”, WIKI Edition.

³The International Federation of Hydrographic Societies (IFHS) is a unique partnership of learned national and regional hydrographic societies that, through its worldwide membership, is able to address every specialism within the hydrographic profession and related disciplines, at all levels of experience and expertise (from IFHS website, www.hydrographicsociety.org).

⁴From the IFHS website www.hydrographicsociety.org.

physics, computer science, etc.) and applied sciences (geophysics, oceanography, etc.). In order to understand and deal with the definition of hydrography, we should know other disciplines. Basic knowledge, necessary to work in the hydrographic field, is systematized in the documents that the FIG/IHO/ICA *International Board On Standards Of Competence for Hydrographic Surveyors And Nautical Cartographers* (IBSC) keeps updated⁵

“omissis... which deals with the measurement and description of the physical features of oceans, seas, coastal areas, lakes, and rivers, as well as with the prediction of their change over time... omissis”: hydrography refers to a measured value, the result of a measurement process, understood as the indissoluble union between a number and the physical reference to which it refers, and its description, understood as an analysis linked to the form and nature of the physical conformation of all environments in which water is present: marine water, including the coast above the water surface level, and internal waters, such as lakes and rivers. The focus of the study is oriented to the physics of the marine environment and to its conformation analyzed from a diachronic point of view: maintaining the databases of the measures collected in the past, focusing the present and providing elements for monitoring, included the safety of navigation, and estimating what could happen in the future. It integrates time with the traditional approach of three-dimensional measurement in space, by studying the environment in four dimensions.

The last part of the definition outlines, probably not exhaustively, the areas within which hydrography could operate. Hydrography focuses on measurement and no longer on what it can do with measurement, and there is only an initial emphasis on the safety of navigation, the traditional task within which Hydrographic Offices (HOs) have operated throughout their history. In this latter field, the goal has always been to identify the minimum depth of water and to represent it on nautical charts, rather than the description of the depth of water as best as possible. Today this bias in the working methodology is very weakened, thanks to the diffusion of multibeam echosounders, capable of measuring the depth from multiple directions, continuously soundproofing the seabed at a certain resolution.

Other goals of hydrography have become competitive with safety of navigation, no longer giving to it a priority purpose. In the definition, the list of other marine activities is certainly not exhaustive, especially with regard to what could be linked to hydrographic data in the future.

The definition of hydrography therefore separates the hydrographic domain from the data representation, shifting the focus from products, traditionally charts, to the physical description of the marine environment. We are within the physical geography, today at least academically disjointed but not independent from human geography, descriptions of the environment without and with the presence of humans and their influences.⁶

⁵The syllabi of programs and individual recognition schemes of hydrographic courses are detailed in the IHO publication S-5 “Standard of Competence for Hydrographic Surveyors”.

⁶The difference between marine, an adjective linked to all sea-related activities, and maritime, more linked to activities related to human actions, should be here underlined.

For a better understanding of the marine environment, another virtuous trend in progress is to centralize data in the analysis processes, data with geographical connotation, including the position. The consequence of this centralization, which takes place in digital databases, is that all data can be managed through the same computer or many computers able to communicate. Such data sharing makes the study of the environment through different types of data possible (for example, bathymetric, nature of the sea bottom, topography of the coastline, etc.), favoring an integrated approach that produces more solid and coordinated information.

Hydrographers focus on the intrinsic quality of data and on the attempt to collect them in the best possible way, considering the limits of resolution and uncertainty. The extraction of products from the collected data that best represent the dangers to navigation may take place at a later stage.⁷ The objective is the creation of a digital database with rules for entering and extracting information, the *Marine Spatial Data Infrastructures* (MSDI).⁸ This type of approach makes it easier to exchange data and use the same data for different applications, which is essential, given the scarcity of high quality data at sea and its cost. The data-centric approach, the need to improve technical capabilities of hydrographers, and finally the collaboration with researchers, stakeholders, and other government bodies, appear to be the main future objectives for the hydrographic community.

In conclusion, if we do not know enough about what the marine environment looks like, we cannot really understand how the sea behaves and reacts to disturbing agents. So, hydrography helps to know the environment.

1.2 4D Reference Frame

1.2.1 *The Measure*

Hydrography aims to measure physical aspects of the marine environment; from the measurements we move on to describe the same environment in an increasingly holistic way, thanks to the diffusion of computer systems and related databases.

So what is a measure? What is it referred to?

The *Bureau International des Poids et Mesures* (BIPM)⁹ gives the following definition of quantity:

“property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a reference”.¹⁰

⁷On this subject, see the Data-Information-Knowledge triangle from IHO C-17 “Spatial Data Infrastructures: The Marine Dimension—Guidance for Hydrographic Offices”, 2017 Edition.

⁸The IHO Marine Spatial Data Infrastructures Working Group is active in this field.

⁹From the BIPM website, you can read: “BIPM is the intergovernmental organization through which Member States act together on matters related to measurement science and measurement standards”.

¹⁰From the BIPM publication “International Vocabulary of Metrology” (VIM), 2008 Edition.

Quantity is therefore a property which can be expressed through a number, and this is quite common and not new in the scientific field, while the reference is more intriguing.

Quantity is also something that is described by numbers and references but it exists before its expression and is somehow disjointed. Without getting as far as philosophy, it is useful to think about how describing reality through measures can sometimes be reductive.

Returning to the definition of quantity, it is useful and opportune to link it to the definition of quantity value, also contained in the International Vocabulary of Metrology (VIM). The definition is as follows:

“number and reference together expressing magnitude of a quantity”.

As can be inferred from the definition given by BIPM, quantity value is an entity more linked to what we are used to dealing with and it does not directly refer to the intrinsic property of the studied phenomenon.

Once we defined quantity and quantity value, the measurement operation is what links them. In particular, the definition contained in the VIM about measurement is as follows:

“process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity”.

In the notes and annotations of the VIM to this last definition, it is made explicit what is meant by the word experimentally; underlining that the measurement is not only the number, but it is also the way in which it is detected. From this point of view, what we mentioned in the first chapter about hydrographers' skills seems more relevant than ever.

Finally, the following annotation 3 to the definition of measurement reported in the VIM is of extreme interest:

“This Note is intended to explain what is needed in order to carry out a measurement. It is first necessary to choose a target measurement uncertainty, and then choose an appropriate procedure and measuring system for performing the measurement in order not to exceed the target uncertainty”.

The uncertainty is linked to the measurement and, as mentioned above, it results in two indissoluble elements: number and reference. Uncertainty on the one hand precedes the measurement operation because it determines how in practice it is appropriate to measure. On the other hand, it follows the measurement because once the measurement has been completed, it is necessary to provide an estimation of the quality of the measurement through the uncertainty.

A certain measured value, representative of a quantity, is ultimately made up of a number, its reference, and an estimation of the uncertainty that accompanies it from the choice of the measurement system to the conclusion of the measurement process.

1.2.2 *The Reference*

The note three to the definition of measurement reported on the VIM contains the most essential operational aspects to establish the reference. It is as follows:

“Measurement presupposes a description of the quantity commensurate with the intended use of a measurement result, a measurement procedure, and a calibrated measuring system operating according to the specified measurement procedure, including the measurement conditions”.

Each measuring instrument goes back to the original definition of the unit of measure through a more or less long chain of measurement samples, to which the individual instruments refer to. Obviously, every single measurement, always affected by uncertainty, has different metrics and leads to a different number. This is why a measurement without the relative metric (i.e., the reference) is not representative.

In particular, hydrographic measurements face the four-dimensional space (three spatial dimensions and one temporal dimension) and it always has a direct or indirect physical connection to the territory. The materialization of the reference can only occur through physically determined points.

These points are chosen through a set of theoretical rules that determine the geometry of the system, but without defining its physical realization. As for example, the set of rules of the position reference system established by the International Earth Rotation and Reference Systems Service (IERS) and named International Terrestrial Reference System (ITRS), within which the dimensions of the ellipsoid to which latitude and longitude are measured and its theoretical positioning respect to the Earth are fixed. Another example is the theoretical center of the transducer of an echosounder, usually explained in the operating manual, to which the depth measurements are referred.

The theoretical set of rules (the reference system) is then physically materialized creating a reference frame.

For the same example given above, the physical implementation of ITRS is a set of physically defined points in the Earth that create the physical frame of the rule set. These points form the International Terrestrial Reference Frame.¹¹ As the points are in motion for the tectonics of the plates, not only the coordinates are reported but also the estimation of their change over time. Since the measurements and estimations of their variations are also affected by uncertainties, the points can be updated (and recalculated) periodically through a new frame construction. In the case of the transducer, measurements will refer to a physical point on the transducer, which may be different from the theoretical point reported on the manual, because it can change over time.

The frame is therefore necessary for each measurement, and may change over time. In the case of hydrographic measurements, the frame has a spatial connotation, and must be physically defined for each individual measure. A frame drift,

¹¹ See <http://itrf.ensg.ign.fr/>.

which usually has slow displacements, can cause systematic errors in the measurement.

All hydrographic measurements also have a temporal reference. It has a material realization in the world through a set of atomic clocks that maintain the Coordinated Universal Time (UTC), to which the measurements should refer. The UTC time is directly measurable by modern Global Navigation Satellite Systems (GNSS) satellite receivers and available at the output of the instrument as well as the position.

1.2.3 4D Reference Frame

The hydrographic measures move in a four-dimensional space, where the time coordinate is added to the spatial ones. Therefore, data are collected in four dimensions (4D) through instruments that have their own reference frame. The raw data packages are combined and transformed into processed data which can be shared for different applications through databases.

Each reference frame is, in practice, a trio of Cartesian axes or polar coordinates in space, accompanied by the knowledge of time.

Every spatial reference is not only a set of rules; however, it is also its physical realization. It presupposes measures to realize it, which are therefore uncertain. As a consequence, a reference frame is not made by perfectly orthogonal axes and points without dimensions, but by axes that can be distorted and points that in reality are small portions of space. The same metric of the reference system (the unit of measurement) can be distorted leading to scale variations between different reference systems. The materialization of the unit of measurement in the instruments that measure length does not physically have the length of a meter, a statement that before introducing the previous concepts might have seemed paradoxical but now appears normal, indeed one would have been surprised at the opposite, maybe.

To pass from one reference frame to another, a six-parameter model is necessary,¹² where the two reference systems have different origins (three different coordinates of the origin that determine three translations) and different orientation of the axes (three angles in space that determine three rotations).

1.2.3.1 The Instrumental Reference Frame

Each instrument needs its own reference frame. It is therefore mandatory to know how the frame is positioned in order to understand the correct information content of the data collected.

¹²A scale variation in the metrics, the seventh parameter, is not considered here.

For a very basic analysis, but strongly founded on the previous rules, we now analyze the main instruments used for hydrographic measures, such as position, depth, attitude, state of the water (speed of sound), and vertical level.

As the measure is four-dimensional, it must contain the necessary temporal reference. Depending on the measurement uncertainties required, the instrument can have its own clock to be manually aligned with the standard, or an automatic interface with a more accurate system – GNSS – that determines the time.

Positioning instruments are today mainly GNSS receivers, capable of measuring codes and multifrequency phases of available satellite constellations. The reference frame of the instrument is represented by the phase center of the receiving antenna. GNSS also measures time, while hydrographic GNSS makes available also the synchronization signal at the output, ready to be sent to other instruments (it is usually the combination of a serial string signal and an electrical impulse called Pulse Per Second, PPS).

Alignment instruments are combinations of several GNSS antennas and inertial platforms consisting of gyroscopes and accelerators. Usually the inertial platforms are calibrated by manufacturers and the reference frame is a physical point marked on the measuring platform associated with a trio of Cartesian axes in space. Sometimes a certain direction (e.g., the bow of the vessel) is measured through two GNSS receivers; the direction is identified by the vector joining the phase centers of the respective antennas.

To measure the depth, hydrography uses transducers to convert electrical energy into acoustic one. The phase center of the transducer and the respective axes (identified on the transducer itself) materialize the reference frame of the instrument.

The auxiliary instruments also have a reference frame. For those that determine the physical characteristics of the medium (for example, the temperature of the water used to determine the speed of sound in water), the temperature sensor must be associated with its position in space, i.e., latitude, longitude, and the height with respect to the free surface of the water.

For the measurement of the water level, the problem is substantially similar, remembering that the distance between the free surface of the water and a certain physical vertical reference needs to be measured.

1.2.3.2 Among the Instruments and the Results: The Body Frame

Each instrument registers the data with respect to its own frame; the final objective is to transform data into a standard frame in order to make data interchangeable and representative for everyone. To convert data into this latest frame, hydrographic measures are converted into an intermediate frame, which is directly linked neither to the measurement nor to the results, but it acts as a bridge to combine the measurements.

This frame is attached to the medium on which instruments are installed and it is called the body frame. In the case of a hydrographic vessel, it is attached to the hull and is usually called vessel reference frame.

The axes of the system are fixed with the vessel and oriented along its longitudinal, transverse, and vertical axes.

1.2.3.3 The Position Reference Frame

The position is expressed with respect to an ellipsoidal reference frame, on which the latitude and longitude coordinates are defined.

Geodetic reference systems and frames with a global orientation were created by measurements and points scattered around the globe. This approach has now evolved from WGS 84, the Global Positioning System (GPS)¹³ reference system, to ITRS-ITRF, a reference independent of the systems that can use it.

1.2.3.4 The Vertical Reference Frame

Once the planimetric coordinates of the measurement have been defined, the most of hydrographic measurements need of a vertical reference too.

Measures at sea have traditionally been linked to the physical position of the free surface of the water. As this profile is in continuous movement (for example, for tides and waves), a fixed position must be decided in order to use it as a reference level. The most direct reference is the mean sea level (MSL). This reference is established by measuring the sea level at a given location and averaging it over a period long enough to filter out the oscillations of short term. At the same time, as the mean level tends to increase in the long term, the interval should not be too long. The IHO, through resolution 3/1919 and subsequent amendments,¹⁴ has identified, at least for ocean tides, 1 year as the balance between the opposite requirements.

The physical position of the MSL in a given position determines the equipotential surface of the gravity field used as reference. The main advantage of using this surface is that it is strongly linked to the position of the water in that period, being representative for all human activities that depend on the position of the water (for example, navigation or port management). It has the disadvantage of varying over time and therefore it needs to be continuously monitored.

From the position of the MSL, all other tide datums are derived, i.e., the levels that instead of referring to the average water position, refer to an astronomical high or low tide. It should be remembered that these tidal datums, which are traditionally used in nautical charts, refer only to the astronomical tide, ignoring the effects that particular weather conditions may have on sea level.

These physical references are nowadays connected to the ellipsoidal datum. As explained in the previous paragraph, the ellipsoidal datum is the reference frame for

¹³ It is the American GNSS.

¹⁴ For resolutions of IHO, see publication M-3 “Resolutions of the International Hydrographic Organization”.

positions, including height. It should be considered that the ellipsoid has a geometric nature, while the MSL has a physical nature. Therefore, the connection between the two can be made only by double and simultaneous measurements. This connection, measured by a vertical difference, changes around the world, because the different definition of the levels does not allow a constant and global difference between them. The advantage of using the ellipsoidal datum is linked to the fact that GNSS can materialize the ellipsoid through the measurement and thus it refers the depth measurement directly to the datum. Known the local difference between ellipsoid and MSL, it is possible to refer the measurements to a more practical physical reference.

The physical reference used for land operations, the geoid, is seldom useful at sea. In practice, as mentioned above, hydrography creates its geoid locally through the MSL, and it is not everywhere on the same equipotential surface of the gravity field.

1.2.3.5 The Time Reference Frame

The time used in hydrography is linked to atomic transitions, very stable and measurable through atomic clocks. A network of clocks scattered around the world, managed by the BIPM, materialize the international atomic time (TAI, temps atomique international). TAI is periodically corrected by a number of integer seconds in order to align it to the real movements of the Earth around its axis. This corrected time is called UTC, and it is the time reference frame more used for hydrographic.¹⁵

UTC is measured and available as output from GNSS designed for hydrographic purposes; the clock signal (called Pulse per Second, PPS) synchronizes the clocks of the various instruments to UTC. As for the positioning, a degradation of uncertainty of the position is also extended to time measurement, making it more uncertain.

1.3 The Hydrographic Measures

A basic hydrographic system is mainly made up of a positioning system, an attitude system, and a system for the detection of the seabed as well as auxiliary measurements. This basic instrumental analysis will be analyzed in the following paragraphs.

¹⁵Resolution number 7/2009 contained in the IHO publication M-3 prescribes its use in all nautical publications.

1.3.1 The Positioning

Today almost all positioning operations use GNSS systems. Even in the absence of a signal (for example, inside tunnels), GNSS is used to determine position at the beginning and end of the route.

Hydrographic GNSS can measure codes or phases of each individual satellite frequency that they are able to receive. This general definition indicates the top quality of the receivers (they receive all satellites and process all frequencies). Actually, depending on the quality of the receiver, tracking can be limited to some constellations of satellites. It is the case of a GNSS that receives only the constellation of the American GPS system or some frequencies, or then just code measurements and not the carrier phase of the signal coming from the satellite.

With reference to the performance of the receiver, there is a long-term trend in the hydrographic world which is moving the real-time positioning to the post processed one. Being linked to the safety of navigation, hydrography has a history linked to real-time positioning. This need, however, has not always been linked to the real usefulness of having position data immediately available for hydrographic surveys.

Today, the possibility of recording the measurements of the receiver - which represent the observable measurements previously mentioned - allows to increase, at the same cost, the quality of the positioning. The constraint is obviously to keep the GNSS measurement synchronized with the instruments that will be analyzed in the following paragraphs. This is also easily achievable by the timing signal available through the pulse per second (PPS).

The position is thus calculated in post processing, making the appropriate calculations on the observations and taking advantage of the possibility of correcting some errors that in real time would not have been possible to manage (amongst others, the recalculation of the ephemeris of the satellites or ionospheric modeling).

GNSS measurements are always time-referenced because the position calculation is always correlated with the time of the UTC frame. The measurements are spatially referred to the phase center of the antenna. In relation to the speed of the vessel, the hydrographer adjusts the recording rate. This rate does not usually fall below one position per second.

1.3.2 The Attitude

The vehicle (vessels in water and/or planes/satellites in air) on which the hydrographic sensor is installed directs rays, acoustic or electromagnetic, toward the seabed. In order to position these rays in space, it is necessary to know not only the position of the sensor but also its attitude.

The attitude is measured using inertial platforms whose operating principle is based on the laws of dynamics, or on combined measurements of several GNSS

antennas using relative positioning and extraction of the vector, rigidly oriented in space, which connects the phase centers of the antennas.

The final objective is to obtain the position and attitude of the transducer of the hydrographic sensor. The transducer can be shaped as a rigid body in space with six degrees of freedom, three linear and three angular. Inertial platforms possibly combined with GNSS receivers determine the three angular measurements. The two linear horizontal measurements are determined by positioning. Vertical measurements, including heave (measured by the attitude sensor) and tide (measured by GNSS or a tide gauge), are the most critical, given the importance of depth.

The attitude system measures the three angles with respect to its coordinated axes and the vertical movement with faster rates. The angles are called roll, pitch, and heading (or gyro). Roll is the angle that the transverse axis of the instrument forms with the horizontal plane. Pitch is the angle that the longitudinal axis of the instrument forms with the horizontal plane. Heading (called also gyro), is the angle that the longitudinal axis of the instrument forms with the North direction. Heave is the fast vertical movement that is combined with the tide to determine – at the time of the observation – the exact position on the vertical axis of the hydrographic sensor.

These three angles and one distance enter into the calculation of the positioning of the measurements; they are also dynamic, because the vehicle (vessels in water and/or planes/satellites in air) from which the measurements are taken, are in motion.

1.3.3 The Depth

At the center of the hydrographic acquisition, there is always an instrument for determining depth, which uses acoustic or electromagnetic waves oriented toward the seabed. The main instruments used for this purpose are described in the following paragraphs.

1.3.3.1 The Singlebeam Echosounder (SBES)

It is the traditional instrument used to measure the depth below a transducer, transforming electrical energy into acoustics in transmission and vice versa in reception. This transducer has a directional acoustic lobe, with certain angular amplitude¹⁶; the direction of maximum irradiation is perpendicular to its surface and it is referred to a point on the transducer, fundamental for the definition of the offsets among instruments.

An acoustic impulse at a certain frequency is emitted at a known time, and the return signal time is measured. Known the profile of the speed of sound in the water,

¹⁶The beam width is defined as the angle between the direction of maximum power of the wave beam and the direction in which the power is half of the maximum. It depends on the size of the transducer in relation to the wavelength of the signal.

the distance from the transducer to the seabed is calculated by measuring the travel time. The result is a precise measurement of the depth over time, taking advantage of the fact that the vehicle on which the instrument is installed is moving along programmed lines. In order to intercept the depth variation profile on each acquisition line, the lines are generally conducted perpendicularly to the average bathymetric trend of the surveyed area.

The depth measure is representative of an area on the seabed, called footprint¹⁷: the smaller the lobe, the smaller will be the footprint. Higher acoustic frequencies need smaller transducers to realize the same beam width. Moreover, lower frequencies have longer wavelengths. As the precision of the measure is a function of wavelength, low-frequency systems have worse precision. Conversely, lower frequencies need bigger transducers.¹⁸ Unfortunately, the absorption of the high frequencies is higher, and for deep waters low frequencies are needed.

The other quantity that influences the measurement is the amount of energy radiated in the water, linked to the amplitude of the emitted signal and its duration. Increasing amplitude and duration of the impulse certainly means increasing the range of the system up to a certain physical limit related to the used acoustic frequency. But, it increases also the noise. The best rule to follow during a singlebeam survey for bathymetric applications is to use the highest possible frequency (if more than one is available), coupled with a minimum amplitude and pulse duration that still allows continuous bottom detection. These parameters should then be changed during the survey to better adapt them to the conditions of the surveyed area.

The measurement of the singlebeam echosounder is time-referenced by the instrument, through the alignment of its internal clock with the signal coming from GNSS.

Modern singlebeam, in addition to recording the digital data of the bottom detection, are able to digitize and record the signal intensity over time. This is very useful to analyze the state of the water column, the nature of the bottom, and in case of penetration below the bottom, the stratigraphy.

1.3.3.2 The Multibeam Echosounder (MBES)

The multibeam echosounder is the main hydrographic system, capable of acquire data not only on the vertical angle but also from lateral direction. Its swath, the lateral opening angle of the fan-shaped lobe, is composed by several beams oriented across track, perpendicular to the direction of the ship (Fig. 1.1).

It can be modeled into a physical level, where the electromagnetic signals are transformed into acoustic ones and transmitted and vice versa, and an analytical

¹⁷It is the area explored by the system calculated by the geometrical spreading of the beam width.

¹⁸With the same wavelength, a longer transducer in a certain direction generates a narrower beam to the perpendicular direction. With the same transducer size, longer wavelengths, and therefore lower frequencies, generate larger lobes. With the same beam width, longer wavelengths need larger transducers.

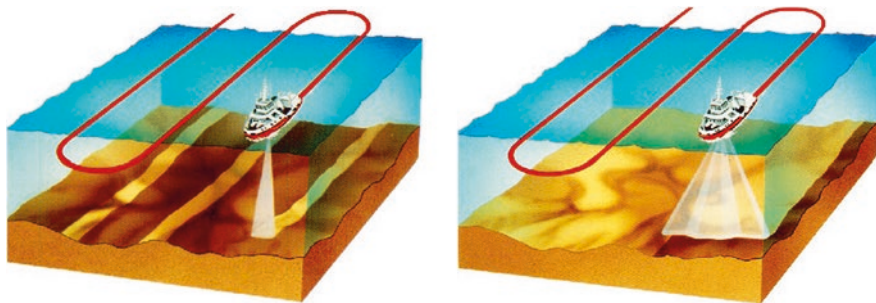


Fig. 1.1 Difference between singlebeam and multibeam survey (courtesy of Kongsberg Maritime AS)



Fig. 1.2 Tx and Rx multibeam transducer (courtesy of Kongsberg Maritime AS)

level, where the received signals are recombined and processed on the basis of algorithms, which represent the real core of the system.

At physical level, a signal transmission projector and an array of receivers are integrated into the multibeam transducer (Fig. 1.2).

The projector, oriented with its major axe per keel, transmits the signal. The transmission acoustic lobe has a width of a few degrees along-track and an across-track width ranging from 120 to 180 degrees, depending on the multibeam model. The lobe has the shape of a crosswise-oriented fan.

To fix the spatial resolution to a certain transverse direction, the system can use two different methods. The first method, called beamforming, is to set a certain number of transverse directions where they are received. From each direction, the travel time is measured. The second method, called interferometry, is set to scan the

received signal discreetly over time, determining for each of the following times $t = t_0, t_1, t_2$ etc., the angle from which the signal comes from.

Beamforming uses a certain number of receiving elements, usually at least 40, that form an array, aligned across-track. At physical level, each element of the array receives independently the same signal radiated by the projector. The signal arrival times, different for each acoustic element of the array and updated with each new ping, are recorded.

The set of measurements then pass to the analytical level, usually consisting of a computer card that performs the beamforming. For each ping the signals of the individual elements that form the array are recombined several times in different ways according to the beamforming algorithm. Each different recombination changes the transverse direction of measurement. Within the beamformer, the signals are differently delayed before being recombined, and these delays are a function of the transverse angle. At the end of the processing, an artificial lobe is formed and it is no longer a fan but a series of pencil beams whose envelope is a fan. This result is a combination of the projector and receiver array directivity.

The interferometric approach is opposite. Making the same considerations as beamforming for the transmission chain, reception takes place by an array that is composed of at most three to four acoustic elements. On a physical level, for each ping, the array samples and records the phase of the received signal over time.

At an analytical level, the difference between the phases of the array's channels over time is calculated and from these differences, for each instant of sampling, signals angles are calculated. The result is similar to the one of beamforming, but the way to calculate the angle-travel time pairs is the opposite. Beamforming fixes angles and measures travel time, interferometry fixes times and measures angles.

In general, the beamforming systems are more complex, physically larger and more expensive. Interferometric systems are more compact, simple, and economical.

The swath angle, which envelopes the individual pencil beams, reaches greater angles in interferometric systems, although data quality at the more lateral areas greatly degrades.

Beamforming systems generally guarantee top data quality. They calculate for each ping from 300 to 1000 high-quality measurements. Interferometric systems can calculate up to 8000 measures per ping, but the vast majority of them are anomalous. A prefiltering of the interferometric data is required, while beamforming systems normally import data directly into the post processing software.

The multibeam is coupled to a positioning system, which also provides the timing signal, and attitude data.

The frequency of the echosounder is very important for different aspects. It fixes the size, performance, and scope of the system. Multibeams usually acquire data using a single frequency. In some models, this frequency can be modulated and changed within a predefined range. Usually, these modes are used for high frequency multibeams (higher than 200 kHz). Systems that can simultaneously manage and measure data on two frequencies are now entering the market.

In addition to traditional depth measurements, through time measurement and applying acoustics' rules, the multibeam records backscattering from the seabed. This measurement is used to study the nature of the seabed.

To complete the package of measurements available, multibeam beamformers are able to sample the signal strength also along the water column. This data package is called water column data (WCD). It is used for many applications, from wreck surveys to gaseous emission studies, from the study of fishes to the detection of water masses at different physical states. The main problems with these data, partially still unresolved, lie in the processing of WCD, which is not automated, due to data dimension, which is about ten times larger than of the one from the bottom.

1.3.3.3 The Airborne Lidar Bathymetry (ALB)

Electromagnetic measures now accompany traditional acoustic ones. Electromagnetic wave sensors are installed on aircrafts (whether manned or unmanned, guided or autonomous) or satellites.

Only the most developed technology, ALB, is analyzed hereinafter. It is based on LIDAR (Light Detection And Ranging) techniques and it collects data compliance with international standards. The other consolidated application from a technological point of view, but not yet from a hydrographic one, is the satellite derived bathymetry, and it is left to other treatments.

The electromagnetic (EM) energy allows the sensor to be used in the air. The EM propagation in water, in fact, is worse than the acoustic one and remains acceptable in the visible field around the blue-green frequencies; moreover, it is strongly influenced by the transparency of the water. For bottom detection, lasers are used on blue-green frequencies in areas where water transparency is high. For the measurement of transparency, even approximate measurements are sufficient, but they should be extended to the entire area of the survey (the depth of the Secchi disc is used). The maximum depth achievable from the ALB is a multiple of the Secchi depth, from 1–2 times for the higher frequency sensors to 3–4 times for the lower frequency sensors. In the best conditions, the system reaches depths up to 40–50 meters, in the worst a few centimeters. Unlike the multibeam, the laser operates beam steering partly mechanically, using a rotating or mobile mirror.

The ALB sensor is totally out of the water. This has the advantage of increasing the area explored per hour, also considering that the aircraft is less dependent on weather conditions than the vessel, and it is faster. It is possible to acquire data in the water and out of the water, integrating the coastal conformation and realizing an integrated approach to the study of the interface between submerged and emerged surfaces.

Being out of the water, however, the ALB measurements of depth presuppose knowledge of the vertical reference. For a vessel, it can be identified indirectly by the position on board of the transducer, applying draft, heave, and tide. The aircraft needs an additional channel to measure the position of the water surface. This

channel transmits in the infrared field, which does not penetrate the water. The instantaneous water level measurement is then corrected for the tide.

Acoustic and electromagnetic measurements, in or out of water, can now use the vertical component of GNSS to fix the vertical datum. In this case, the IR channels of the ALB or the transducer immersion data are not useful as they are referred to the ellipsoidal height.

The considerations expressed on the auxiliary sensors for the MBES can be transposed to the ALB. For GNSS and attitude sensors, only operational differences do exist. Aircraft moves faster than ship, so the measurement frequency and the filters to be applied (especially for heave) are different.

Finally, it should be considered that while MBES can be used autonomously by a surveyor, independently from the manufacturer, an ALB survey should be carried out by specialized hydrographic surveyors.

1.4 The Hydrographic Standards

In order to be representative, measures must be collected according to certain common rules, standards, through which the data can be associated to a certain quality standard and then exchanged and used for different needs.

At national and international level, three levels have been consolidated for the management of the rules to be applied in hydrography.

The first level is the international one. The standard is the framework of hydrographic rules and today is represented by the publication of the IHO S-44 “IHO Standards for Hydrographic Surveys” Edition 2020, recently updated to its sixth edition.

The second level, the national one, transposes and applies the international standard to the national level. It can eventually integrate the international standard, giving more detailed and restrictive indications.

The third level includes all residual materials, such as good practices, guidelines, and operating manuals. In practice, this level is useful to apply the standards and make them usable in hydrography.

Hydrographic standards are hierarchically organized among themselves. The definition of hydrography indicates the way forward: the context related to the safety of navigation appears to be only one of the applications, as the collection of data accordingly to the quality rules imposed by the authoritativeness of the BIPM is paramount.