

Bathymetries, history of an evolution in precision and performance

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Abstract— Bathymetries are a fundamental element in civil engineering when the work to be made must be based on the study of submerged terrain. In this sense, they are necessary in many situations: marine constructions such as dikes, docks, etc; dredging volume control, river flood study, etc.

Traditionally bathymetries have been a difficult and costly job both in time and effort. However, over time and supported by the development of topographic and geodetic technologies, they have undergone an important transformation and progress in both precision and performance.

In this sense, this article reviews the evolution of the different topographic techniques used over time, emphasizing the investigation and study of the accuracies and efficiencies typical of them; especially those that are used today.

In this way, it can be concluded that, with the appropriate methodology, currently, bathymetries can be made with centimeter accuracy and with an efficiency that can exceed several square kilometers each day depending on the desired accuracy and the conditions of the bottom to be measured.

Keywords—Bathymetry, echosounder, accuracy, GPS, performance.

I. Introduction

Bathymetry can be understood as any topographic operation which object is the measurement of a set of points in order to model an area of submerged terrain, or more generically, it is any process which purpose is the measurement of any type of terrain located under water in a given moment, providing it with coordinates in a given reference system.

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Historically, these types of measures have been complicated because the points to be measured are not directly accessible; having been marginal works due to both the cost and the lack of the obtained precision. So much so, that until recently, bathymetric campaigns were executed in a isolated manner and were very expensive, as well as inaccurate. However, technological advances suffered by topographic devices have revolutionized bathymetries to the point of converting them into highly demanded works and, when properly executed, they provide data quickly, cheaply and with a precision comparable to those obtained with other topography methodologies used in the emerged terrain, presenting specific features: certain typical instrumentation, own methodologies, “blind” elevation models...; and certain similarities: common instrumentation, need for topographic vertices, reference systems ...

Thus, today, bathymetries are required in a multitude of civil engineering circumstances, especially those related to the construction of dykes, docks and submarine emissaries, even in the control of reservoir capacity and control of riverbeds in order to limit the risks of avenues.

This article aims to review those methodologies that have been used in civil engineering, investigating the precision and efficiency obtained in them, making special mention in current methodologies.

II. Instrumental

The special characteristics of bathymetries make the used instrumentation, in addition to having evolved with the advancement of technological development, has elements intrinsic to it. For that reason its study deserves special attention [1].

The first topographic instruments used in the observation of bathymetries were theodolites, which implies the exclusive measurement of angles in order to position the observed points and always following their own methodologies. Some characteristics of this type of works did not require the participation of theodolites with special precision, which led to use theodolites with appreciation of the order of 20^{cc}. These works were not precise but they were laborious.

Subsequently, total stations appeared, which allowed both the measurement of angles and distances, and the storage of these measurements digitally. In its latest evolution, fundamentally motorized stations with prism tracking capacity, often 360°, were used to perform bathymetries.

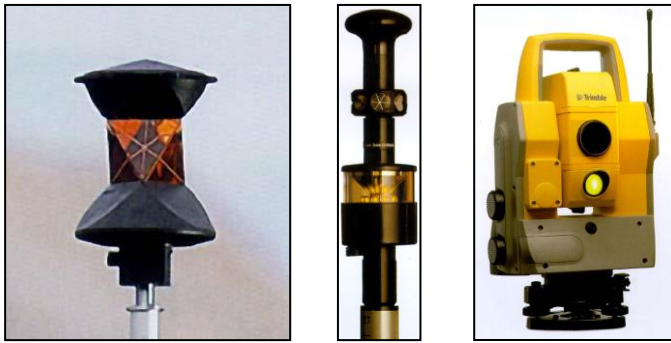


Figure 1. Total Station and total reflection prism. Source Leica and Trimble.

Total stations have now been replaced by GPS receivers. In fact, its appearance has meant a significant improvement in both performance and precision. In general, double frequency GPS receivers operating in RTK mode are used for the observation of bathymetries.

But the most important element of bathymetries might be echo sounders, being an exclusive device of these sort of works. The first operative echo sounder appeared in 1919, created by the German physicist Alexander Behm. But it is with the Second World War and with the development of electronics when this type of apparatus underwent a great technological development until its application in the measurement of bathymetries.

The operating principle of an echo sounder is simple: a certain wave pulse is emitted at a solid angle, at one or several frequencies, towards the bottom and the received echo is processed. By measuring the time elapsed from the emission to the reception it is possible to calculate, knowing the pulse speed in water, the depth existing at that time. Working frequencies can vary from 15 kHz to 250 kHz.

The classification of the echo sounders can be carried out based on several factors, possibly being the most descriptive the following:

- Mono-beam echo sounders: they only emit a wavelength beam at a certain solid angle, between 4° and 25°, obtaining a depth reading per pulse.
- Multi-transducer echo sounders: They constitute the union of several transducer, having become obsolete.
- Multi-beam echo sounders [8]: They are mainly characterized by being able to measure different directions from the vertical, have different transducers for the transmission and reception of sound pulses and operate at frequencies ranging from 12 kHz to 455 kHz. They are widely used today. The usual echo sounders have a single transducer whose pulses are transmitted perpendicular to the path; and a transducer for the reception of the echo equipped with multiple beams (or multiple transducers) that receive the signal according to the direction of the ship's trajectory.

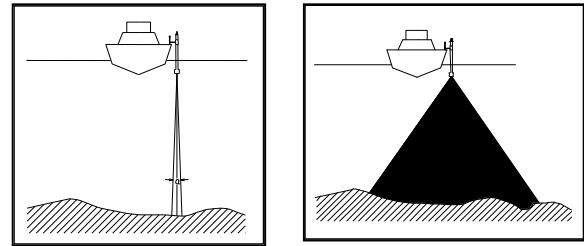


Figure 2. Echosounder mono-beam and multi-beam.

- Interferometric echo sounders: Like multi-beam echo sounders, they are capable of obtaining depths according to measurement angles different from the vertical. However, unlike these, they not only measure the travel time of the pulses, but also interferometric measurements are made, hence their name. They are simpler and cheaper than multi-beam echo sounders but less accurate.
- Side scan echo sounders. They are echo sounders designed to obtain precise but few measures, being used especially for the detection of small objects. They have a single transducer that acts as both the emitter of the sound pulses and the receiver, as well as the mono-beam echo sounders. They use high frequencies in order to reduce the width of the signals, which makes the usual measuring range less than 200 meters.

The working depths of the echo sounders, in any case can exceed several hundred meters.

III. Methodologies.

The different bathymetric methodologies have evolved together with the instrumentation which has been used. In this sense, its classification can be carried out according to these that do not use topographic supports and these that do, which, in turn, will depend on the used instruments.

On the other hand, another classification can be distinguished according to the way of measuring the depth.

This article focuses on the first case, studying and classifying bathymetries according to the method which has been used for positioning, with the consequent variations in depth measurement.

A. Bathymetries based on direct measurements.

These first bathymetric techniques can be considered to be these performed without resorting to the help of any topographic apparatus, being normally these of lesser precision. Different typologies can be distinguished depending on the way that depth is measured:

- Measurement with lead: The measurements are made from profile heads previously arranged on the ground, in such a way that the profiles are sufficiently

representative, placed in esteem or by topographic techniques. In them a slider is attached, a rope graduated by indications which indicate the distance, in this case, to the head of the profile.

- Use of echo sounder: This is a case similar to the previous one, differing in that the depth was measured by first generation echo sounders, which had paper registration.

B. Bathymetries based on measurements made with theodolite.

The position of the element from which the depth was measured was determined by bisection. As in the previous case, the following cases derived from the depth measurement methodology can be distinguished, being the first two similar to these already exposed:

- Measurement with lead.
- Measurement with echo sounder.
- Measurement with surveying rod or similar: this type of bathymetries, as well as these which use total station, has been used for small depths (up to 20 meters depending on the case). For this purpose the aiming element is made integral with a structure, which can be self-propelled, which moves through the area to be measured, usually beaches, including sledges and the so-called Crab.

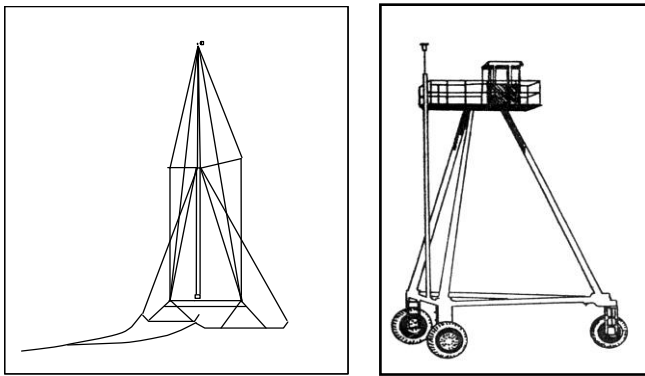


Figure 3. Sled and Crab.

C. Bathymetries based on measurements with total station.

The bathymetries executed in this way, are characterized by the use of total topographic stations, and therefore the points are defined measuring angles and distances. In this sense, the coordinates of a prism or set of prisms are calculated measuring the necessary observables, from a single device. In order to obtain the position of the corresponding submerged point, it is sufficient to add the measured depth value to the Z coordinate. This can be defined in different ways, giving rise, like the previous cases, to several bathymetric methodologies:

- Measurement with lead: In this case its use has been normally restricted to small rivers that due to its flow rate did not allow another measurement system.
- Measurement with surveying rod or similar: As it has been explained, structures have been used, and are still in use, to carry the prism. The position of the points, which are usually located on beaches, is determined by trigonometric levelling.
- Measurement with digital echo sounder: Once the technology advanced sufficiently, echo sounders with digital depth recording began to be used. In this way, and following several methodologies, the depth measurement that corresponds to the observation from the total station is sought, either by recording the time or with a motorized station. This type of methodology is called polar bathymetry.

D. Bathymetries with GPS.

Conceptually they are similar to these previously exposed, except that the “positioner” system is GPS and the depth is obtained from means of a modern echo sounder and digital record. The process of carrying out bathymetries is, at present, practically automatic, being able to take data continuously and emerging new unknowns in the measurements performed.

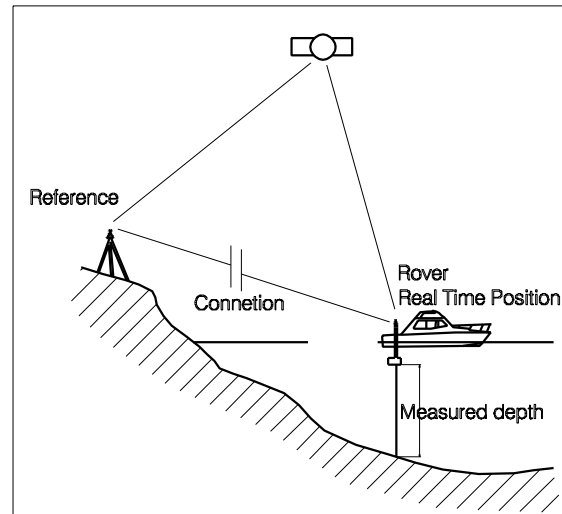


Figure 4. Bathymetry with GPS.

These methodologies are, today, the most common when it is necessary this kind of work in civil engineering. The different varieties that can be found are defined from the echo sounders which is used. All of them are based on time synchronization between the GPS and the echo sounder measurement.

iv. Accuracy and performance.

Bathymetries have certain peculiarities which make the study of their accuracy and their performance very variable. External aspects such as waves and other features of this type of work, such as the nature of the measured background, the

error in time synchronization, etc. make both, precision and performance, have this characteristic of variability [5].

This article will only study these aspects derived from the bathymetry measurement, omitting those related to other aspects such as modeling errors, representation, etc.[2]

A. *Bathymetries based on direct measurements.*

The precision that it is possible to obtain is, in any case, quite poor and will depend on many factors: state of the surface of the water (waves), currents, quality of the slide and lead, etc. A typical quantification could be defined in the following values: Planimetric error 2 meters, altimetric error: 1meter. Although, in both cases they could be greater depending to a large extent on the conditions previously stated.

It is noteworthy that the made errors will be significantly smaller in the vicinity of the head of the profile, being able to rocket with respect to planimetric positions when a measurement is taken away from it, and especially with unfavorable conditions of wind and waves, so observations remote from the coast line have never been advisable.

The performance is also a few points per hour, depending largely on the distance between them in the profile. In addition, there is a large number of down times, understanding as such these occupied in the change of profile, movement of the boat, etc.

B. *Bathymetries based on measurements made with theodolite.*

The accuracy, in this case, compared to the case described above, is significantly better, especially in the planimetric positioning of the point to be measured. However, a fundamental factor is the difference between the point which has been referenced with theodolites and the place where the depth measurement is performed. The immediate consequence is that the tolerances will depend on the type of existing bottom, in any case some indicative values might be: 1 meter in planimetric error, up to 1 meter in altimetric error depending on the bottom. It should be borne in mind that these error ceilings are also strongly influenced by the conditions of the measurement: waves, lead quality, currents, wind, etc.

The performance is also a few points per hour, depending largely on external factors such as waves and wind that can make it difficult to position the boat, etc. In addition, the “down times” between measures are significant, which makes the bathymetries observed in this way laborious and long.

C. *Bathymetries based on measurements with total station.*

The precision which is obtained in the bathymetric work can be established according to the planimetry and altimetry separately.

The first one depends primarily on radiation. The altimetric precision depends largely on the situation of the lead, since this is really the place where the depth is determined, and not on the vertical of the aiming element. Therefore, the uncertainty depends on the underwater topography in the sense that for substantially uniform bottoms this will be less than for irregular, rocky and large uneven bottoms.

It is possible to carry out the opposite development, that is, for the point at which the depth is determined with the lead's own precision (dependent, in turn, on its appreciation, modulus of elasticity, inclination, etc.), determine the planimetric precision that will be the composition of the uncertainty of radiation and the relative situation between the lead and the prism. In this case the correct verticality of the depth measurement is critical.

This given peculiarities, of each bathymetry, makes difficult to define standard values for uncertainty. However, a ceiling that should never be reached could be: altimeter accuracy of 1 meter and 0.5 meters of planimetric uncertainty.

The performance of this bathymetries is penalized by the form of depth measurement which, many times, is slow and not very accurate.

External factors such as depth, currents, wind, etc. can slow down depth measurements with what the performance can become, as indicative values, from about 10 points / hour to 5 points / hour.

An exception to this is when an echo sounder is used, especially if it is digital. In this case, the performance can be reach about 200 points per hour as an average value. Its variability will be produced by the distance between points to be measured and waves, mainly.

D. *Bathymetries with GPS.*

Precision bathymetries with GPS have a large number of error sources. Some of them are common with the methodologies already described, but others have not been previously studied since the maximum accuracy that could be achieved masked their effect.

As described, this article focuses exclusively on these that depend on the depth measurement itself. In this way, the depth measurement is affected by a set of uncertainties and can be expressed as follows:

$$P_v = P_m + \Delta_{rs} + \Delta_{cs} + \Delta_{co} + \Delta_{mo} + \Delta_{of} \quad (1)$$

Where: P_v is the real or true depth; P_m is the depth obtained in the echo sounder; Δ_{rs} is the uncertainty produced by system delays; Δ_{cs} is the uncertainty due to probe calibration; Δ_{co} is the uncertainty produced by the effect of the cone of waves and the terrain; Δ_{mo} is the uncertainty about the lack of verticality of the probe foot; and Δ_{of} includes the rest of the other factors that influence the value of the depth reading.

The term corresponding to the system delays reflects the time difference between the GPS measurement and the echo

sounder. Today there are methodologies to minimize it (profiles in both directions, cross-point method)[4], and may not have a very important impact since its value is usually very small.

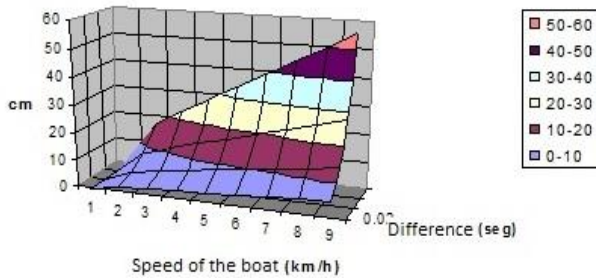


Figure 5. Positioning error due to lack of measurement synchronization (cm)

Echo sounder calibration, or calculation of the speed of sound in water, is another essential factor of any bathymetric campaign. Therefore it is an operation that is performed before any measure. However, this value may vary along the water column, so if necessary it would be convenient to model it [3], [6]. In the field of civil engineering, this occurs occasionally, since the usual depths are small. Its variation responds to the following expression [7]:

$$v = 1449.2 + 4.6 T - 0.055 T^2 + 0.00029 T^3 + (1.34 - 0.01 T) (S - 35) + 0.016 Z \quad (2)$$

Where v is the speed of sound in water; T the temperature expressed in ° C; S the salinity expressed in parts per thousand; and Z the depth in meters.

Calibration should be carried out whenever and when a significant change in the characteristics of the water is suspected since its influence can lead to an error of up to 15% of the depth.

The influence of the effect of the cone of emission of waves and the inclination of this one, cause that the measured depth does not correspond to the planimetric position that is assigned to it. To minimize the effect of the inclination, an inertial system is available on the ship that allows determining the direction of each of the measuring beams.

The effect of cone of emission of waves and the terrain is a field in which it is still investigating and that has the effect that the depth is not obtained in the axis of this cone but in another point that can become at the end of it.

Together these types of bathymetries, made the corrections indicated, produce an accuracy of centimeters, which together with the uncertainties not addressed in this article provide accuracies according to a 1/500 scale.

In terms of performance it is important to note that in addition to the environmental conditions and the measured terrain, it depends largely on the type of echo sounder used. Thus, for a mono-beam echo sounder, they can be measured in

the order of 2000 points per hour, which, depending on the topography of the bottom, results in surveys of several hectares per day. In the case of multi-beam echo sounders, the performance is multiplied by the number of beams available. Thus it is not uncommon for several hundred thousand points per hour to be measured. As for the covered area, it will correspond to tens of hectares per day, although with a higher density of points than in a survey with a single beam echo sounder.

v. Conclusions

From the above, the exponential advance is shown in both precision and performance in modern bathymetries. However, effects that previously went unnoticed now have great importance.

In this sense, in open areas, bathymetries provide cartography with 1/500 precision or, sometimes, better. However, in areas of more difficult access, for example in rivers [9], often not so modern techniques are used, for example a total station.

Other techniques such as surveys with Lidar have not been studied since, due to cost, their use in civil engineering is residual, however, it is expected that in the future this type of sensors mounted on drones will appear.

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