Development of Bathymetric Techniques

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ABSTRACT

Preparation of modern nautical charts which are very essential to marine commerce safety, location of underwater works, coastal zone management, volume of underwater excavation, volume of water in lakes, fish and mineral industries are examples of application of underwater depth.

Historically, the first hydrographic method used in water depth determination was the sounding line which has then been replaced by the acoustic sounding techniques that solved the problem of deep water depth measurement. Both techniques were shipboard instruments that have the limitation of efficiency and time consuming. This is why a vast area of world water bodies are still not covered for water depth determination.

Recent techniques, all classified as remote sensing techniques including airborne LIDAR, airborne and satellite sensors that work with optical or radar waves are used to determine water depth especially for vast water areas such as seas and oceans.

This paper is an attempt to review techniques used for water bathymetry, comparing them as far as accuracy, limitations, cost and efficiency. Some examples of applications of recent methods will be outlined too.

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Introduction

Preparation of modern nautical charts are very essential to marine commerce safety, location of underwater works, coastal zone management, volumes of underwater excavation, volume of water in lakes, fish, ship and mineral industries are examples of application of underwater depth. Knowledge of ocean bathymetry is important not only for navigation but also for scientific studies of the ocean's volume, ecology, and circulation.

Water depth determination (usually called sounding or bathymetry) has passed long way of development, starting from rope (lead line), passing through acoustic techniques, air borne sensors and now satellite borne sensors.

This paper is an attempt to review these developments, considering merits and disadvantages of the techniques.

Early History

The first evidence that man was measuring the depths is found in tomb paintings of ancient Egypt dating from 1800 B.C. The bas-relief carvings of Deir al-Bahri were ordered by Queen Hatshepsut to commemorate a voyage to the land of Punt in approximately 1500 B.C. One of these carvings shows a man using a long slender pole as a sounding pole on the bow of a large vessel under oar and sail (Soule 1976). There are also paintings of men taking deeper soundings by means of a weight attached to a line dating from this period (A. Theberge, 1989).

The Greek historian Herodotus writes of a sounding in 66 feet of water, far offshore from the mouth of the Nile River, bringing up yellow mud similar to that deposited on land by the annual flood of that great river.

About 100 B.C., Posidonious lowered a line into the Mediterranean. Strabo, a Greek geographer is quoted: "The sea of Sardinia, than which a deeper sea has never been sounded, measuring, as it does, according to Posidonius, about 1,000 fathoms – one fathom is equal to 1.8m (Soule 1976)." This isolated incident marks the only successful recorded deep sea sounding in the entire history of mankind up to that time and remained so for the next 1900 years (Theberge, 1989)

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Figure 1. Lead Line (www.lanfallnavigation.com)

By 1584 Lucas Jans Waghenaer of Holland had published his famous atlas *Spiegel der Zeevaert* which included some of the earliest charts showing actual depths.

On September 4, 1773, Captain Constantine John Phipps lowered a line with a 150-pound weight attached from H.M.S. RACEHORSE into the Norwegian Sea. He sounded and found 683 fathoms with a very fine blue soft clay bottom (Deacon, 1962). It is noted that Ferdinand Magellan attempted to sound off the Unfortunate Islands on January 24, 1521, and found no bottom (Morison 1978). Various accounts state that he put out anywhere from 200 to 750 fathoms of line before giving up.

Improved Mechanical Sounding Devices

Charles Wilkes, while leading the United States Exploring Expedition (1838-1842), was the first to attempt using wire as opposed to heavy rope for sounding. Because Wilkes used copper wire, the tendency of the line to break, kink, and snarl far overcame any speed of sounding increase. As a consequence Wilkes gave up, although his first sounding on the Antarctic shelf in 320 fathoms was with copper wire (Stanton 1975). In 1840 Sir James Clark Ross conducted the first open ocean deep-water sounding in 2425 fathoms in the South Atlantic at Latitude 27° 26'S, Longitude 17° 29'W (Deacon 1962). Deep-ocean sounding was given added impetus by the desire to lay a Trans-Atlantic cable. By the mid 1850's sufficient depth information had been acquired that Lieutenant Matthew Fontaine Maury, the "Pathfinder of the Seas", was able to publish the first bathymetric map of the North Atlantic Ocean basin. However, many of the soundings on this map were erroneous and, coupled with the paucity of data, led to missing of some major features and the delineation of some features that did not exist.

Mechanical sounding instruments took a leap forward in 1872 with the invention of a sounding machine using small diameter pianoforte wire. This machine was introduced by Sir William Thomson (later Lord Kelvin). In 1872, Sir William made a test of this instrument from his private yacht, and described this first successful wireline sounding (Agassiz 1888).

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Sir William Thomson also invented the pressure tube method of sounding which became known as "self-acting sounding" (U.S. Naval Hydrographic Office 1962). This method allowed the ship to continue steaming while dropping the sounding tube over the side. It used a long sinker equipped with tubes lined with silver chromate. The compression of the air in the tubes indicated by the white line of the silver chromate, was a measure of water depth. By 1888 the steamer BRITANNIC had sounded using this method in one hundred and thirty fathoms over the Newfoundland Banks while cruising at sixteen knots (Agassiz 1888).

Although Sir William invented the pianoforte wireline sounding instrument and provided the great CHALLENGER expedition with his instrument, the British naturalists chose to use the Baillie sounding machine, a fibre-line machine using hemp No.1 line weighing 200 pounds to the nautical mile, for the 363 soundings taken during the four-year expedition. It remained to the Americans to perfect the use of wire sounding (Tanner 1897).

Commander Tanner invented a shallow water wire sounding machine called the Tanner sounding machine.
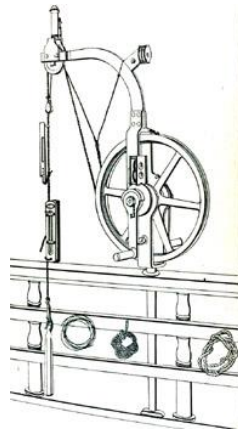

Figure 2. Tanner Sounding Machine (Tanner, 1897)

Many variations of the wireline sounding machine were developed over the next 50 years, most notably the Lucas Sounding Machine which was primarily used on British ships and the LL type and Deep-sea sounding machines used by the Coast and Geodetic Survey (C&GS).

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Figure 3. Leadline sounding operation in the 1930s
(celebrating200years.noaa.gov.transformation/hydrography/side.html, revised 2012)

Taking soundings, or casts of the lead, is done when the vessel has headway on, the leadsman casting the lead forward and getting the depth as the vessel passes over the lead, resting on the bottom.

While these measured depths were accurate, they were limited in number. Information between the soundings was missing, so that mariners would often be unaware of bottom features and depth information necessary for navigation safety.

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Early Echo Sounding

Aristotle was one of the first, if not the first, to recognize that sound could be heard in water as well as air. Two millennia later, Leonardo da Vinci observed that by placing a long hollow tube in the water and the other end to the ear one could hear ships from far away. Francis Bacon also discovered that sound can travel through water.

In the mid-eighteenth century, scientists began experimenting with sound in water. In 1807, Dominique Francois Jean Arago made the specific suggestion that water depths might be measured by sound propagation, although, unfortunately he did not act on this proposal (Adams 1942). In 1826 Daniel Colladon and Charles Strum made measurements of the speed of sound in Lake Geneva that averaged 1435 meters per second and reported on the work of Francois Sulpice Buedant, who measured an average sound velocity of 1500 meters per second in the sea off Marseilles in 1820 (Hersey 1977). In 1859, Matthew Fontaine Maury wrote of various methods and suggestions for using sound to measure ocean depth (Maury 1859).

In 1901, the Submarine Signal Company was formed and provided underwater signaling devices to the United States Lighthouse Service. In 1910, the brilliant Reginald Fessenden joined the company. He invented an oscillator in 1911 that he steadily improved. Within a few years, his massive 250kg transceiver went to sea on the U.S. Coast Guard Cutter MIAMI, and on April 27, 1914 he was able to detect an iceberg over 20km away (Bates et al. 1987). This breakthrough paved the way for rapid advances in sounding technology over the following few years.

In 1922 U.S.S. HULL were equipped with a Hayes Sonic Depth Finder and produced the first bathymetric map based solely on echo sounding. This map covered the area of the Southern California Continental Borderland (Nelson 1982).

Improved Echo Sounding Systems

In the late 1950's and early 1960's a number of evolutionary concepts were advanced to determine water depth using sound signals. Sidescan technology was developed as a qualitative means of obtaining the sonar equivalent of an aerial photograph.

The first operational Sonar Array Sounding System (SASS) was developed by General Instrument Corporation, GI, using fan beam technology (White 1989). The SASS mapped a swath of seafloor by using beam-forming techniques to obtain up to 61 individual depths for each emission of the sonar system and, by so doing, developed a high resolution contour map of the seafloor. Narrow Beam Echo Sounders (NBES) of two and two third degree beam width were developed by GI.

With these new systems it was possible "to fill in the details". Although it is tempting to believe that the final word in defining the seafloor is occurring with swath mapping technology, it is more probable that succeeding surveyors and cartographers will have access to ever more

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advanced technology of higher resolution. Faster techniques such as airborne laser hydrography for the near-shore area and high resolution systems such as interferometric side scan sonar systems, providing both imagery and bathymetry, are already emerging as operational tools for the modern hydrographic surveyor.

The invention of sonar changed the way that the seafloor is mapped. A combined transmitter and receiver, called a transducer, sends a sound pulse straight down into the water. The pulse moves down through the water and bounces off the ocean bottom. The transducer is able to pick up the reflected sound. Computers precisely measure the time it takes for the sound pulse to reach the bottom and return.

The primary disadvantages of acoustic measurements are the time and cost associated with making measurements from a ship in deep waters or a small vessel in shallow waters. - In order to build up coherent images at high resolution many survey lines with overlapping tracks must be run. This is why other techniques are searched to promote the speed of water depth collection.

Radar Bathymetry

According to the laws of physics, the surface of the ocean is an "equipotential surface" of the earth's gravity field. These bumps and dips in the ocean surface are caused by minute variations in the earth's gravitational field. For example the extra gravitational attraction due to a massive mountain on the ocean floor attracts water toward it causing a local bump in the ocean surface; a typical undersea volcano is 2000 m tall and has a radius of about 20 km. This bump cannot be seen with the naked eye because the slope of the ocean surface is very low.

These tiny bumps and dips in the geoid height can be measured using accurate radar mounted on a satellite. Radar signals sent from satellite are reflected from the surface of the sea. Rough surface given different reflected intensity than smooth one. Surface roughness is a function of the underwater topography. Hence, a relation between satellite sensor received signal density and underwater topography can be detected.

Examples of Tests of Radar Bathymetry

Ludeno G, et al, tested Marine X-band radar based systems to provide information about sea state and bathymetry. It is also well known that complex geometries and non-uniform bathymetries provide a much bigger challenge than offshore scenarios. In order to tackle this issue a retrieval method was proposed, based on spatial partitioning of the data and the application of the Normalized Scalar Product (NSP), which is an innovative procedure for the joint estimation of bathymetry and surface currents.
The strategy is then applied to radar data acquired around a harbor entrance, and results show that the reconstructed bathymetry compares well with ground truth data obtained by an echo-sounder campaign, thus proving the reliability of the whole procedure.

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Ziemer, F. et al, (2004) presented preliminary results from the OROMA project (Operational Radar and Optical Mapping in monitoring hydrodynamic, morphodynamic, and environmental parameters for coastal management). They gave an overview on the flow of information within the project in addition to an example on one of the methods used, which is the inverse modelling of radar observations, to measure bathymetry.

Giovanni, L., et al (2015) tested Marine X-band radar based systems to provide information about sea state and bathymetry. It is also well known that complex geometries and non-uniform bathymetries provide a much bigger challenge than offshore scenarios. In order to tackle this issue they proposed a retrieval method based on spatial partitioning of the data and the application of the Normalized Scalar Product (NSP), which is an innovative procedure for the joint estimation of bathymetry and surface currents. The strategy was then applied to radar data acquired around a harbor entrance, and results show that the reconstructed bathymetry compares well with ground truth data obtained by an echo-sounder campaign, thus proving the reliability of the whole procedure. The spectrum thus retrieved was then analyzed to show the evidence of reflected waves from the harbor jetties, as confirmed by chain of hydrodynamic models of the sea wave field.

Water depth from Optical Light

Lyzenga (1978) reviewed Ratio processing methods, and proposed a new method for extracting water depth and bottom type information from passive multispectral scanner data. Limitations of each technique are discussed, and an error analysis is performed using an analytical model for the radiance over shallow water

Lyzenga (1985) described a method of measuring water depths using a hybrid airborne sensor which incorporates both a lidar system and a passive multispectral scanner system. The methods of processing the data collected by this sensor are described and results are presented for data from two test sites in the Bahama Islands. Errors in the depth measurement are quantified, and an analysis of the probable source of these depth errors is presented.

Recently, developments in light and imaging technology have been made to help make more quantitative assessments of bathymetry. In the past, cameras were utilized to get a qualitative measure of the conditions in benthic habitats. These cameras could be handheld by divers, pulled behind boats and ships, or attached to a remote operate vehicle (ROV). However, capturing a complete image of the benthic habitat by these methods is often time-consuming, as cameras have a limited spatial coverage, defined by the lenses used. For this reason, wider scanning techniques, such as acoustical surveys or satellite mapping, are employed first.

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In contrast, Laser Line Scanning (LLS) is bridging the gap between side-scan sonar and still photography/video, with a modest scope and high resolution, typically 0.1-1 cm. However, the technology is still new and in the trial phase, and is not yet widely available.

All light and imaging techniques are dependent on the water clarity and focal distance. Thus, all light and imaging techniques are susceptible to error with murky water.

Fonstad et al, (2005) used a combination of remote sensing imagery and open-channel flow principles to estimate depth for each pixel in an imaged river.

Bell (1999) used X-band marine radar data to determine shallow water bathymetry. The calculated depths were comparable to those given by admiralty chars.
To illustrate the improvement possible, these maps show how Appalachia and the Grand Canyon would look if the topography had been generated by the space bathymetry technique using existing data left image, and data that are less noisy by a factor of four right image. The better data show faults and drainage patterns in the Grand Canyon, and individual ridges and valleys and their curvature in the Allegheny Mountains (Sandwell, et al 2002).

A new space bathymetry mission would furnish—for the first time a global view of the ocean floor at the proper scale to enable important progress in basic and applied science. Ocean and climate modelers and forecasters would be able to account for how the ocean bottom steers currents and how bottom roughness controls the mixing of heat, greenhouse gases, and nutrients. The details of the tectonic and volcanic processes that shape the ocean floor could be studied in their full complexity, beyond the over-simplified view given in the plate tectonic theory. The hazards to coastal communities posed by tsunamis could be more realistically assessed, as fi ne-scale bathymetry determines the likelihood of undersea earthquakes and landslides, the propagation of tsunami waves generated by these sources, and the height of the wave that ultimately arrives at the coast.

Algorithm Description for optical (MSS and TM imageries) Bathymetry

A simple water reflection model (Lyzenga, 1978) relates water depth and the radiance in a single band as:

$$L_i = L_{si} + K_i\, R_B \exp(-K_i f Z_i) \text{ ----------------------- (1)}$$

Where k_i is a constant which includes solar irradiance, the transmittance of the atmosphere and the water surface and the reduction of the radiance due to refraction at the water surface, Ls_i is the radiance observed over deep water, R_B is the bottom reflectance, K_i is the effective attenuation of water, f is a geometrical factor to account for path length through water and Z_i is the water depth.

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Rearranging Eq. 1 for a water depth determination algorithm gives

$$Z_i = [\ln C_{1i} - \ln (L_i - C_{2i})] / C_{3i} \text{------------------------(2)}$$

Where $C_{1i} = K_i R_B$, $C_{2i} = L_{s1}$ and $C_{3i} = K_i f$
By defining $X_i = \ln (L_i - L_{si})$, the water depth, Z (determined with data from multi bands), can be written as a linear combination of logarithms of the radiance (Paredes and Spero 1983)

$$Z = b_0 + b_1 X_i + \ldots b_n X_{n .} \text{------------------------------------ (3)}$$

Where n < 3 in this case, and b_0, $b_1 \ldots b_n$ are the regression coefficients.

Eq. 3 is based on the hypothesis that the bottom reflectance and the water composition remain constant within the major part of the image and that the signals in all three bands are influenced by the bottom reflection.

Applications of Optical Imagery in Bathymetry

Derivation of bathymetry from multispectral imagery in the highly turbid waters of Singapore's south islands was carried out by Bramnte, et al. They used four algorithms for the determination of bathymetry from multispectral imagery (8-band images from DigitalGlobe's Worldview-2) satellite. All four were evaluated for accuracy in Singapore's extremely turbid coastal waters and were used to evaluate the effects of Worldview-2's additional four multispectral bands. Of the four, the linear band algorithm developed by Lyzenga et al. and a comparative classification algorithm performed best, with normalized RMSE of 0.229 and 0.313 meters, respectively. The additional four bands provided by Worldview-2 decreased RMSE by 9% and 27% for these two algorithms, respectively.

William D. Heyman (2008) developed an automated method for calibrating the parameters for a non-linear inversion model. The method has been successfully applied to an IKONOS multispectral image. We compared depth data derived from our model to those estimated using a conventional log-linear inversion model. Bathymetric data derived from the non-linear inversion model are slightly more accurate and stable, particularly for deeper benthic habitats, than those derived from a conventional log-linear model although their overall performances are very similar.

G. Doxani, et al (2012) tested the potential of 8-bands image acquired by Worldview-2 satellite in providing precise depth measurements. Multispectral image information was integrated with available echo sounding and GPS data for the determination of the depth in the area of interest. The existence of sea grass in a part of the study area influenced the linear relationship between water reflectance and depth. Therefore the bathymetric model was applied in three image parts: an area with sea grass, a mixed area and a sea grass-free area. In the last two areas the model worked successfully supported by the multiplicity of the imagery bands.

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Sarker (2012) made an attempt to prepare a digital map showing the distribution of bathymetry and SST using Landsat-TM data over coastal area of Bangladesh. The average water depth depicted this image in between 1 to 12.5 meter.

Abduallah (1991) studied the feasibility of using SPOT and Landsat TM data for bathymetric studies on coastal areas near Qatar and the United Arab Emirates. They have used one SPOT and two TM sets of data. The applications of single band, two band ratio and three-band hybrid and principal components methods were investigated. Accurate geometrical rectification of each data set was first performed. Test areas were selected for the calibration of depth-intensity algorithms for each data set using known sounding points. The algorithm was first tested with other known sounding points within the test area and then used for two previously unscrewed areas with each data set. The investigation showed that new information about the depth of the water in relatively shallow areas can be obtained from these types of satellite data. They concluded that the use of multiple band regression is superior to the exclusive use of any single band. Better accuracy is expected in the multiband algorithms if the statistics of the deep water radiance in all the bands considered are known.
The residuals generally increase with depth in all cases and therefore it is necessary to include an estimate of depth measurement errors in the least squares regression to minimize inaccuracy at high values of estimated water depths.

Merits of different techniques

The advantage of depth sounders is that they are commonly available at a relatively low cost. Acoustics can be adapted to scan beneath the water bottom's surface (sub-bottom profiling), scan across a seabed to identify bathymetric qualities, and combined with others to provide higher resolutions.

However, acoustic surveys are typically time-consuming, as they typically have a relatively narrow scope. Most acoustic surveys cover approximately 10% of the water depths in an area, leaving many gaps. Multi-beam depth sounders, which scan wider area, are more costly and usually require additional monitoring tools. Scanning across a seabed offers a relatively wide coverage area, but lacks detail, and requires sampling to support findings.

Acquiring an image over a vast area, a great deal of information can be delineated from a satellite or aerial image in a short amount of time.

However, satellite imagery and aerial photography are best used in conjunction with other bathymetry techniques to create a complete bathymetric mapping. Typically, satellite and aerial images are of low-resolution, and cannot be used by themselves to determine bathymetry. Furthermore, environmental conditions, such as cloud cover, haze, waves, and water turbidity, can reduce the quality of the images.

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