Performance assessment of a bathymetry system in open inland waterbodies

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Bathymetry of an open waterbody can be estimated remotely using airborne and space-borne sensors with wide coverage. However, unmanned aerial vehicle (UAV)-borne bathymetric systems are current trends for applications with limited depth subjected to the quality of water. Estimation of accurate bathymetry using surface-based sensors is essential for validating the remote sensing-derived results. To cater to the requirements of the *in situ* measurement system, especially for supporting the airborne (aircraft/UAVs) remote sensing-based bathymetry systems, a customized and compact, immersion-type bathymetry system using single-frequency (typ. 500 kHz) transducer was developed in-house at the National Remote Sensing Centre (NRSC), ISRO, Hyderabad. In the present study, we assess the performance of the developed system in the field against physical measurements and a reference acoustic transducer for shallow and deep inland open waterbodies. Performance testing was carried out in the Asan Lake, a shallow waterbody, with a depth of up to 4 m and in the Tehri reservoir for deep bathymetry with a depth of more than 150 m. The results show that the estimated TVU for the developed system during shallow bathymetry assessment was 0.272 m which complies with the IHO order 1. The observed performance of the developed system was consistent with the system specifications, which advocate its utility for hydrology and water resource management applications along with its intended use to support remote sensing-based bathymetric systems.

Keywords: Acoustic transducer, bathymetry, echo sounder, waterbodies, water-depth measurement.

ACCURATE water depth estimation is essential in many applications of hydrology and water resource management. Bathymetry[1], water depth estimation, is a fundamental parameter for studying underwater topography of sea and inland waterbodies like lakes, rivers and reservoirs. In remote sensing, the bathymetric information of open waterbodies is usually derived indirectly through empirical methods from space-borne imaging and/or non-imaging type sensors with wider coverage[2–6]. Moreover, active remote sensing using airborne sensors like bathymetric lidar (light detection and ranging) is also being used to get direct measurements of depth with limited coverage compared to space-borne sensors[7–9]. Unmanned aerial vehicle (UAV)-borne bathymetry lidar systems are the current trend for bathymetry applications with limited depth subjected to water quality parameters, mainly turbidity[10–13]. The depth estimations either by satellite or airborne sensors (aircraft/UAVs) need *in situ* data to evaluate the efficacy of the methods/models. Therefore, the performance of the *in situ* bathymetry systems is critical for the validation of bathymetric estimations by space-borne and airborne sensors. Traditionally, acoustic transducers, also called echo sounders, are being used as *in situ* sensors which include mainly single-beam and multi-beam-type transducers. Preferably detailed underwater topography studies are carried out using multi-beam transducers, however, single-beam transducers are widely used as depth profilers in water-borne platforms such as classical boats, ships and remotely operated vehicles (ROVs)/unmanned surface vehicles (USVs) with other supplementary sensors. The acoustic transducer measures depth by the propagation of an acoustic signal in the water column to the water bottom and receives back the reflected signal, similar to the lidar system using the time-of-flight principle.

System overview

To serve the requirements of an *in situ* measurement system, especially for airborne (aircraft/UAVs) bathymetric systems, a customized and compact immersion-type bathymetry system was developed at the National Remote Sensing Centre (NRSC), Indian Space Research Organisation (ISRO), Hyderabad (Figure 1). This system can measure water depth up to 100 m. It also measures surface dissolved oxygen (DO) and water temperature along with geo-locations in a synchronized manner[14].

The system comprises a single-beam acoustic transducer (typ. 500 kHz), an optical-type DO transducer, an integrated temperature and attitude sensor, a survey-grade Global Navigation Satellite System (GNSS) receiver and acquisition hardware with on-board data storage using a removable memory card. Power to the system is supplied through a compact lithium polymer rechargeable battery with resulting endurance of 3.5 h on a single charge. Table 1 lists the

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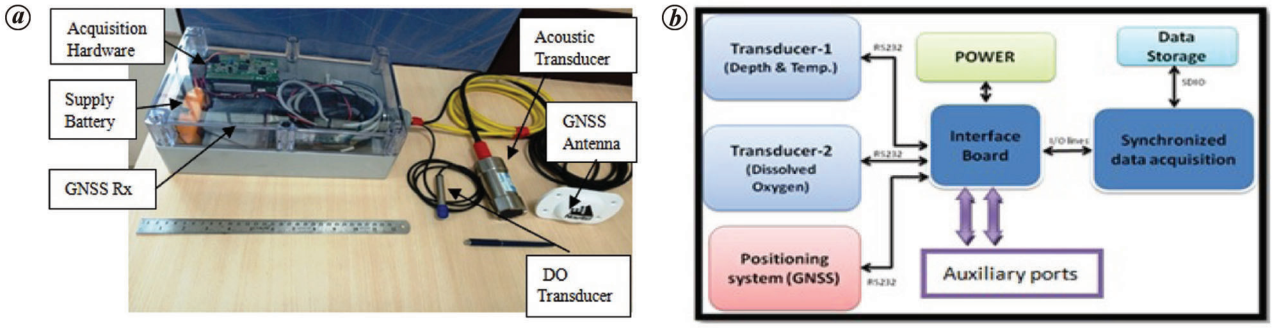

Figure 1. ***a***, Field model of the developed system. ***b***, Block diagram.

Table 1. Technical specifications

System parameters	Specifications
Acoustic transducer (single-frequency)	Depth range: Up to 100 m Frequency: Typ. 500 kHz Accuracy: <1 cm ± 0.1% of depth Resolution: 1 mm Swath coverage @ 10 m Depth: 1.04 m
DO transducer	Measurement range (optimal): 0–22.5 mg/l Resolution: 0.4 mg/l ± 0.009 mg/l
Temperature	Operating: –10°C to 40°C
Attitude	Heading: ± 180° Pitch, roll: ± 90°, ± 180°
Geo-position	Post-processing position accuracy: <15 cm
Power consumption	<5 W
Physical dimensions ($L \times W$)	11.8 × 9.4 inches
System weight	4.3 kg
Waterproof rating	IP68

technical specifications. Moreover, provision for two auxiliary ports has been made in the system for the users to add additional water quality assessment sensors such as turbidity, pH, etc. for use in specific applications like water pollution assessment and aquaculture studies.

The features of the developed system include customization, portability, attitude compensation and PPS-synchronized on-board data logging.

Compact size of the developed system makes it suitable for installing ROV/USV platforms results in minimizing the logistic efforts during field activity. However, the system provides measurements using a single-frequency acoustic transducer, which limits its usage in direct silt estimation studies, where dual-frequency transducers are preferred.

Background about echo-sounder evaluation

The calibration of echo sounders in the control environment was carried out by higher-precision measuring instruments such as total stations and GPS[15], simulation methods[16], and standard sphere calibration described in the literature[17,18]. However, the sphere calibration method consumes expensive survey time and has limitations[19]. The field performance of an echo sounder can be estimated through the comparison method described by Demer *et al.*[17], along with other methods. The comparative measurements can be acquired using a reference echo sounder, preferably of distinct acoustic frequency, to avoid interference in simultaneous operation and closeby installation[20]. Moreover, a reference echo sounder with the same acoustic frequency of the test echo sounder can be used by ensuring non-interference data acquisition.

In this study, we assess the bathymetric performance of the developed *in situ* bathymetry system in shallow and deep inland open waterbodies against feasible physical measurements and a reference echo sounder with a distinct frequency.

Materials and methods

Study area and reference echo sounder

The study area includes Assan barrage (site-1), locally known as Asan Lake, located (30.4358°N, 77.6657°E) on the Asan River, a tributary of River Yamuna, for shallow bathymetry and Tehri reservoir (site-2) for deep bathymetry (30.3781°N, 78.4804°E), in Uttarakhand, India. Figure 2 is a satellite map (Google Earth) showing the study areas (orange colour).

The availability of boats and other resources for conducting the testing with the necessary permissions of control authority was the rationale for selecting these sites for conducting performance analysis of the developed bathymetry system.

Under shallow bathymetry evaluation, physical depth measurements and integrated echo sounder of commercial-grade EchoBoat (Figure 3; yellow colour), of Indian Institute of Remote Sensing (IIRS), Dehradun, were used as references for validation of the developed bathymetric system. During deep bathymetric assessment, due to some technical issues, the echo sounder of EchoBoat did not work for a depth range greater than 20 m. However, a fishfinder echo sounder, Hondex (HE-51C), available with IIRS, Dehradun, is used as the reference echo sounder, which operates at 200 kHz acoustic frequency[21].

Shallow and deep bathymetry samples

At site-1, the acoustic transducer of the developed bathymetric system was also mounted on the EchoBoat using locally fabricated mechanical provision and horizontally aligned with the integrated echo sounder of EchoBoat. Both the reference and the developed bathymetry system data were recorded at 1 Hz sampling rate. As shown in Figure 3, the EchoBoat with the installed acoustic transducers of the developed system was dragged with a passenger paddling boat (blue colour) provided by the lake authority. Both sounder measurement data were collected by the team along with physical measurements at feasible location points using standard measuring tape mounted on a light-weight plastic pole of 6 m height (Figure 3).

Under deep bathymetry testing at site-2, the reference fishfinder probe and acoustic transducers of the developed system were mounted on either side of the fabricated mechanical fixer installed on the EchoBoat. The display and monitoring units were placed in the engine-operated boat provided by Tehri Hydro Development Corporation (THDC) India Limited (Figure 4 *a*; window at right bottom).

During operations, the EchoBoat was maintained at a safe horizontal distance from the engine-operated boat using galvanized iron (GI) pipe manual arrangements to avoid collision (Figure 4 *a*). However, during deep bathymetry performance testing, where physical measurements were not feasible, fishfinder data were recorded manually, as this echo sounder only displays the depth measurement and does not have the provision for measurement storage in the unit. The operator manually measured the developed bathymetry system and reference fishfinder by using the monitor to display at every significant change in observation along the trajectory path of around 4 km (Figure 4 *b*; dark green colour).

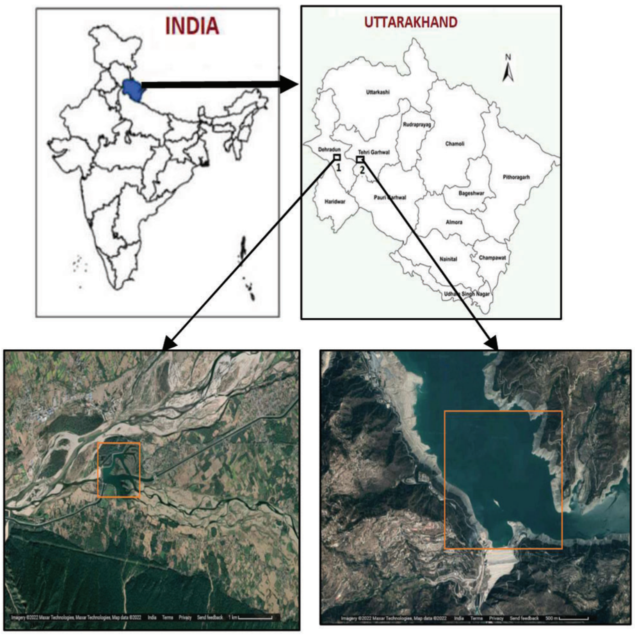

Figure 2. Testing sites – site-1: Asan Lake and site-2: Tehri reservoir.

Accuracy/uncertainty estimation

The sources of uncertainty include platform, sensor measurement, environment, system integration and synchronization, etc.[22]. However, as summarized by the International Hydrographic Organization (IHO) Standards for Hydrographic Surveys[23], the primary factors contributing to vertical uncertainty of an echo sounder include (a) vertical datum uncertainty, (b) uncertainties of vertical positioning system, (c) uncertainties in water-level measurement, (d) instrument uncertainties, (e) sound speed uncertainties, (f) uncertainties of ellipsoidal/vertical datum separation model, (g) motion uncertainties of platform (roll, pitch and heave), (h) platform/vessel draught, settlement and squat (for sonars), (i) seabed slope and (j) time synchronization/latency.

The uncertainty in measurement of any quantity is of two types: (i) random error (precision) and (ii) systematic error or bias (accuracy). The former indicates the relative variability or repeatability of the measurements, whereas the latter indicates the closeness of these measurements to the true value[17].

Recognizing that there are error sources, both depth-dependent and depth-independent that affect the measurement of depth, eq. (1) was used to compute the maximum

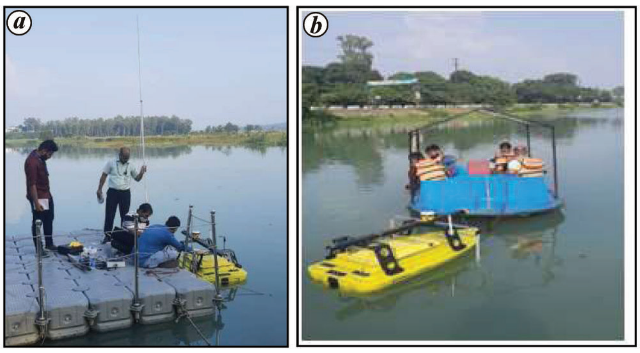

Figure 3. Shallow bathymetry tests at site-1.

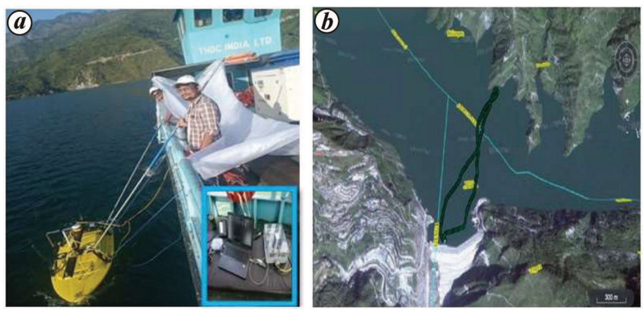

Figure 4. Deep bathymetry test at site-2. ***a***, Data collection. ***b***, Survey trajectory overlaid on BHUVAN geo-spatial portal.

Table 2. Measurement error details for shallow bathymetry

Sample	Physical measurements ($Depth_{phy}$) (m)	EcoBoat sounder ($Depth_{eboat}$) (m)	Bathymetry system ($Depth_{bathy\text{-}sys}$) (m)	$Error_{eboat}$ ($Depth_{phy} - Depth_{eboat}$) (m)	$Error_{bathy\text{-}sys}$ ($Depth_{phy} - Depth_{bathy\text{-}sys}$) (m)
1	2.1	1.51	1.99	0.59	0.11
2	2.8	2.75	2.64	0.05	0.16
3	3.9	3.7	3.79	0.2	0.11
4	2.4	2.4	2.49	0	–0.09
5	2.2	2.34	2.19	–0.14	0.01
6	3.3	3.1	3.39	0.2	–0.09
7	3.6	3.39	3.69	0.21	–0.09
8	2.8	2.77	2.59	0.03	0.21
9	2.03	1.7	1.79	0.33	0.24
10	2.17	1.91	2.04	0.26	0.13

$RMSE_{eboat}$ = 0.2591 m, $RMSE_{bathy\text{-}sys}$ = 0.1388 m.
For EchoBoat, total vertical uncertainty with 95% confidence level (TVU_{eboat}) = 0.5079 m.
For bathymetry system, total vertical uncertainty with 95% confidence level ($TVU_{bathy\text{-}sys}$) = 0.2721 m.
For IHO order 1, maximum allowable total vertical uncertainty (TVU_{max})@4 m depth = 0.5026 m.

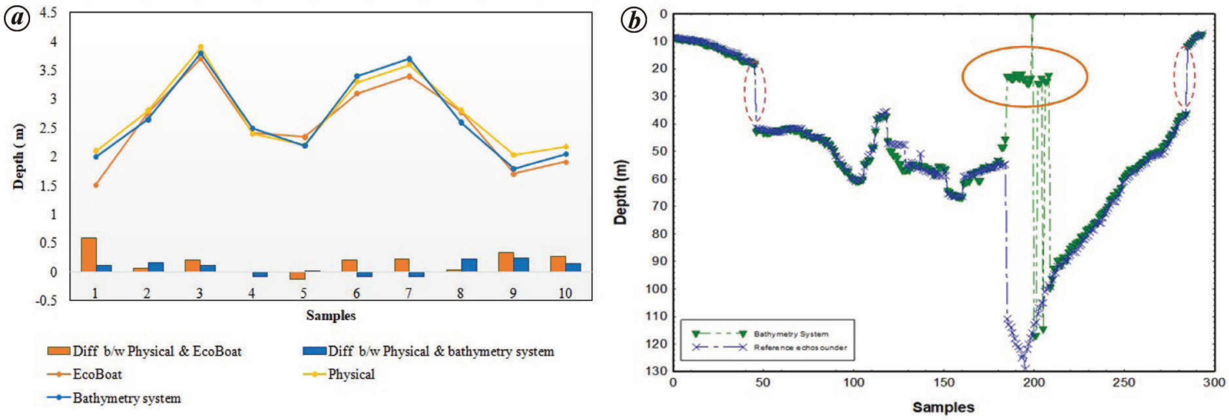

Figure 5. Performance results: (***a***) Shallow bathymetry and (***b***) deep bathymetry.

allowable total vertical uncertainty (TVU_{max}) per the method described in IHO[24].

$$TUV_{max}(d) = \sqrt{a^2 + (b \times d)^2}, \tag{1}$$

where a represents that portion of the uncertainty that does not vary with the depth and b is a coefficient which represents that portion of the uncertainty which varies with depth (d; m). According to IHO[24], for order-1 and order-2, the coefficients values are $a = 0.5$ m, $b = 0.013$ and $a = 1.0$ m, $b = 0.023$ respectively.

However, the TVU at 95% confidence level is defined as 1.96 times the root mean square error (RMSE)[22,24] and it must not exceed TVU_{max}.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - x_t)^2}, \tag{2}$$

where x_i is the known or reference value, x_t the measured value and n is the number of observations.

Results and discussion

Table 2 provides details of measurements and error estimation for the shallow bathymetry test. Figure 5 *a* shows the results considering physical measurements as true values. The water-level offset (+0.19 m) was measured and considered in the computation. The RMSE was computed using eq. (2) and the estimated errors mentioned in Table 2.

The estimated TVU with a 95% confidence level (TVU_{estm}) of the developed bathymetry system for shallow bathymetry was 0.272 m, which complies with the IHO order-1. Similarly, estimations were made for deep bathymetry at test site-2. Further, according to the IHO[24], the survey at site-2 was systematic with bathymetric coverage less than 100%, and the horizontal distance between the registered positions of depth was (below 3 m) no greater than three times the average depth or 25 m.

Figure 5 *b* shows the depth profiles of the reference echo sounder and bathymetry system at site-2. Moreover, due to restriction by the control authority of test site-2, depth measurements along with geo-location trajectory are not presented here.

Site-2 is located in a valley surrounded by hills and the sudden variations observed in the depth profile indicate sudden changes in the bottom surface due to underwater valley topography. During the deep bathymetry test, manual measurements of the reference echo sounder could not be recorded twice (shown as a dashed red circle in Figure 5 *b*) due to engagement of the team members in collecting water samples for laboratory.

From the site-2 depth profile, it was observed that the system had performed consistently within its specifications. Beyond the system specification of 100 m depth, the acquired measurements (around samples 180–200) are not encouraging due to the weak signal return below the system threshold (shown by a solid orange-coloured circle in Figure 5 *b*).

The estimated RSME and TVU_{estm} from depth measurements at site-2 with 95% confidence level were 1.7225 m and 3.376 m respectively, whereas the computed TVU_{max} for 100 m depth was 2.507 m for order 2 of the IHO standard.

Conclusion

In this study, performance of the developed bathymetry system was assessed against physical measurements and a reference echo sounder for shallow and deep bathymetry in open inland waterbodies. The estimated accuracy of the bathymetry system agrees with the physical depth measurements up to an accuracy of ~27 cm for shallow bathymetry assessment.

From a deep bathymetry assessment, it was observed that the system performed consistently within the specifications. Here, the higher value of TVU_{estm} compared to TVU_{max}, manual is due to the following: (a) Both echo sounder (fishfinder) and the acoustic transducer of the bathymetry system operate at different frequencies, viz. 200 and 500 kHz respectively. (b) Distinct constant value for sound velocity may have been used internally, in the reference echo sounder which was unknown. (c) The reference echo sounder is primarily used for fishfinder applications and depth accuracy details are unavailable in the datasheet.

Nevertheless, the experience gained during this field activity will provide a strong base for further, more extensive studies of this kind.

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