A Design for a Trusted Community Bathymetry System

B.R. Calder*, S.J. Dijkstra†, S. Hoy‡, K. Himschoot§, and A. Schofield¶

***Abstract*—Crowd-sourced bathymetry (CSB), meaning volunteered geo-spatial information collected from whatever GNSS and SONAR system is available on the volunteer's vessel, has received a significant amount of attention in recent years. Although increasing amounts of data are being collected, attributed with metadata (to different degrees), and archived, finding a route to the nautical chart has so far been problematic. Partially, this is to do with a lack of a formal and robust means to represent data quality on the chart (paper, raster, or vector), but mostly it is to do with a lack of qualifying metadata associated with data collected in this manner. CSB efforts generally suffer from a lack of calibration, and are therefore limited by uncontrolled vertical offsets with respect to the waterline that are not necessarily constant over time. Indeed, even applying appropriate tidal correctors can be difficult. Assumptions that these issues can be resolved by having a sufficient number of independent observations (the "wisdom of crowds" argument) are often frustrated by basic physical limitations: the ocean is big, and ships are (relatively) small. Except in limited circumstances, or specific areas, the chances of having any repeated measurements are vanishingly small.**

As an alternative to the collection of unqualified data which then needs to be corrected and/or qualified, we propose the use of a data collection system which, by construction, can provide sufficient guarantees of data quality as to allow the measurements to be considered for hydrographic use. We call this method Trusted Community Bathymetry (TCB).

A TCB system resolves many of the issues associated with CSB data by providing for significantly improved positioning accuracy in the vertical. High-accuracy, high-precision post-processed 3D GNSS solutions allow for the estimation of offsets between GNSS antenna and echosounder so that appropriate calibration of the system can be done autonomously. This then allows for reference of depths to a suitable ellipsoid, obviating the need to apply tidal corrections to the data. Given a known offset between antenna and sonar, the same techniques can be used to autonomously establish calibration sites. TCB systems also have the potential to act as a force multiplier (through cross-calibration) for other CSB efforts where calibration is lacking.

We demonstrate these ideas using a prototype TCB system developed by SeaID Ltd., which combines a NMEA data logger with a GNSS system capable of being post-processed for high-precision solutions. By comparison with survey-grade GNSS and INS systems, we demonstrate how to establish the vertical offset calibration in a system, and the construction of a calibration site. We also qualify the performance of the prototype system.

***Index Terms*—Trusted Community Bathymetry, Crowd-Sourced Bathymetry, Post-processed GNSS Solution, Volunteered Geographic Information, Ellipsoidal Survey Methods**

*Corresponding author. Center for Coastal and Ocean Mapping and NOAA/UNH Joint Hydrographic Center (CCOM/JHC), University of New Hampshire, Durham, NH 03824, USA. e: brc@ccom.unh.edu. t: +1 603 862 0526.

†CCOM/JHC. e: semmed@ccom.unh.edu. t: +1 603 862 0525.

‡CCOM/JHC. e: shoy@ccom.unh.edu.

§SeaID Ltd. e: kenneth.himschoot@sea-id.org. t: +33 6 80 86 29 24.

¶SeaID Ltd. e: andrew.schofield@sea-id.org

I. Introduction

The topic of "crowd-sourced" bathymetry has raised much interest in the recent past [1]–[4]. A number of companies and organizations who make navigation devices (e.g., chart plotters and electronic navigation systems) optionally capture the data being observed by their users and make products (e.g., Olex, Navionics, Garmin, Lowrance, etc.) or databases (e.g, Active Captain), and other organizations (e.g., SeaID, TeamSurv, OpenSeaMap) make devices specifically to capture data passing through the ship's NMEA bus that can be used to report positions and depths into their own, or an international, database. The IHO have also confirmed their support for "crowd-sourced" data [5], and have established a working group to help define a "best practice" document on the topic as IHO B.12[1]

While there has been much effort in collecting "crowd-sourced" data (although "Volunteered Geographic Information" (VGI) is a better description), data from these efforts have been used primarily for special purpose products not intended primarily for navigation. For example, data might be interpolated or averaged into a DTM product and then rendered in 3D as an auxiliary product for users, formally as an adjunct to an official chart. Some hydrographic offices have also taken advantage of this type of data in order to better target surveys where changes seem likely to have occurred, but routine use of VGI for charting has so far been considered incompatible with the liability assumed by the chart-maker.

Use of VGI for chart making has a number of problems. Most significantly, the provenance of the data is often poorly documented in the sense that the required metadata may be incomplete, inconsistent, or entirely missing. Data collectors have to rely on the end-user to provide sufficient metadata, but doing so increases the level of effort required of the end-user, and therefore reduces the uptake of systems, and compliance of users who do adopt.

In addition, there is rarely an assessment of the quality of the information being provided, either in the horizontal or, especially, in the vertical. In combination with the lack of metadata, this makes it difficult to even detect mis-configurations or sounding blunders for a system, or collection of systems. The basic argument of crowd-sourcing is that given enough people answering the same question, it does not matter if some of them are wrong: the "wisdom of the crowd" is more often than not right in aggregate. It seems likely, however,

[1]See `https://www.iho.int/srv1/index.php?option=com_content&view=article&id=635&Itemid=988&lang=en` for more details of the Crowd Source Bathymetry Working Group (CSBWG) and the status of the developing B.12.

that there is only rarely a bathymetrically-able crowd, for example where there are restrictions on where ships can go, such as a maintained channel or traffic separation scheme. Otherwise, the ocean is large and ships are (relatively) small: it may be vanishingly rare for any two observers, or even the same observer, to actually answer the same question about the depth at a point, since they are very unlikely ever to repeatedly observe exactly the same area. Consequently, it is difficult to detect vertical offsets, or acoustically-driven noise effects in VGI. This is not to suggest that there is no value in uncontrolled VGI; clearly it can successfully answer some questions. It seems unlikely, however, that "what is the depth anywhere?" is one of them.

Finally, due to the effects above, uncontrolled bathymetric VGI can generally only be considered in aggregate, often over relatively large areas. This makes it possible to assess a mean depth, and possibly an uncertainty, but immediately admits the potential for bathymetric variability to contaminate these estimates. Essentially, such techniques inevitably result in answering a question that is incompatible with most hydrographic practice.

Hydrographic Offices have therefore been reluctant to routinely use this data for official purposes, and have sometimes expressed reluctance to even be responsible for the data at all. Once one has the data in hand, and suspects that they might indicate some danger to navigation, it is difficult to argue that this information should not be published in some form for the mariner. But then, of course, one is also responsible for the liability engendered, which can be a bitter pill to swallow.

Yet the need is clear. Many countries have charts with large areas of limited data, and limited resources to conduct primary surveys or re-surveys; internationally, efforts are underway to ameliorate the situation in the deep ocean [6], but shallow water areas provide their own challenges, not least jurisdictional. Temporal change in many areas is poorly understood, and the repeated surveys required to provide even baseline estimates are often difficult to manage over sufficiently long periods to be useful. Falling and/or limited budgets to carry out systematic surveys make it imperative to take advantage of every potential observation.

The potential for VGI efforts are also clear. There are possibly large numbers of potential observers among professional (non-surveying), semi-professional (e.g., U.S. Power Squadron), and recreational mariners, not being used to their full potential. VGI can also provide free[2] observations. The question is therefore how to take advantage of this potential in a principled manner.

While processing methods for uncontrolled VGI will likely continue to improve, there will always be some concern as to their provenance and the "total cost of ownership" for the data—meaning the cost in time and effort to qualify the data for use—will remain high. Therefore is seems logical that an alternative solution would be to devise a means of autonomous data collection that would generate (simple) bathymetric data by a trusted, portable, method such that the data could be used for (auxiliary) hydrographic practice by supplying the Hydrographic Office (HO) sufficient guarantees of accuracy, precision, calibration, and reliability metrics.

We call this concept "Trusted Community Bathymetry" (TCB).

The advantages of such a system are clear. It would provide a ready source of qualified data for charting purposes. The quantification of the uncertainty of the data, along with quality control measures, would reduce or eliminate HO concerns over liability assumption. By design, such a system would be essentially independent of the user, which both assists with the guarantees of quality and veracity for the HO and minimizes the effort required of the user in installing the system. In addition, a TCB system would potentially be capable of increasing the value of uncontrolled VGI observations through cross-calibration.

This paper considers the requirements of a TCB system, and describes a series of experiments conducted on a prototype TCB system developed by SeaID Ltd. to demonstrate the concept. Through a series of ground-truthed experiments, we demonstrate that the prototype system provides consistent 3D positioning, can auto-calibrate for vertical offsets and measurement uncertainty, and provides ellipsoidally-referenced soundings with quantified uncertainties. We show that the resulting soundings have horizontal uncertainty on the order of 0.10 m (1 s.d., most probably) and vertical uncertainty on the order of 0.16 m (1 s.d., most probably) with respect to the ellipsoid after post-processing. The system is capable of completely autonomous operation, and can time-tag NMEA SDDBT (depth below transducer) strings from any NMEA-capable echosounder with low latency. We believe that this system could therefore potentially provide soundings that a HO could use for charting purposes.

II. Concept of Operations

The goal of a Trusted Community Bathymetry (TCB) system is to provide data with sufficient guarantees that it can be used directly for hydrographic purposes, but at the same time be sufficiently simple that it can be installed unaided by the end-user, and run autonomously so that the user does not need to attend to it (the concept of "frictionless operation"). In order to meet this goal, any TCB system must be capable of:

1) Resolving depths with respect to a suitable reference surface without detailed knowledge of the ship's environment,
2) Determining autonomously, automatically, and regularly over time, any vertical installation offset,
3) Estimating the uncertainty of the horizontal and vertical components of the declared depth,
4) Recording the depth data provided by the ship's echosounder in an appropriate form, with (minimal) controlled latency,
5) Being installed by the end-user with minimal effort, and
6) Running autonomous, including back-end data processing, for extended periods of time.

Potential design solutions to these objectives are considered following.

[2]As with the Free Software movement, the intent here is "free" as in speech, rather than "free" as in beer.

A. *Integrated* GNSS *Receiver*

Most current CSB systems are essentially passive data loggers: they capture whatever information is passing over the ship's NMEA bus, and extract the GPGGA message for position, and the SDDBT (or other) message for depth from the echosounder; timestamps are applied based on either the data logger's internal clock, which may or may not be (approximately) synchronized to UTC time through messages from the GNSS on the ship. The resulting data is stored on the logger, and later downloaded to a central server for processing.

Such systems are inherently limited in accuracy because they rely on whatever system the ship has on board, over which the logger's manufacturer has no control. Specifically, without a great deal of metadata (which implies significant initial and on-going effort on the part of the end-user), it is difficult, if not impossible, for the data logger to determine the relative location of the echosounder with respect to chart datum, since the location of the echosounder relative to the waterline of the ship may be unknown, or difficult to determine. This location may also change over time as the loading of the ship changes, and may be subject to the effects of settlement and/or squat. Motion effects are also integrated into the soundings.

As an alternative, consider a TCB system with an integrated GNSS receiver system. This provides much greater control over the positioning, especially in the vertical, with the added benefit of a reliable time source with which to time-tag NMEA messages from the echosounder. Given a sufficiently accurate vertical position, and knowledge of the vertical offset between the GNSS antenna and the echosounder, such a system would allow soundings to be positioned with respect to a geodetic datum, removing the need to know the draft of the boat, and avoiding the need for water level corrections to be applied to the data.

Providing high-accuracy vertical positioning in real-time is problematic, and typically requires some real-time correctors from a base station though a real-time kinematic (RTK) solution, or satellite-derived augmentation correctors. These typically imply a proportionately more complex GNSS receiver, with concomitant cost implications. For TCB applications, however, real-time performance is not necessary—there will be an inevitable delay before the soundings are sent to the central facility for processing in any case—and cost is a factor in the design since the data logger is expected to be an end-user, retail system.

Consider, therefore, a design that has the integrated GNSS server record the observables in real-time, and provide them in a suitable format for post-processing. With an appropriate delay, the precise ephemeris for the satellites can be determined, and the 3D solution recomputed. With a sufficiently accurate GNSS receiver, the vertical position can be resolved on the order of a decimeter or less, providing good control for soundings. Uncertainty estimates are produced automatically as a byproduct of the recomputation of the 3D position.

Note that one might argue that having an integrated echosounder would also make sense for the same reason: the system has much tighter control over time-tagging, and the echosounder is a known quantity that is more easily qualified. It is significantly simpler, however, to install a new GNSS antenna than it is to install a new echosounder, and therefore it would make installation much harder if this were required. There may be reasons to consider this for new installations in the future, however, which are considered further in Section V.

B. *Static Auto-calibration*

The integrated GNSS receiver provides, after post-processing with the precise ephemeris, 3D positions of the antenna phase center or reference point. In order to reference soundings to the ellipsoid, however, the system must also know the offset between the antenna and echosounder. In principle, this is a straightforward problem, and in a survey context it would be solved by traditional land surveying methods (e.g., through a laser scan of the vessel with appropriate monumentation). In a retail context, however, this would be prohibitively expensive, and it is unreasonable to expect every end-user to become a surveyor without training. While some end-users will have better background experience and/or higher levels of interest, and may be keen to take on the challenge of measuring offsets, the design must assume that the majority will not. For frictionless operations, therefore, the system must be able to auto-calibrate the offset.

Consider the configuration of Fig. 1. Given knowledge of the depth, z, to chart datum at the location of the echosounder, and the separation between chart datum and the ellipsoid, s, the GNSS reports the antenna height with respect to the ellipsoid, and the echosounder reports the depth below the transducer, d, using the NMEA SDDBT message. Clearly, with appropriate consideration for sign,

$$s + z = h + v + d, \tag{1}$$

and the only unknown is the vertical offset between the antenna phase center and the echosounder, v. So long as the ship is stationary in a location that meets the requirements outlined, therefore, any observations can be used to estimate the vertical calibration offset, and the longer the observation period, the better able the system will be to eliminate outliers and reduce the uncertainty of the offset estimate. Moreover, this can be done independently of any action of the user, since it is trivial to determine from the positioning solutions when the ship is sufficiently stationary to enter a calibration period. At the data processing center, therefore, such calibration periods can be identified in the historical record, which allows for calibration monitoring over time.

The auto-calibration assumes that the depth to datum, and a datum-ellipsoid separation, are known where the ship is located. This may not be a reasonable assumption in all locations, which would limit the system's ability to auto-calibrate. It might be possible to separately establish "known locations" where ships are habitually positioned—for example at the fuel dock, or a preferred berth—but in many cases, ships may have to provide their own calibration points.

With the minimal assumption that a water level datum has been established, and that the observations are taken close to a tide gauge, consider the configuration of Fig. 2. The distinction here from Fig. 1 is that the offset between GNSS antenna and

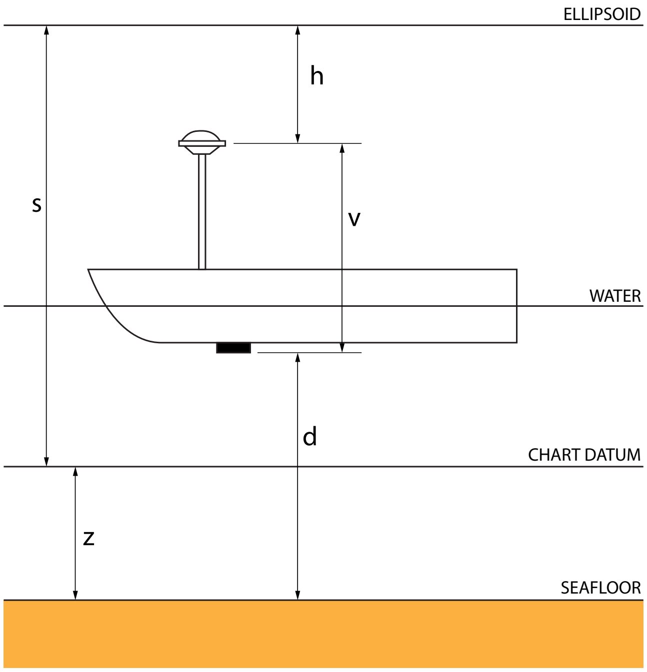

Fig. 1. Configuration diagram for static calibration of the vertical offset, v, between the GNSS antenna phase center and echosounder, given knowledge of the depth to datum, z, and the datum-ellipsoid separation, s. Observed depth, d, and antenna height, h, are measured by the system.

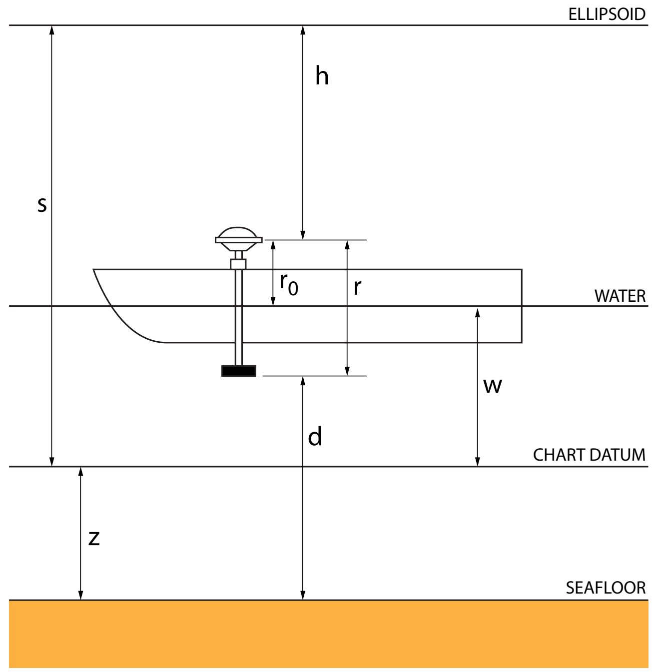

Fig. 2. Establishing depth to datum, z, and datum-ellipsoid separation, s, using the TCB system and a known-offset pole of length r. The end-user would have to provide antenna-water separation r_0, and the length of the support. water level observations, w, from a local tide gauge, for which datum had been determined, would also be required.

echosounder is assumed know, for example by placing the antenna and echosounder transducer temporarily on a support of known height, r. This configuration allows the antenna-water separation, r_0, to be measured. Therefore, again with due respect to sign, since

$$z + w = d + r - r_0, \tag{2}$$

where w is the tide-gauge observed water level, the only unknown is the depth to datum, z, allowing the observations to determine the (acoustic) depth to datum at the observation location. Similarly, since $s = w + r_0 + h$, the same observations can be used to establish a datum-ellipsoid separation.

Clearly, the accuracy with which the depth and separation can be determined depend on the quality of the measurements from the GNSS; in principle, however, any TCB system could be used to autonomously determine a calibration location. This process is not entirely frictionless, however: the end-user would have to provide the antenna-water separation value, the length of the support, and when the TCB system had been deployed in this fashion in order to allow the central servers to identify the data to use for calibration location development[3]. This is not expected, however, to be something that every end-user would do, and the potential for advanced "super observers" to do this kind of observation might be used as a marketing incentive to end-users to get more involved in the project.

[3]The system of course records timestamps through the GNSS solution, but has no way to determine whether the system is on a fixed-length pole or not.

C. Uncertainty Estimation & Dynamic Calibration

Quantification of the level of uncertainty of soundings is required for modern hydrographic practice. For a TCB system, the uncertainty of the 3D GNSS position is generated as part of the solution process, and is readily incorporated. The uncertainty of the offset estimate can be determined through propagation of uncertainty applied to (1), since the uncertainties of separation and depth to datum are given by the HO (or determined by the central processing center through super-observer calibration as described previously), and sample estimates of uncertainty for observed depth d can be readily determined from the observations. Consequently, it is straightforward to provide an uncertainty of the sounding depth with respect to the ellipsoid, and its horizontal positioning.

The level of observational uncertainty from the echosounder is, at least to some extent, a function of the acoustic environment, and may be adversely affected by bubbles engendered by motion through the water, among other sources of noise. Estimates of the measurement uncertainty generated during static calibration are therefore likely to be a lower bound for the true uncertainty. Since the central processing facility will have access to an arbitrarily long time series of observations, however, it will be possible to autonomously and without end-user interaction identify regions of the record where the seafloor is approximately flat, and where the system has travelled at different speeds. Sequential differences in ellipsoid-referenced soundings can then be used within these regions in order to assess the measurement uncertainty of the echosounder while cancelling out any common offsets, such as water level, or draft, and partially accommodating motion effects in the data. End-users could of course accelerate this process by conducting speed trials in a relatively flat area, which might appeal to more engaged observers. This process is considered further in Section IV-C.

D. Low-latency Timekeeping

Availability of an integrated GNSS receiver provides for a steady time reference clock with good long-term stability. The embedded computer in the TCB system can therefore discipline the local oscillator to UTC time using, for example, Network Time Protocol (NTP) [7].

Local oscillator time is formally redundant for GNSS operation, since time is determined as part of the computation. Having a reliable and steady local time is, however, essential for reliable time-tagging of SDDBT NMEA strings for depth information. (Other NMEA strings, for example, water temperature, might also be interesting, if they are available.) As with any serial communications system, however, any latency associated with transmission, reception, or time-tagging is a cause for concern [8], [9]. Little can be done to control latency at transmission short of selecting a reliable echosounder system, but a TCB system can attempt to reduce the latency at reception by providing high-priority, hardware, serial transceivers (Universal Asynchronous Receiver/Transmitters, UARTs), and arranging for hardware interrupts on reception to be delivered to custom driver code directly, rather than through a conventional operating system driver stack. In this way, the opening "$" symbol on a NMEA sentence can be time-tagged with as low a latency as possible, which time-tag can then be used to reference the entire sentence, irrespective of length. If necessary, it would also be possible to provide for a dedicated microcontroller (e.g., an Arduino) to manage the UARTs, further reducing the latency by eliminating the operating system entirely. It is believed, however, that this effort would do little to reduce the effective latency, due to the effects of transmission latency at the echosounder.

E. Autonomous Operation

As outlined previously, the proposed TCB system can auto-calibrate, and therefore requires no more effort from the end-user than to install the antenna, route the antenna cable, plug in the power, and attach a NMEA feed for SDDBT messages. More interested users might consider establishing their own calibration location, confirming their 3D positioning uncertainty, and/or gathering data for dynamic calibration, but none of these are required. Once installed, the system can in principle operate entirely autonomous so long as power is maintained.

Without upload of data, however, the observations are of limited use, although the optimal method of upload may depend on the installation. The possibilities are considered in Section V.

An essential part of a TCB system is calibration, and data management. Logically, therefore, a central processing facility is required to provide these services. Within the IHO approach to CSB, this would likely qualify as a "Trusted Node". Such a facility can provide, for example, calibration computations for each TCB device, monitoring of device performance over time, database management for the observations and metadata, uploads of software updates (and possibly other information), download of the data from the observers, and packaging of the data with appropriate metadata for submission to a wider repository (e.g., the IHO Data Center for Digital Bathymetry at the U.S. National Centers for Environmental Information in Boulder, CO). The processing center could also provide for the construction of value-added products from the raw data, as required by the system's operator.

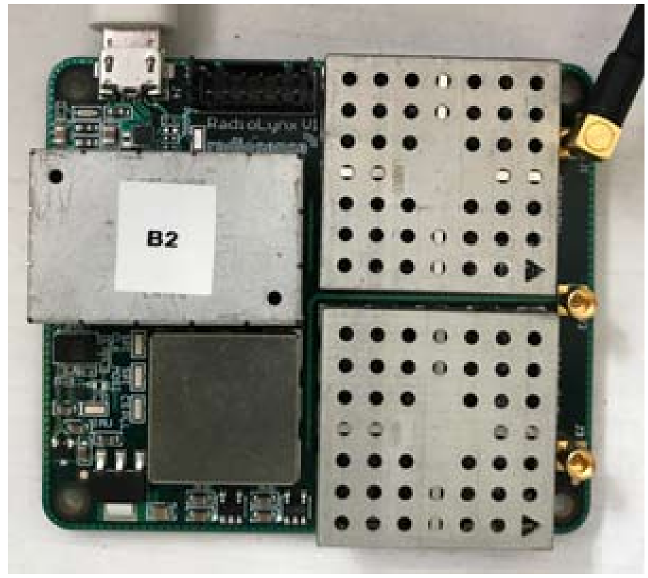

Fig. 3. The SeaID Lynx GNSS receiver board. The board has dual GNSS receivers (right, under shields), although only one receiver is currently being used, and an integrated motion sensor (left). A USB interface (top left) is used to communicate with the host processor.

In any case, while the solution is certainly involved, there is no particular difficulty to be overcome in establishing such a system, most of the major problems already having been solved by various Internet companies and their spin-off technologies.

III. A Prototype Trusted Community Bathymetry Data Logger

SeaID Ltd. have been developing and deploying conventional CSB data loggers for a number of years. Their next-generation unit, however, is designed to fit the description of a TCB data logger, as outlined above. Specifically, the system consists of three main components: a low-cost integrated GNSS receiver, Fig. 3, an Odroid C-2 embedded microprocessor, Fig. 4, and a custom-designed interface board to provide hardware UARTs, a real-time clock, and other features, Fig. 5.

Developed first at Cornell University [10], and then at the University of Texas at Austin Radionavigation Lab[4] and subsequently purchased by SeaID, the Lynx board is a low-cost dual GNSS receiver with integrated motion sensor deployed by SeaID Ltd. in their TCB data logger. Utilizing the GRID (General Radionavigation Interfusion Device) software-defined GNSS receiver [11], the Lynx board allows the system

[4]See: `https://radionavlab.ae.utexas.edu`

Fig. 4. The Odroid C-2 embedded processor used to manage the GNSS receiver, capture NMEA inputs, store data for later transmission, and manage a network uplink, if configured.

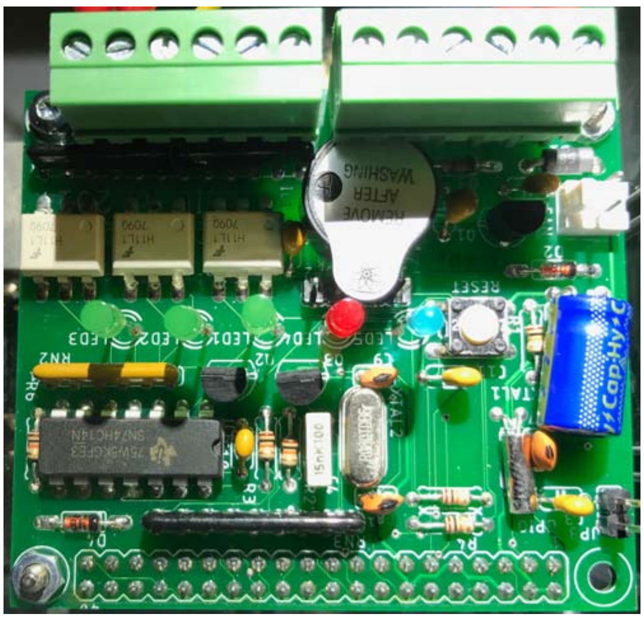

Fig. 5. Custom-designed input board to provide hardware UARTs, a real-time clock, and other features.

to record observables in real-time for later post-processing with a precise ephemeris; a separate executable is used to convert from internal representation to RINEX (Receiver Independent Exchange) format for external post-processing. In addition to GNSS observables, the Lynx board provides a time reference to the Odroid C-2 embedded processor, which disciplines the local oscillator with NTP.

The Odroid C-2 is a low-cost, quad-core, 64-bit, 1.5GHz single-board computer based on the ARM Cortex-A53 processor core, running a customized version of Ubuntu Linux. In addition to providing CPU cycles for the GNSS reception and logging processes, the C-2 provides on-board gigabit Ethernet for permanent network installations, and a collection of general purpose (GPIO) pins that are used to connect to the custom interface board for low-latency UARTs, etc. Data storage is managed on a Secure Digital (SD) memory card, which also hosts the operating system image; download is currently via the Ethernet interface. The C-2 auto-starts the GNSS reception and NMEA logging processes on boot, and therefore has no user-accessible controls other than to connect power, making operation completely autonomous for the end-user. If a network connection is available (e.g., through a Very Small Aperature Terminal (VSAT) or cellular modem), the C-2 can also forge a Virtual Private Network (VPN) to the SeaID processing center, which allows for up-load of data, and download of software updates.

The custom-designed interface card hosts a hardware dual-UART chip, a real-time clock, and watch-dog timers for power monitoring. The GPIO extensions for Linux provide for user-space interrupt service routines triggered by hardware interrupts generated on reception of a character by the UARTs. The estimated interrupt latency of $10\,\mu$s is negligible with respect to the character duration of the input, typically $208\,\mu$s for the NMEA-standard 4,800 baud data transfer rate. A custom driver for the UARTs avoids operating system involvement, allowing for a time-tag to be generated on each character received; if the character is the introductory “$” of a NMEA sentence, and that sentence is later found to be valid (i.e., meets the checksum requirements, and contains no non-printable characters), the whole sentence is time-tagged with the initial value generated for the “$,” minimizing the latency. The real-time clock allows the Odroid board to maintain a sense of time while powered down, which assists in rapid convergence of the NTP algorithm once started, and provided with GNSS-based timestamps.

In volume production, the materials cost of the TCB-capable data logger is expected to be on the order of U.S. $2,000[5], including enclosure, cables, and GNSS antenna, making it suitable for mass distribution.

IV. Performance Evaluation

In the period 31 October–9 November, 2017, the prototype TCB-capable SeaID data logger (SDL) was tested at the University of New Hampshire Judd Gregg Marine Facility in New Castle, N.H., Fig. 6, in order to assess its performance characteristics, and demonstrate the auto-calibration components of the TCB concept design.

A total of three experiments were conducted:

1) Static positioning over a U.S. National Geodetic Survey (NGS) horizontal control mark using a geodetic-quality GNSS receiver and antenna, and the SDL,
2) Static auto-calibration of vertical offset between GNSS antenna and echosounder while installed on the R/V *Gulf Surveyor*,
3) Dynamic auto-calibration of measurement uncertainty and positioning robustness while underway with the R/V *Gulf Surveyor*, and

The experimental methods and results of these experiments are described following.

A. Static Positioning

To check for 3D positioning capability, observations were taken, using both the SDL and survey-grade instruments. A

[5] In 2017 dollars.

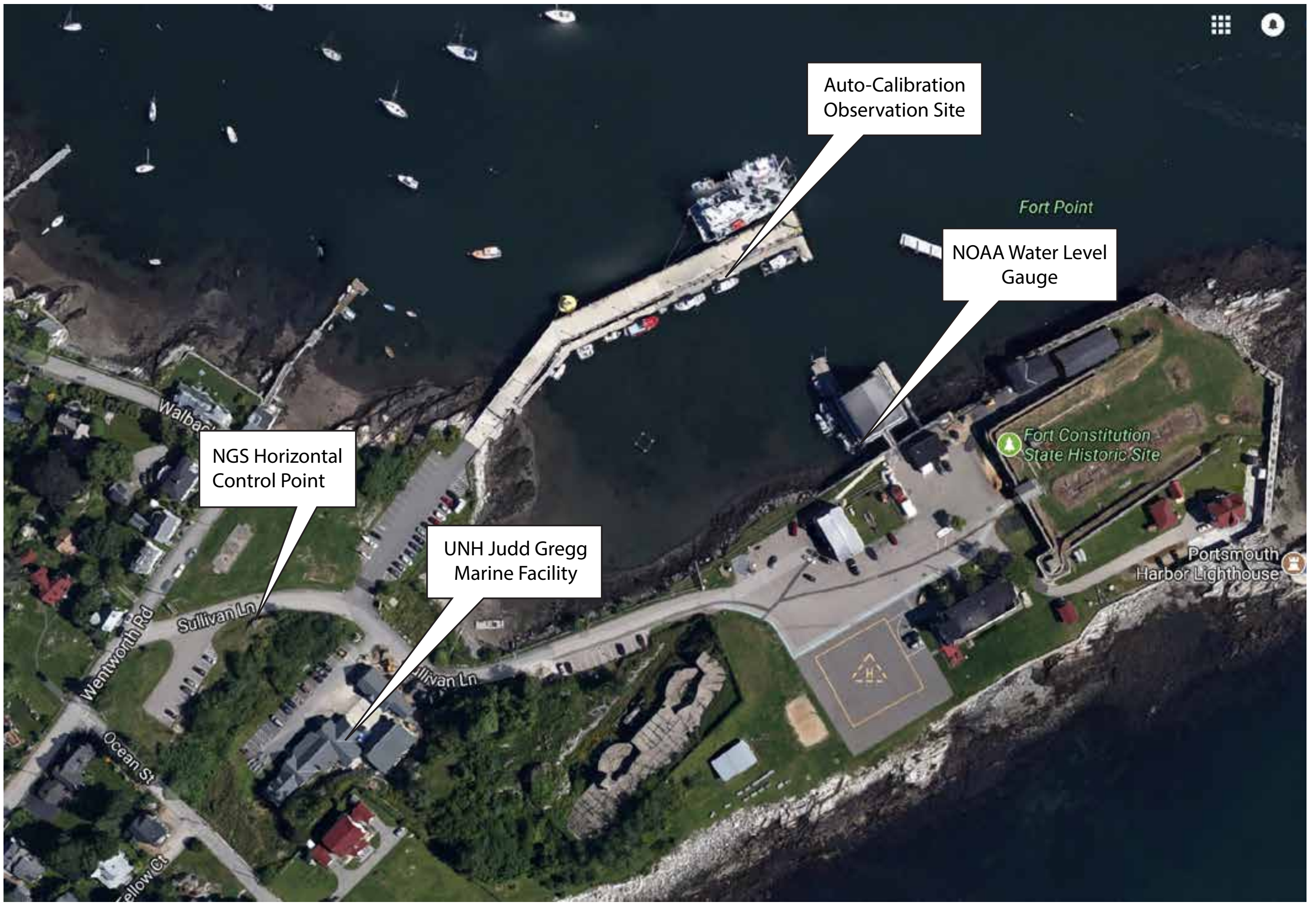

Fig. 6. Location of the field experiments with the SeaID data logger from 31 October–9 November, 2017, at the UNH Judd Gregg Marine Facility at New Castle, N.H.. (Imagery: Google Maps.)

survey tripod was leveled and centered over a U.S. National Geodetic Survey horizontal control mark (station ID AB2631), Fig. 7, using a tribrach with optical plummet. This station has a published position and ellipsoid height derived from adjusted GNSS observations conducted in 2012. Observations with a Trimble Zephyr Geodetic antenna and 5700 GNSS receiver[6] were conducted 2017-10-31/1409 to 2017-10-31/1710 UTC, with receiver vertical offset from the control mark of 1.331 m measured to the bottom of the notch on the antenna (a standard position for correction of the results to the elevation of the control mark). SeaID observations with a NovAtel Pinwheel antenna[7] were conducted on the same setup, after checking, but without adjusting the position, 2017-10-31/1724 to 2017-10-31/2033, with vertical offset from the control mark of 1.319 m to the top of the antenna flange, respectively. The NovAtel documentation specifies that the flange is 100 mm from the center of the antenna, and that the phase center is 25 mm above the top edge (65 mm above the antenna reference point, which is the bottom of the mounting nut).

The observations for each system were downloaded and submitted to the U.S. NGS OPUS (On-line Positioning User Service) site for post-processing. The resolved positions, and the published position for the control mark are given in Table I. As expected, the positioning accuracy of the survey-grade instrument is better than the SDL GNSS position both with respect to the positions computed with different base stations by OPUS, and with respect to the published location of the control mark. However, the peak errors for the SDL are less than a decimeter in each axis, and the actual offset

Fig. 7. Trimble geodetic GNSS observation station over NGS horizontal control mark AB2631.

[6]Antenna serial 60073787, receiver serial 0220358293, firmware 2.32.
[7]Antenna model GPS-702-GG, rev. 1.03, serial NAE16440036.

Fig. 8. The R/V *Gulf Surveyor*, the Center for Coastal and Ocean Mapping's survey platform. The Garmin echosounder is mounted on the port hull, and the Odom on the starboard.

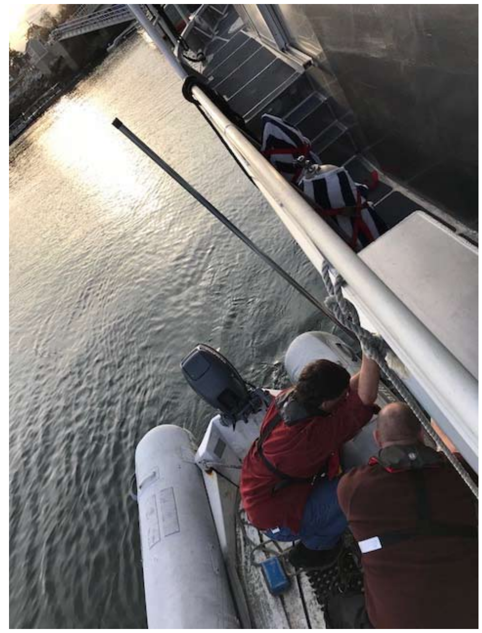

Fig. 9. Measuring the depth adjacent to the Garmin transducer on the port hull of the R/V *Gulf Surveyor*, 2017-11-04/2024 UTC. A steel pole with end-flange was lowered to the sea-floor, marked, and then measured with a steel tape.

from the published location of the control mark are order 0.02 m in horizontal, and 0.043 m in vertical, which is perfectly serviceable for the TCB application.

B. *Offset Calibration*

The offset calibration experiment was conduced on board the R/V *Gulf Surveyor*, Fig. 8. The SDL antenna was installed on the auxiliary GNSS mount on the port side of the antenna platform, and the SDL was interfaced to the ship's Garmin GSD-25 echosounder, coupled to a GT51M-TH transducer, using a standard NMEA SDDBT message at 4,800 baud. This combination represents a "typical" installation expected for the TCB system in the field. An Odom CV200 echosounder was used to provide survey-grade depths for the observations. Positional offsets for a variety of points on the R/V *Gulf Surveyor* were determined by a laser-scan survey in 2015, which provided positions with accuracies on the order of 1 mm (std. dev.) in all axes.

The Garmin system was configured for 80 kHz operation, and the Odom for 200 kHz. Data recording (SDL GNSS observables and NMEA strings, and Odom DSO binary files) was started 2017-11-04/0107 UTC, and continued until 2017-11-05/0130 UTC, observing a complete tidal cycle during King tides (total tidal range 3.803 m, rather than the documented great diurnal range of 2.863 m). Power issues with the Garmin and Odom systems led to some missing data segments, but data were otherwise available throughout the cycle. Physical measurements of depth adjacent to the transducers was conducted at 2017-11-04/2024 UTC, Fig. 9, using a steel pole lowered to resistance, and water level observations were downloaded from the NOAA gauge immediately adjacent to the calibration site (see Fig. 6), CO-OPS station number 8423898 (Fort Point, N.H.). The waterline of the ship was measured at 2017-11-04/1325 UTC, and a sound speed profile was recorded at 2017-11-04/2040 UTC using a DigiBar Pro[8] adjacent to the location of the Garmin transducer.

The physical measurements used for the calibration computations are given in Table II. The SDL GNSS observations were converted from the logger's binary format to RINEX using code provided by SeaID, and then archived along with the ASCII NMEA strings, augmented by a timestamp (seconds since 1970-01-01/00:00:00 UTC, with millisecond resolution); the NMEA data were parsed with custom C++ code, while the RINEX data was processed using RTKlib[9]. The Odom data were parsed with custom C++ code. All data was subsequently transferred into MATLAB for further analysis.

As a preliminary processing step, the observed depths from each echosounder had their measurement uncertainty assessed by computing the sample standard deviation in 30 s windows about each point in the data series. The estimates have a slight depth dependence, but are generally small, Fig. 10, with the Odom measurement slightly smaller as might be expected. The data were then adjusted for measured sound speed, observed water level, and ship's draft, keeping track of the uncertainties associated with each adjustment. The distribution of adjusted depths in comparison with the physical depth, Fig. 11, shows that the Garmin depths are compatible with the physical depth within the assessed uncertainties, and show an overall standard deviation of 0.046 m; the Odom depths are deeper, reflecting local knowledge that the depth increases towards the dock (the ship was starboard side to the dock during the experiment), and show standard deviation 0.025 m. These standard deviations reflect the repeatability of the depth measurements to datum, which is higher than the measurement uncertainty, but lower

[8]Serial number 98139.
[9]http://www.rtklib.com

TABLE I
OBSERVED AND PUBLISHED POSITIONS FOR CONTROL MARK AB2631.

Variable	2017-10-31		Published
	Trimble/5700	NovAtel/SDL	
Latitude[1]	43° 04' 15.17383" N	43° 04' 15.17311"N	43° 04' 15.17378"N
Longitude	70° 42' 48.58711" N	70° 42' 48.58607"N	70° 42' 48.58715"W
Height	-19.266 m	-19.209 m	-19.252 m
Lat. Peak Error[2]	0.003 m	0.021 m	N/A
Lon. Peak Error	0.006 m	0.080 m	N/A
Hgt. Peak Error	0.009 m	0.046 m	N/A
Lat. Offset [3]	0.001 m	0.021 m	N/A
Lon. Offset	0.001 m	0.024 m	N/A
Hgt. Offset	0.014 m	0.043 m	N/A

[1] Positions are given to NAD83 in order to match the published location of the control mark.
[2] The "peak error" values are OPUS peak-to-peak errors for solution with three different CORS base stations.
[3] The "offset" values are distance offset with respect to the published location of the control mark, computed in UTM coordinates in zone 19N.

TABLE II
MEASUREMENTS TAKEN DURING THE STATIC CALIBRATION EXPERIMENT, 2017-11-04.

Variable	Value	Uncertainty[1]	Source
Water Depth	4.066 m	0.10 m	Physical measurement.
Waterline	0.245 m	0.05 m	Physical measurement.
Sound Speed	1485 m/s	0.3 m/s	DigiBar Pro sing-around transducer.[2]
Waterline Reference	0.729 m	0.001 m	Ship's reference survey.[3]
Transducer Height	1.785 m	0.001 m	Ship's reference survey.[3]
Antenna Mount Height	-4.259 m	0.001 m	Ship's reference survey.[3]
Antenna Mounting Offset	0.022 m	0.005 m	Antenna specification.[4, 5]
Antenna Phase Center Offset	0.065 m	0.005 m	Antenna specification.[4, 6]
Garmin Assumed Sound Speed	1502.664 m/s	-[7]	Garmin[8]
Odom Assumed Sound Speed	1500 m/s	-[7]	System parameter settings.
Datum-Ellipsoid Separation	29.297 m	0.13 m	NOAA VDatum

[1] All uncertainties are given as standard deviations.
[2] The profile was observed to be almost isovelocity; this is the harmonic mean.
[3] Locations on the ship are given in the ship's reference frame, established during the laser-scan survey. The ship's reference frame is right-handed with the x-axis positive forward, and z-axis down.
[4] The antenna used is a NovAtel GPS-702-GG, rev. 1.03, which has an antenna reference point at the bottom of the mounting nut.
[5] This is the depth of the antenna mounting nut thread, i.e., the antenna reference point height below the mount point location.
[6] Manufacturer's specification, an average of the offsets for L1/L2.
[7] Assumed sound speeds are constants used to convert time to depth for reporting purposes, and therefore have no uncertainty.
[8] Personal communication, 2017-11-27. Garmin's systems convert time to depth assuming a sound speed of 4930 feet/s.

than the total propagated depth uncertainty, due to common factors in the observations. The distribution of estimated total vertical uncertainties (TVUs) is shown in Fig. 12, and demonstrates that a large portion of the TVU in this scenario comes from corrections, rather than the measurements themselves. Although the Garmin uncertainties are still, on average, higher, they are typically below one decimeter more than 99% of the time. The movement of the ship during the observation period as determined by the SDL, Fig. 13, shows that the ship moves less than 0.7 m in the horizontal during the course of the survey, and most likely less than ±0.1 m from the modal location. The Garmin transducer beamwidth is specified as 24° at 80 kHz, giving a footprint of 1.28–2.55 m diameter over the range of depths observed below the transducer during the experiment. Consequently, the motion of the ship did not exceed the beam footprint of the echosounder at any time.

As well as showing how the uncertainty of the reduced

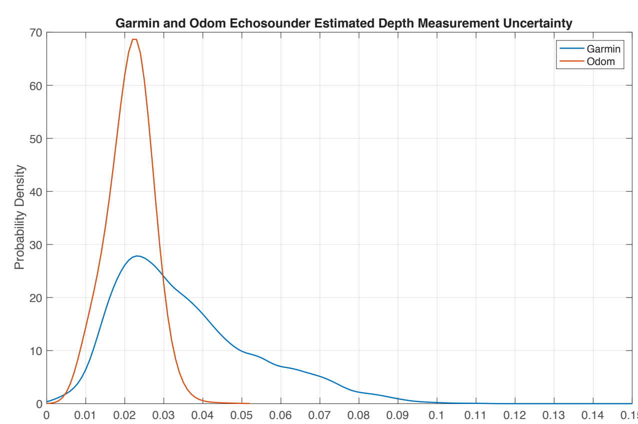

Fig. 10. Probability density function estimates for the measurement uncertainty of Garmin and Odom echosounders, based on 30 s windows during the auto-calibration experiment.

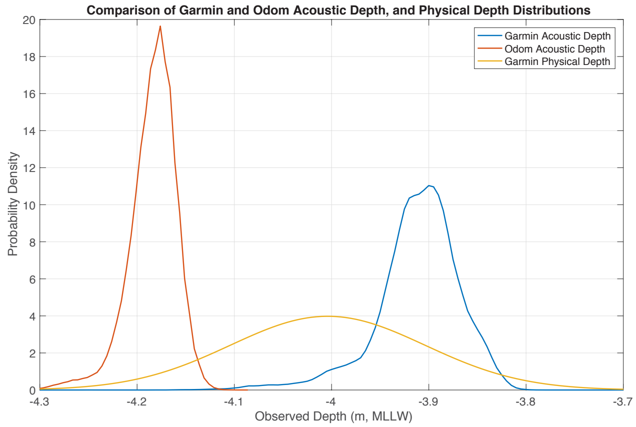

Fig. 11. Probability density function estimates for the reduced depths derived from the Garmin and Odom echosounders during the auto-calibration experiment. The physical depth distribution is predicted analytically based on the measured depth, corrected for water level, and the estimated measurement uncertainty.

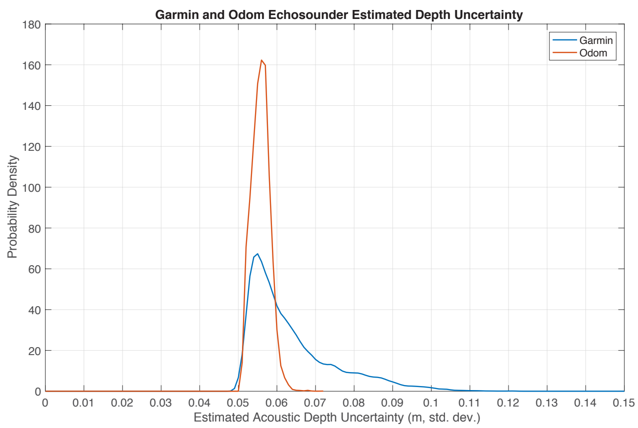

Fig. 12. Probability density function estimates for the total vertical uncertainty (TVU) of the reduced depths from the Garmin and Odom echosounders during the auto-calibration experiment.

depths can be quantified, these observations demonstrate how a calibration site depth would be established by a suitably motivated end-user. Note of course that the end-user portion of this process would be solely to measure the waterline of the ship (i.e., the physical depth is measured here only as groundtruth), since the correct gauge could be identified by the ship's location, and the water level observations could then be downloaded by the central processing facility.

The second requirement for a calibration site is to know the separation between the local tidal datum and the ellipsoid. To provide the known-length offset pole as outlined in Fig. 2, the ship's survey information was used to determine an offset from the SeaID antenna to the Garmin transducer of 6.087 ± 0.0016 m (std. dev.), and the previously-derived acoustic depth of 3.911 ± 0.05 m was used for the depth to datum. Ellipsoid heights from the SDL output were generated through RTKlib. The estimated separation measurement distribution, Fig. 14, shows that the estimate of separation matches that predicted

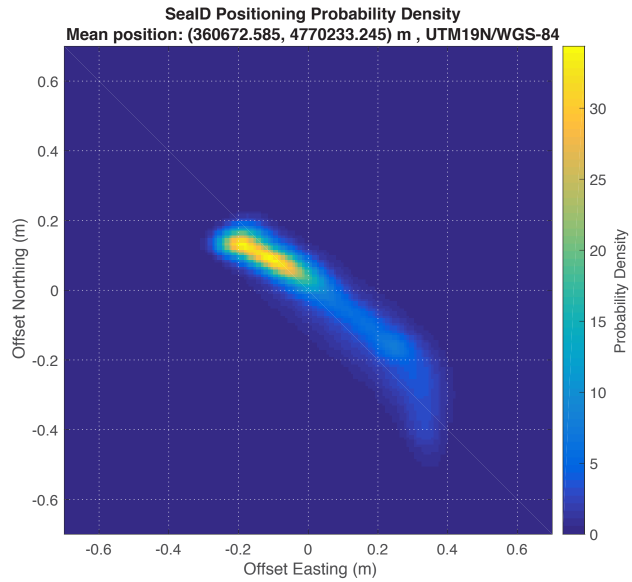

Fig. 13. Bivariate probability density estimate for SeaID position reports during the auto-calibration experiment on the R/V *Gulf Surveyor*, offset by the mean position.

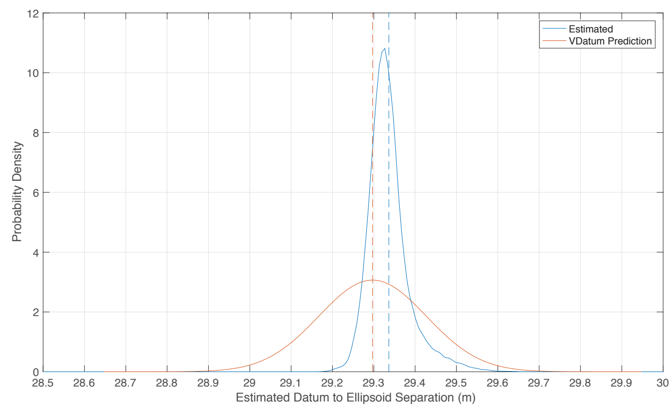

Fig. 14. Probability density function estimate for the datum-ellipsoid separation at the calibration site derived from the Garmin depth measurements and SDL ellipsoidal heights. Dashed vertical lines indicate the location of the mean of each distribution. The VDatum distribution is a theoretical prediction based on the predicted separation of 29.297 ± 0.13 m (std. dev.).

by NOAA's VDatum product[10], with a mean value of 29.336 ± 0.060 m (sample std. dev.) and predicted uncertainty, Fig. 15, of 0.219 m on average, for any single observation; clearly, the standard error of the mean is considerably smaller, using the 80,318 observations available ($\sqrt{N} \approx 283.4$). The accepted separation predicted by VDatum is 29.297 ± 0.13 m (std. dev.). There is a small bias in the mean of approximately 0.0394 m, which is currently unresolved, but if intrinsic would form the lower bound on the achievable uncertainty of the separation assessment.

Most end-user installations are unlikely to be used to determine a calibration site: the goal of the static calibration is to determine the vertical offset between the antenna and the echosounder. To demonstrate this, the VDatum separation and

[10]https://vdatum.noaa.gov

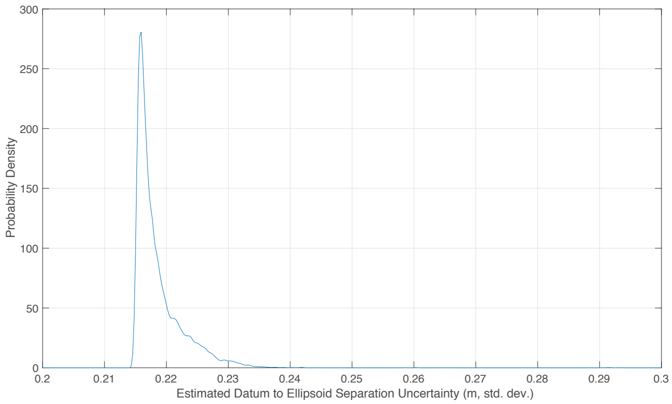

Fig. 15. Probability distribution function estimate for the datum-ellipsoid separation of Fig. 14.

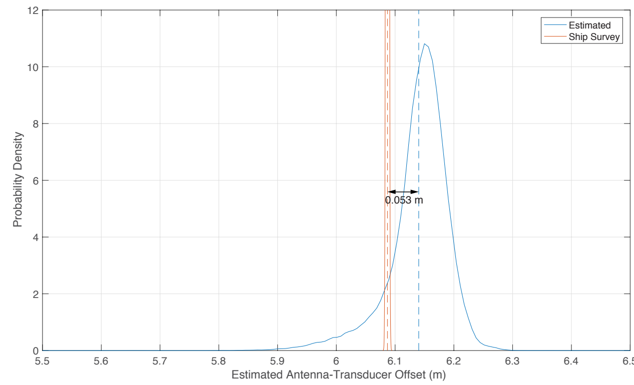

Fig. 16. Probability density function estimate for the antenna-transducer offset for the R/V *Gulf Surveyor*, derived from Garmin soundings and SDL ellipsoid heights. Dashed vertical lines indicate the location of the mean of each distribution. The bias is due to the combination of acoustic depth-derived bias as illustrated in Fig. 11 and height bias as illustrated in Fig.14.

physical depth measurement adjacent to the Garmin transducer were selected as "groundtruth" for the calibration, and the Garmin observed depths (uncorrected for sound speed, as they would be in most cases), and SDL ellipsoid heights were used to predicted the offset as outlined in Fig. 1. The distribution of offset estimates, Fig. 16, shows a clear bias with respect to the accepted figure of 6.087 ± 0.0016 m (std. dev.) derived from the ship's survey, which is due to the combination of the bias in acoustic depth from the Garmin observations as illustrated in Fig. 11, and the unresolved bias in height determination illustrated in Fig. 14. The potential for bias, which cannot be easily reduced, irrespective of the number of observations used, is likely always to be present at small levels in this computation: the groundtruth depth may itself be biased (e.g., derived from an acoustic measurement at another frequency), and the potential for acoustic depth bias cannot be ruled out. It is conceivable, however, that this effect might be estimated (e.g., with an experiment such as that described here) either by super-observers, or by the central processing facility, or a suitably motivated echosounder manufacturer.

In any case, the estimated mean offset of 6.140 ± 0.060 m (sample std. dev.) with an uncertainty of 0.170 m on average (for any one observation) matches the known value within the estimated uncertainties. (Apart from the mean difference, the shape of the uncertainty probability density function is otherwise as Fig. 15.) Unlike the separation estimate, the known acoustic depth-derived bias means that the standard error of the mean cannot be reduced with averaging, and a lower limit of total uncertainty of approximately 0.15 m (std. dev.) is likely. For the following computations, the modal value of 0.166 m was used.

C. Uncertainty Calibration

An assessment of underway uncertainty and positioning stability was conducted with R/V *Gulf Surveyor* from 2017-11-09/1300 UTC until 2017-11-09/1805 UTC. After configuring the ship's systems as for the auto-calibration experiment, the waterline was measured as 0.858 m[11], and the ship conducted a series of figure-eight maneuvers at different speeds in the area south of the "2KR" buoy, off the mouth of the Piscataqua River, Fig. 17. The ship was then maintained in approximately the location of the crossing of the figure-eight, and a sound speed profile was taken. Finally, the ship proceeded up the river through the center of Portsmouth, N.H., passing under both Memorial Bridge and the Sarah Long Bridge in the process, and then back to the dock. The waterline on arrival at the dock was 0.861 m. The observed depths, and associated event times, are shown in Fig. 18.

The apparent increase in uncertainty in the depth observations while undertaking the figure-eights is easily shown to be the effects of motion on the signal by comparison of the antenna height and observed depth, Fig. 19. This also demonstrates the latency of the Garmin-SeaID pair (i.e., it is impossible to say where the latency arises, only the composite), since the depths lag behind the observed height variations. (Note that identification of this latency would not be possible with a conventional CSB system.) Simple nested grid-search of the cross-correlation between the zero-mean versions of the signals allows this latency to be estimated as 1.585 s, which was used to correct the depth timestamps before combining them with the antenna heights and antenna-transducer offset (using the estimated offset of 6.140 ± 0.166 m (std. dev.)) to form ellipsoidally-referenced soundings.

The ellipsoidally-referenced sounding record was split into four segments according to the event time-stamps indicated in Fig. 18, and for each, simple sequential differences were used to remove any residual effect of slowly-varying bathymetric variation during the experiment. The sequential differences were then used to determine the measurement uncertainty of the soundings, Fig. 20, which demonstrates that there appears to be no significant effect of speed on uncertainty on this ship, although the station-keeping uncertainties are very slightly smaller on average. The measurement uncertainties are slightly higher than those observed during the static calibration, Fig. 10, due to the effects of motion that are not being compensated in this signal by the antenna height measurements. (Note, of course, that conventional CSB systems

[11]Note that a different reference position was used from the static calibration experiment, which is easier to get to while underway.

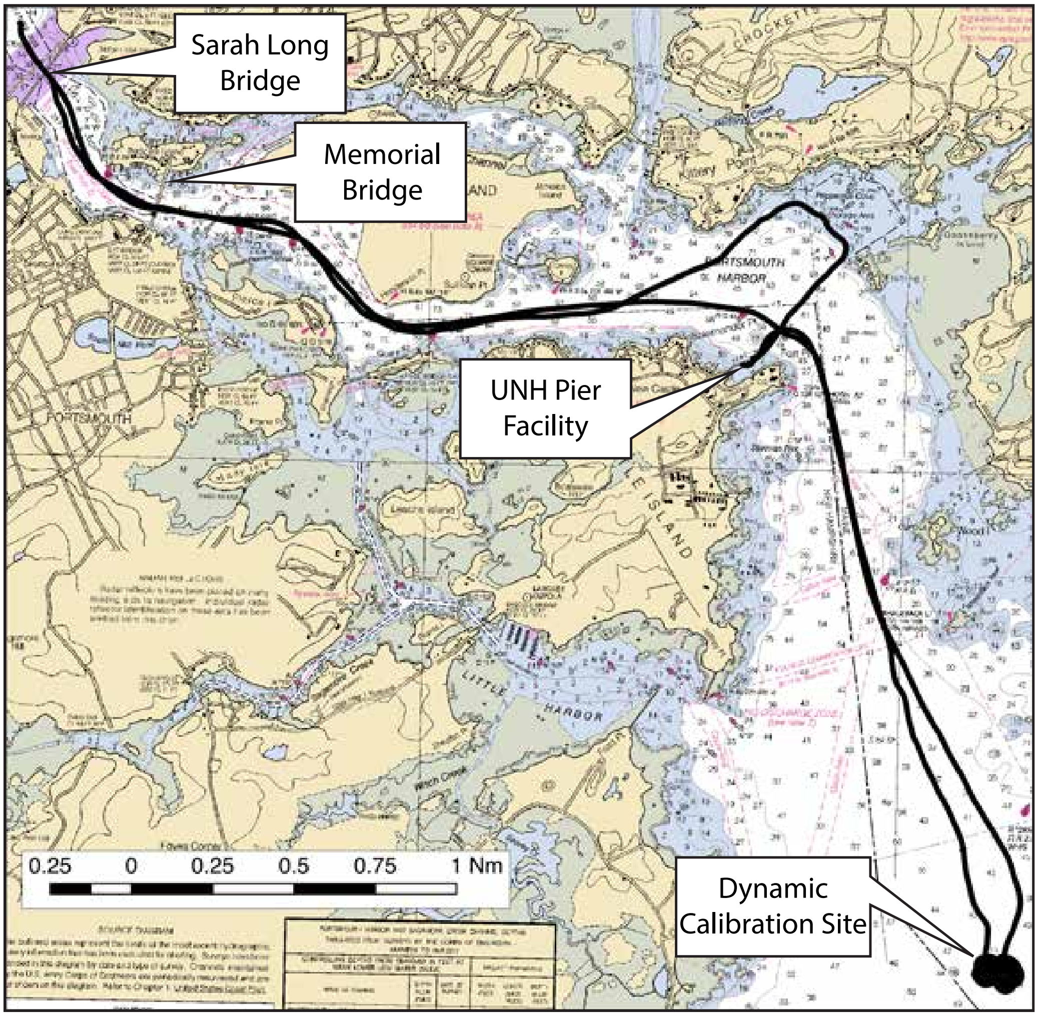

Fig. 17. Ship route during the dynamic uncertainty calibration experiment, shown over NOAA chart 13283. The R/V *Gulf Surveyor* transited from the UNH pier facility out to the calibration site, and conducted figure-eight maneuvers, stopped to take a sound speed profile, and then proceeded up river under two bridges, and then back to the dock.

would correct for no motion effects, and therefore would be subject to this effect to a much larger degree.) Including the uncertainties used to transform the soundings to the ellipsoid provides for a TVU estimate, Fig. 21, which is dominated by the uncertainty associated with the offset between antenna and transducer, and therefore in turn by the acoustic depth-driven bias. Note, however, that in the depth regime considered (14-15 m below datum), IHO S.44 [12] Order 1b survey would require a TVU of no more than 0.53–0.54 m (95%); clearly, with a 95% CI of 0.30–0.50 m more than 95% of the time (and much more predominantly on the lower end of this range), these measurements would be very competitive.

The uncertainty of the positioning solution as a function of time, Fig. 22, readily demonstrates the effects of significant multi-path GNSS reception and strong occlusion of the satellites, leading to cycle slip in the receiver. In this case, this is due to the Memorial and Sarah Long bridges across the Piscataqua River (seaward and landward, respectively), under which the R/V *Gulf Surveyor* passed twice during the experiment (see Fig. 17 for approximate locations of the bridges). Clearly, the positioning solution degrades, although the uncertainty estimated increases to indicate this. In practice, the central processing facility would have to identify, and remove, data of this type from consideration, or at least mark it in some fashion so that users are clear as to the quality of the data.

V. Discussion

The results of the experiments carried out here clearly demonstrate that the prototype TCB data logger can meet the design requirements of the TCB concept of operations, and that it is possible to auto-calibrate such a system, and thus provide autonomous ellipsoidally-referenced soundings using a very low-cost system.

The current configuration does, however, ignore a number of factors that may need to be taken into consideration before the soundings are fully acceptable for hydrographic practice. First, although it has been corrected here, the system perforce ignores the effects of sound speed on the measurements of depth since there is no instrument to measure the harmonic sound speed during data capture. The extent to which this effect is significant is of course location dependent, and in

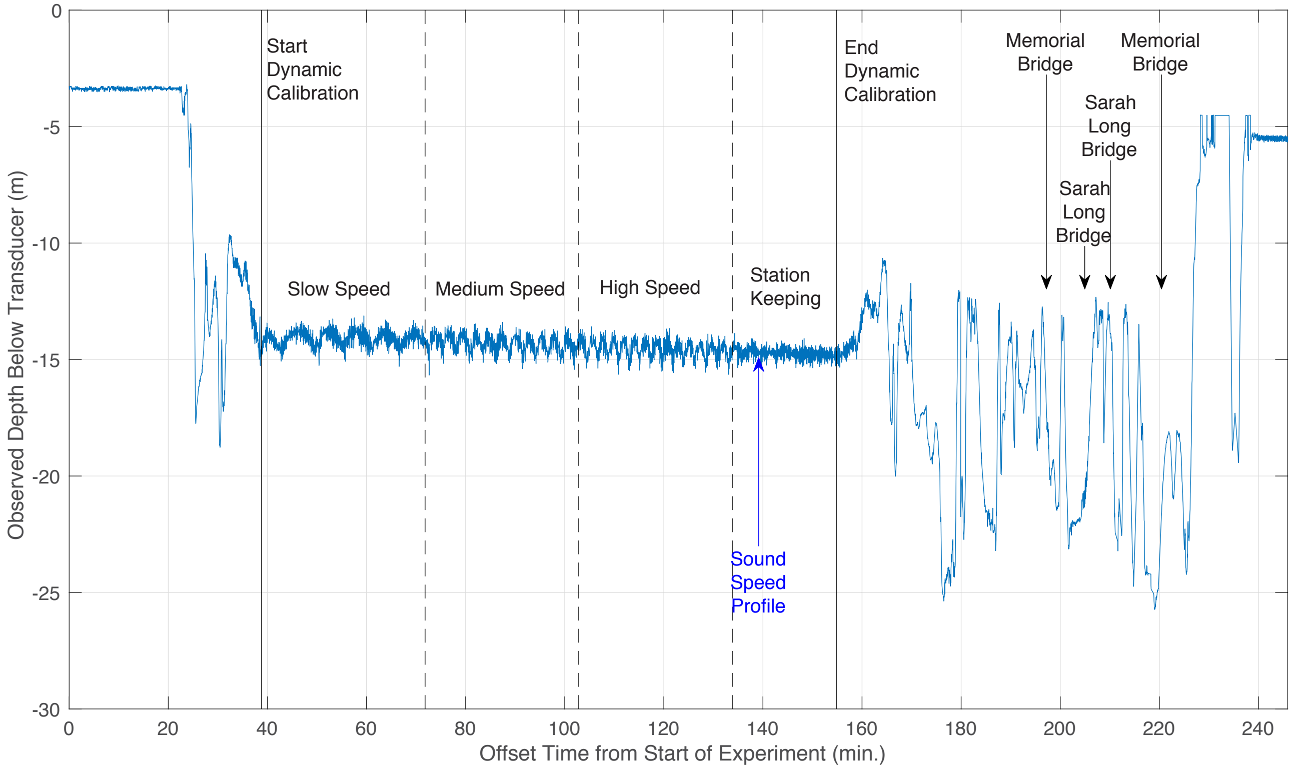

Fig. 18. Observed depths from the Garmin echosounder, and associated events, during the dynamic uncertainty and positioning stability tests.

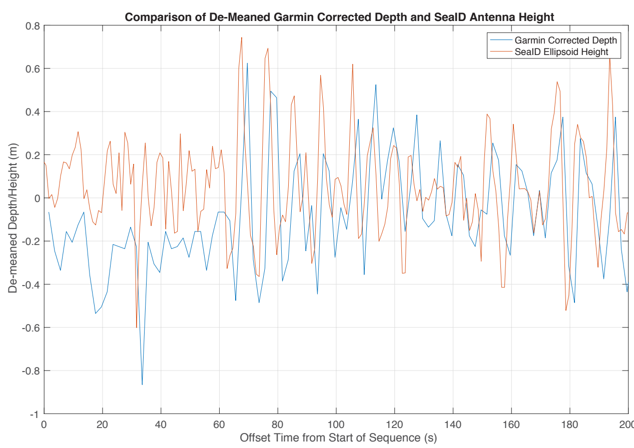

Fig. 19. Comparison of Garmin observed depths and SDL antenna heights, demonstrating that the motion effects are captured in the antenna height to some extent as well as in the depths, and that there is a significant latency in the timestamps associated with the Garmin observations logged by the SDL. Note that the means have been removed from both signals to allow for plotting on the same scale.

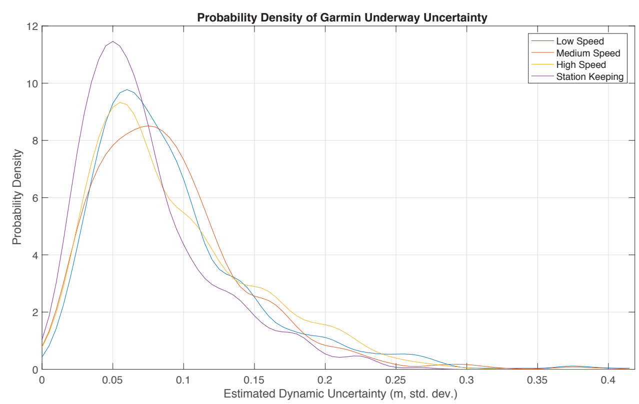

Fig. 20. Probability density function estimate for the measurement uncertainty of the Garmin-derived, ellipsoidally-referenced soundings in different speed regimes. There is a very slight difference between station-keeping and underway.

shallow water may be less of an issue. However, it may be possible to ameliorate the lack of corrections through a number of different mechanisms. For example, many recreational echosounders include an embedded temperature sensor, which can also be logger via a NMEA sentence. Capturing this data, and assuming a salinity value, could allow a crude estimate of sound speed to be constructed, and corrections made. Alternatively, model predictions for sound speed could be used where they exist. Global atlases of oceanographic properties (e.g., World Ocean Atlas[12]) could be used in many areas of deeper water, and higher-resolution oceanographic models (e.g., NOAA operational forecasting models[13] or their equivalent) could be used in near-shore areas. At the outer extreme, it is entirely possible to provide relatively low-cost sensors that measure sound speed or a suitable proxy, although it is likely that measurements of this kind would be limited to only the most dedicated of super-observers in practice.

Second, the methods outlined ignore the horizontal offsets

[12]See `https://www.nodc.noaa.gov/OC5/woa13`
[13]See `https://oceanservice.noaa.gov/facts/ofs.html`

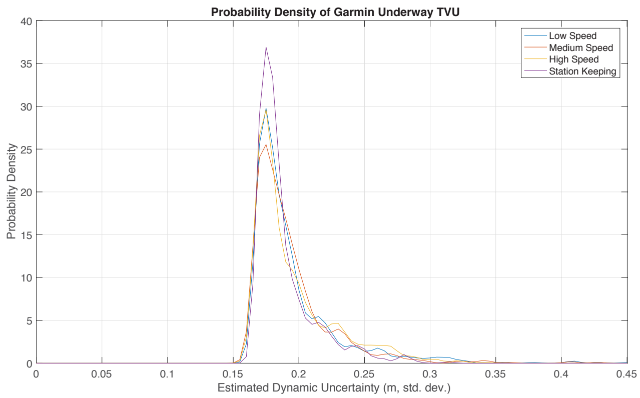

Fig. 21. Probability density function estimate for the total vertical uncertainty (TVU) of the Garmin-derived, ellipsoidally-referenced soundings.

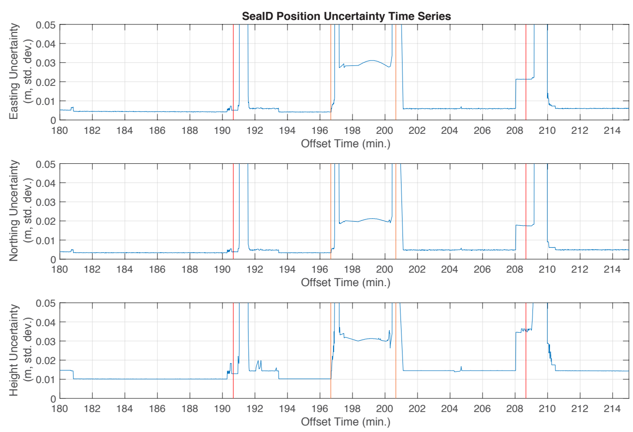

Fig. 22. Detail of the positioning uncertainty predicted by the SDL while passing under bridges in the Piscataqua River, Portsmouth, N.H.. The increase in uncertainty, particularly in the vertical, is due to multi-path reception and occlusion of the satellites.

between the echosounder and the GNSS antenna. There is currently no way to autonomously determine these values, and although a few super-observers may be willing to estimate them, this cannot be assumed in most cases. The significance of the horizontal offsets depends on the installation, but for many observers, the effect might be simply to increase the horizontal uncertainty of the depths by perhaps half the length of the observing vessel, although it might be possible to reduce this estimate per vessel by correlating a time series of reported depths along-track in a suitable choke-point (e.g., the entrance to a harbor) to either other ships or reference depths from the HO. In many cases, however, the actual effect in a charting context may be minimal. The positioning uncertainty is almost certainly no worse than the lead-line and pre-GNSS single beam soundings that are prevalent on many charts without any qualification, and may in fact be smaller than the size of the physical digits written on the chart (or displayed in the ECS) at any reasonable scale of representation. One intriguing option to reduce the uncertainty is to "survey" the ship from a LIDAR-equipped unmanned aerial vehicle, using the returned point cloud to approximately reference the relative offset between the GNSS antenna and the surface expression of the echosounder's location.

The other consequence of horizontal offsets is their interaction with the third neglected effect: motion. The effects of roll and pitch are expected to be small due to the beamwidths generally present on the consumer-grade echosounders that will provide the majority of the data. However, the effects of heave may be significant, particularly induced heave on larger vessels. Direct heave effects can be partially compensated through the antenna ellipsoid height measurements, so the primary concern is induced heave. To some extent this can be reduced by a thoughtful installation of the GNSS antenna, but it may also be possible to use the IMU built in to the SDL to estimate, to some degree, the motion of the platform, and thereby correct. Implementation of this idea would require further research.

In order to provide for widest possible adoption, it is wise to accommodate as many echosounders as possible by using the least common denominator of a NMEA `SDDBT` sentence for depth information. There may, however, be some advantage in also recommending a "preferred" echosounder system for users who are doing a new installation, or to work with echosounder manufacturers to better characterize their systems. Doing so may provide for better quality assurance, and opens up the possibility of using advanced features of the echosounder to enhance the TCB data. An integrated temperature sensor is a simple example, but the Garmin transducer used in these experiment also has small, high-frequency, integrated sidescan imaging arrays, which could be used to provide stand-off observation of suspected obstructions, or other areas of interest provided by the local HO, potentially without any user interaction. That is, when the user connects the system to a network (either directly, or by proxy through a smartphone, for example) and uploads the observations, the data processing center could also provide in return a list of potential areas of interest about which the local HO would like more information. Then, as the end-user goes about their normal activities, the TCB system could autonomously sense when the ship was in an advantageous position to observe these areas, and either turn on, or start recording, the imaging data, turning off the sensor when the area of interest was no longer in view. Such a technique would minimize data storage requirements, but provide a much richer dataset for the HO without putting the end-user at risk by asking them to approach what might potentially be a chartable danger.

Whether to provide for real-time or delayed upload of data is a complex question. There are a number of potential solutions to this problem, ranging from providing a cellular modem within the device to recording the data onto a memory card which can subsequently be mailed back to the system's operation center. An intriguing idea, however, is to provide a low-power Bluetooth radio within the device so that it can connect to the end-user's smart-phone, allowing for bidirectional transfer of data (with the user's permission), and monitoring of the device without having to provide a physical hardware interface. In larger installations with a ship-wide network, it may also be possible to permanently connect the TCB device to the network, and therefore allow for more detailed interaction with the device. For example, this might allow for the operations center to remotely access the TCB device, downloading the data, and uploading software updates. The blend of solutions required to satisfy many different installation types is yet to be determined, and may require further research.

VI. CONCLUSIONS

The experiments described here, although using preliminary data processing products, demonstrate the TCB concept of operations is feasible. That is, it is possible to auto-calibrate for the vertical installation offset between the antenna and echosounder transducer with reasonable accuracy, to reference the soundings to the ellipsoid, to estimate the underway TVU for them, and to monitor the performance of the echosounder's solutions to check for anomalies. It is also possible to generate a calibration site autonomously with a little extra end-user effort.

The performance of the SeaID system has still to be fully explored, but these preliminary results suggest very strongly that the positioning, both horizontally and vertically, of the resulting soundings are more than sufficient for purpose. In addition, the system allows for principled estimation of uncertainty for the soundings, and provision of metadata.

The attitudes of Hydrographic Offices to this type of system have still to be determined. However, it is to be hoped that the features outlined here should very heavily weight the balance of probabilities in favor of adoption.

VII. ACKNOWLEDGEMENTS

This work was supported through a collaboration with SeaID Ltd. (K.H. and A.S), and funding from NOAA through grant NA15NOS4000200 to the Joint Hydrographic Center at the University of New Hampshire (B.R.C, S.J.D., and S.H.). The use of particular equipment here is not intended to imply endorsement on the part of CCOM/JHC, the University of New Hampshire, or NOAA. The authors would like to thank the Captain and crew of the R/V *Gulf Surveyor*, without whom the work could not have been completed, for their hard work, dedication, and willingness to put up with long hours during set-up and trouble-shooting. Thanks also to Emily Terry, Mike Tuttle, and Andy McLeod at CCOM/JHC for logistical support, and Dave Shay and Nate Rennels at the UNH Judd Gregg pier facility for local support and hosting.

REFERENCES

[1] M. Casey, "Citizen mapping and charting part 1: The concept of crowdsourcing and its applications," *Hydro International*, October 2009.

[2] ——, "Citizen mapping and charting part 2: How crowdsourcing is helping to revolutionise mapping and charting," *Hydro International*, October 2009.

[3] T. Thornton, "TeamSurv–surveying with the crowd," *Hydro International*, July/August 2011.

[4] M. van Norden and J. Hersey, "Crowdsourcing for hydrographic data," *Hydro International*, October 2012.

[5] R. Ward, "IHO crowd sourcing," *Int. Hydro. Review*, 201X.

[6] M. Jakobsson, G. Allen, S. Carbotte, R. Falconer, V. Ferrini, K. Marks, L. Mayer, M. Rovere, T. Schmitt, P. Weatherall, and R. Wigley, "Nippon Foundation-GEBCO Seabed 2030 Roadmap for Future Ocean Floor Mapping," Nippon Foundation-GEBCO, https://seabed2030.gebco.net/documents/seabed_2030_roadmap_v10_-low.pdf, Tech. Rep., June 2017.

[7] D. Mills, "Network time protocol (version 3): Specification, implementation and analysis," Internet Engineering Task Force, [online: http://www.rfcs.org], Tech. Rep. RFC-1305, 1992.

[8] B. Calder and A. McLeod, "Ultra-precise absolute time synchronization for distributed acquisition systems," *IEEE J. Oceanic Eng.*, vol. 32, no. 4, pp. 772–785, 2007.

[9] B. Calder, R. Brennan, J. Marcus, C. Malzone, and P. Canter, "High-precision, high-accuracy timekeeping in distributed survey systems," *Int. Hydro. Review*, vol. 9, no. 1, pp. 9–24, 2008.

[10] T. Humphreys, M. Psiaki, P. Kintner, and B. Ledvina, "Gnss receiver implementation on a dsp: Status, challenges, and prospects," in *Proc. Inst. of Navigation GNSS*. Fort Worth, TX: Institute of Navigation, 2006.

[11] B. O'Hanlon, M. Psiaki, P. Kintner, and T. Humphreys, "Development and field testing of a DSP-based dual-frequency software GPS receiver," in *Proc. Inst. of Navigation GNSS*. Savannah, GA: Institute of Navigation, 2009.

[12] International Hydrographic Bureau, "IHO standards for hydrographic surveys, 5ed," International Hydrographic Bureau, 4, quai Antoine 1er, B.P. 445-MC 98011 MONACO Cedex, Tech. Rep. S-44, 2008.