Performance Analysis Using an Uncertainty Model for HydroChart 5000

Sonar Propagation Model Allows Estimation of Uncertainty In Depth Measurements, Meets IHO S-44 Requirements

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Shallow-water bathymetry is important for many survey applications, some of which include port and harbor navigation and inspection, environmental assessment and mapping, underwater construction and rapid area assessment. Many of these surveys are conducted in water depths of less than 20 meters and require accurate, high-resolution data with the ability to detect small objects while providing full bottom coverage. Survey data that require adherence to bathymetric standards such as the International Hydrographic Organization (IHO) Publication S-44 must meet strict statistical data quality requirements for accuracy, resolution and coverage of the processed data.

Swath sonars utilizing phase-difference bathymetric processing are particularly well suited for these shallow survey environments and offer distinct advantages over multibeam echosounders, including increased portability, lower costs and wider swath coverage. In 2010, L-3 Communications Klein Associates Inc. introduced the HydroChart 5000 (HC5000), which combines a dynamically focused multibeam side scan sonar with a high-resolution phase-differencing bathymetric sonar (PDBS) to produce simultaneous and coregistered acoustic backscatter imagery and seafloor bathymetry that meets IHO S-44 requirements.

This article will describe the HC5000 system and then focus on the development of a sonar propagation uncertainty model and its application to survey data with results meeting IHO S-44 requirements.

HC5000 System Description

The HC5000 system has two primary components. The submerged component is a lightweight, portable sonar head unit designed to be mounted to an over-the-side fixture (via standard pipe flange) that suspends the sonar in the water. The topside component, the transceiver processing unit (TPU), interfaces with the sonar head unit, the data acquisition and display computer, and the motion sensor (for correction of ship-induced motion). The sonar head contains a set of transducers providing measurements for dynamically focused, multibeam side scan imagery as well as phase-difference bathymetry, sonar electronics, an altimeter and a sound-speed sensor.

The sonar electronics include a sonar transmitter capable of ensonifying the seabed with a frequency-modulated chirp or continuous wave pulse; a pair of multichannel receiver modules for analog signal processing of the received bottom backscatter; a multiplexer module that performs digitization of sonar backscatter and facilitates bidirectional data telemetry; and a power distribution subsystem. Putting the sonar electronics in close proximity to the sonar transducers helps to improve the overall performance of the system.

Accurate time tagging of sonar data, ship motion and navigation is important for accurate motion correction and sounding position. Systems trying to perform this function in software can run into significant latency issues, reducing the accuracy of the data. In the HC5000, the time tagging of this data is done by hardware in the TPU, reducing latency to tens of microseconds. One pulse-per-second and NMEA-0183-compliant serial interfaces are provided on the TPU to facilitate this function.

An HC5000 sonar installed aboard a small, shallow-water survey platform.

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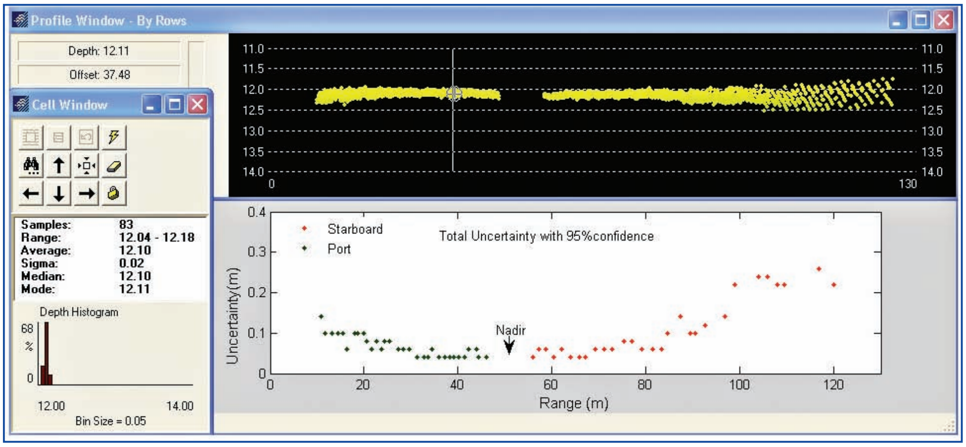
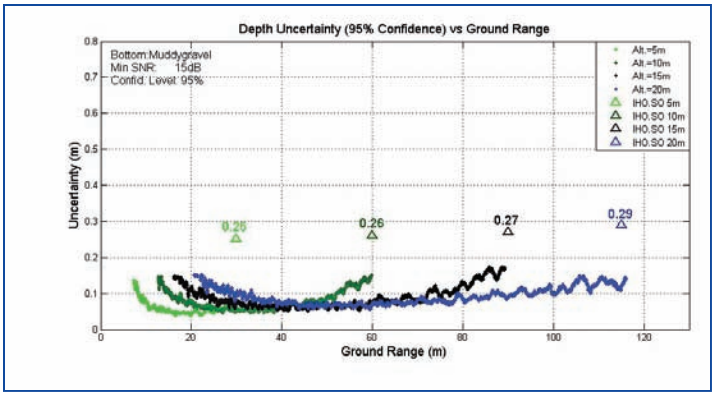


(Left) Data analysis results using HYSWEEP showing total propagated depth uncertainty (95 percent confidence) within IHO S-44 Special Order requirements over a swath of approximately 12 times altitude.

(Below) Sonar model simulation results showing depth uncertainties (95 percent confidence) with levels below IHO S-44 Special Order requirements to 10 to 12 times altitude.



The HC5000 can interface with a variety of third-party motion sensors, allowing for accurate motion correction of acquired bathymetric data. The HC5000 can also be interfaced to a variety of sound-speed sensors. The data acquisition and processing computer is provided as an option to the system. It connects to the TPU via an Ethernet interface and runs L-3 Klein's SonarPro software, a Windows-based application used to acquire, display and log real-time side scan, bathymetry and sensor data. Several real-time displays are provided specifically for the bathymetric component of the HC5000 to facilitate sonar quality control during survey operations.

Dual-Use System

Because the HC5000 has similar core components to its cousin, the S5000 V2 multibeam side scan sonar, it is also capable of performing high-speed, high-resolution side scan sonar surveys while deployed in an over-the-side configuration. This provides an added capability to suit applications that require rapid area assessment. Acquired bathymetric data can then be used to facilitate the measurement of local bottom slope for more accurate target positioning, and/or for aiding side scan sonar image interpretation.

Bathymetric Data Processing

Processed HC5000 data are compatible with a number of third-party hydrographic post-processing packages. To facilitate this post-processing, L-3 Klein provides a separate batch-processing graphical user interface, the BatchProcGUI application, to compute both the beam-formed side scan solution and the bathymetric solution for a batch (or folder) of selected files.

For bathymetric processing, the application allows the user to apply a variety of options to the solution, including ship geometry (lever arm correction), motion sensor source, sonar calibration and a sound-velocity profile. Processed data can be stored in L-3 Klein's *SDF* format or industry-standard formats such as *XYZ* or *GSF*.

Development of a Sonar Uncertainty Model

L-3 Klein has recently developed a sonar propagation uncertainty model for the HC5000 system. The purpose of this model is for use in bathymetric post-processing to provide an estimation of the uncertainty in the depth measurement from the sonar. This can then be combined with uncertainties from other elements such as the motion sensor, navigation, environmental parameters and tide estimation. The result is a total propagation uncertainty model.

This sonar model makes use of existing theoretical models of acoustic propagation, bottom and surface scattering, array processing, bathymetry signal processing and statistical processing. It is used to generate the uncertainty surfaces of angle and depth estimation with ambient noise level, bottom type, surface roughness and any other random sources that affect the sonar performance.

Uncertainty for the HC5000 sonar is defined as the uncertainty of the angle or the depth estimate (from the sonar head to the seafloor) at a 95 percent confidence level, as defined in IHO S-44. In a PDBS system, the bottom is estimated from the

Equation 1

$$\theta_n = \frac{\pi}{2} - \alpha + \arcsin\left[\frac{\Delta\Phi_{AB} + 2m\pi}{2\pi \cdot f \cdot a / c}\right]$$

Equation 2

$$Z_n = 0.5 \cdot T_n \cdot c \cdot \cos(\theta_n)$$

time of flight, T_n, and the received angle of each backscatter measurement is treated as an individual source. The T_n of the backscatter is not estimated as it is in a multibeam echosounder system. Instead, it is simply estimated by the time lag from the ping start time to the moment the backscatter is received.

Therefore the only estimation made from the sonar raw data is the phase difference, $\Delta\Phi_{AB}$, between multiple pairs of array elements, from which the receiving angle Θ_n (between the direction of the returning signal and the nadir) and the depth Z_n, both at sample time *n*, are derived from Equation 1 and Equation 2, where, *a* is the element spacing between multiple pairs of elements *A* and *B*, *f* is the signal center frequency, α is the array installation angle between the normal direction of the array and the sea surface, and *c* is the sound speed.

If we treat *a, f,* α, *c* and T_n as static values and $\Delta\Phi_{AB}$ as a random variable with a probability density function, then Θ_n and Z_n can also be treated as random variables, and the system performance will be determined by the quality of the estimation of $\Delta\Phi_{AB}$.

This phase difference can be used to capture sources of error from environmental inputs (e.g., ambient noise level, surface roughness, bottom type, reverberation level and multipath pattern), sonar system parameters (electronic noise, array aperture functions, etc.) and the bathymetric processing method being used. Therefore, the sonar propagation uncertainty model will determine how the estimation of $\Delta\Phi_{AB}$ will affect the uncertainties of Θ_n and Z_n, given all the uncertainties from random sources that affect $\Delta\Phi_{AB}$.

Uncertainty Model Results

Simulation scenarios for several case studies were executed as part of the effort to develop the model. A typical deployment scenario has the sonar suspended two meters below the sea surface with a flat muddy-gravel sea bottom located at altitudes of 20 meters, 15 meters, 10 meters and five meters, respectively, with the sonar ensonifying the bottom with a two-millisecond chirp pulse.

Depth uncertainties (95 percent confidence) with ground range were computed to include the effect of surface scattering (multipath interference) over the full extent of the swath, including the nadir region beneath the sonar. Acceptable depth uncertainties were observed for five to six times the altitude per side (or 10 to 12 times the overall swath) while still providing overhead for other nonsonar error sources and meeting IHO S-44 Special Order and Order One requirements.

This model can also be used by the combined uncertainty and bathymetry estimator (CUBE) algorithm developed by the Center for Coastal and Ocean Mapping (CCOM) at the University of New Hampshire (UNH), to provide an estimate of the true depth, given measurements and errors from all contributing sources.

Sea Test Results

In late 2010, NOAA deployed the HC5000 for research and development purposes (not for navigation and charting) aboard the NOAA Ship *Thomas Jefferson* in the vicinity of Key West, Florida.

The HC5000 was hull-mounted to the bottom of a hydrographic survey launch and interfaced with an Applanix (Richmond Hill, Canada) POS MV for ship motion correction. As part of the calibration process, data were acquired over a flat patch test area with the sonar.

The resulting data were processed using the L-3 Klein batch processing GUI and HYPACK's (Middletown, Connecticut) HYSWEEP processing software. A 1.5-by-1.5-meter bin size was used to allow for a sufficient number of data points to support statistical processing with the HYSWEEP cell processing tool. Analysis of the results showed that the total propagation of uncertainty of the depth (with 95 percent confidence) is obtained over six times the altitude (12 meters) for each side (12 times altitude for the total swath).

Overall, the depth uncertainty (95 percent confidence) was lower than the IHO S-44 Special Order (27 centimeters) over the full ground range. This data can also be used as a sanity check on the sonar error model. The model predicts a depth uncertainty of 10 centimeters at 50-meter ground range while the processed test data show an uncertainty of around 15 centimeters, with the additional error being predominantly from propagations of uncertainties from the motion sensor measurements.

Conclusions

The HC5000 is a lightweight, portable, combined multibeam side scan sonar and PDBS for use in shallow-water survey applications including port and harbor navigation and inspection, environmental assessment and mapping, underwater construction and rapid area assessment.

The system can interface with a variety of standard bathymetric survey sensors and produces data that are compatible with third-party post-processing software.

A sonar propagation uncertainty model was developed that can be used as a component of a total propagation uncertainty model. Results from the model indicate IHO S-44 Special Order and Order One performance can be achieved with suitable overhead for other error sources.

The statistical results from an evaluation survey of the HC5000 demonstrated good correlation with the combined depth uncertainties from the sonar model and the uncertainties from other contributing error sources. Total depth uncertainties (95 percent confidence) fell within those allowable by IHO S-44 Special Order, measured more than 12 times the altitude.

Future Work

In upcoming months, L-3 Klein will be working with CCOM and UNH to validate the HC5000 sonar propagation uncertainty model using acoustic test data acquired with the system. Upon completion, the final model will be integrated into the HC5000 data-processing flow to provide uncertainty estimates for the individual depth measurements such that they can be used seamlessly with third-party bathymetric post-processing applications using the CUBE algorithm.

Acknowledgments

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