Uncertainty Modeling for AUV Acquired Bathymetry

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Abstract

Autonomous Underwater Vehicles (AUVs) are used across a wide range of mission scenarios and from an increasingly diverse set of operators. Use of AUVs for shallow water (less than 200 meters) mapping applications is of increasing interest. However, an update of the total propagated uncertainty TPU model is required to properly attribute bathymetry data acquired from an AUV platform compared with surface platform acquired data. An overview of the parameters that should be considered for data acquired from an AUV platform is discussed. Data acquired in August 2014 using NOAA's Remote Environmental Measuring UnitS (REMUS) 600 AUV in the vicinity of Portsmouth, NH were processed and analyzed through Leidos' Survey Analysis and Area Based EditoR (SABER) software. Variability in depth and position of seafloor features observed multiple times from repeat passes of the AUV, and junctioning of the AUV acquired bathymetry with bathymetry acquired from a surface platform are used to evaluate the TPU model and to characterize the AUV acquired data.

Introduction

AUV Hydrographic Bootcamp is a weeklong event co-hosted by the University of New Hampshire (UNH) and the University of Delaware to provide an engineering and development forum for furthering the state of the art of hydrographic survey from autonomous underwater vehicles (AUVs). The event provides engineers, software developers, AUV operators and hydrographers an opportunity to scrutinize every detail regarding survey operations and hydrographic data processing.

AUV Hydrographic Bootcamp 2014 was held this past August at the University of New Hampshire marine facility in New Castle, NH. The event included participants from Black Laser Learning, CARIS, DOF Subsea, Hypack, Hydroid, Kongsberg, Leidos, QPS, University of Delaware, University of Rhode Island, the Monterey Bay Area Research Institute, the U.S. Naval Academy, the Naval Oceanographic Office, and NOAA's Offices of Coast Survey and of Exploration and Research. NOAA's REMUS 600 AUV with EM3002 multibeam echosounder (MBES) was operated on three days during the event, allowing participants to plan and execute missions and to collect operational and hydrographic data, affording the ability to establish and test operational models and data processing workflows. These in turn allowed the group to understand operation of the systems, see problems not uncommon to mapping from surface platforms, scrutinize old methods and explore new ones. Much of this effort has been aimed at better understanding and testing uncertainty models for AUV acquired bathymetry.

To illustrate, data collected during AUV Bootcamp 2014 is presented here along with a method for generation of Total Propagated Uncertainty (TPU) from the AUV. One of the AUV datasets is junctioned with a reference bathymetry surface, previously acquired from a surface platform, and thereby providing an opportunity to quantitatively assess the AUV TPU model.

The AUV navigation data was processed in real-time onboard the vehicle using the Kongsberg NavP integrated navigation system, and was post-processed using the Kongsberg NavLab tools. Workshop participants worked with the navigation data and the EM3002 data using a wide variety of software packages including CARIS HIPS and SIPS®[1], Coastal Oceanographics HyPack™[2], MBSYSTEM, and Leidos' SABER. The TPU model results presented here and the quantitative dataset comparisons were produced using the Leidos SABER software package.

TPU Model

Total Propagated Uncertainty (TPU) Modeling for AUVs, as described here, is fundamentally similar to the Hare-Godin-Mayer model [1] [2] made popular in TPU libraries, and providing uncertainty attribution required for the Combined Uncertainty Bathymetric Estimator [3] (CUBE). The TPU model provides an estimate of the total horizontal uncertainty (THU) and the total vertical uncertainty (TVU) for every seafloor depth value. The individual component uncertainties for each parameter contributing to the calculation of seafloor depth at a specific location are separately measured or estimated and propagated using the law of propagation of variances to produce the total horizontal and total vertical uncertainty estimates. For simplicity, the model assumes uncorrelated component uncertainties. The TPU values are used to characterize the quality of the data to assist in decision making about the suitability of the data

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[1] SIPS is a registered trademark of Universal Systems Ltd in the United States and/or other countries.

[2] HYPACK is a trademark of Hypack, Inc. (formerly Coastal Oceanographics, Inc. in the United States and/or other countries.

for its intended purpose. The TPU values are also used as input to various processing technologies such as CUBE [3].

Horizontal Uncertainty

AUV systems operate submerged for extended duration, pushing the limits of today's energy storage technologies. Absolute position fixing using Global Navigation Satellite Systems (GNSS) is limited to when the vehicle is on the surface. When submerged, AUVs use an inertial measurement unit (IMU) as one component of their position, navigation, and time (PNT) solutions. The IMU provides angular rate and acceleration measurements. These angular rate and acceleration measurements are integrated with position measurements and with velocity measurements to achieve suitable position uncertainty. The drift rates from IMU measurements alone would be too large to provide sufficient positioning. However, the short-term stability of the IMU data provides invaluable information necessary to overcome positioning issues with a short timescale such as when the true AUV velocity components are not at steady state for example, to eliminate the unwanted effects of surface waves on the vertical navigation solution. A pressure sensor provides a measure of the vertical location of the AUV in the water column. A Doppler Velocity Log (DVL) provides velocity measurements relative to the seafloor (and sometimes water column [4]) as components of fore-aft, athwart, and downward vehicle speed. When combined with true heading, the DVL measurements provide an absolute velocity reference which can be used to constrain the effect of the inertial drift rates. AUV operations may require continuous absolute position input such as is available from an acoustic ranging system in order to meet data product positioning requirements.

Integration of these disparate, asynchronous measurements requires a sophisticated and robust integrated navigation system (INS) in order to meet the PNT requirements for subsea mapping operations. The INS must be capable of accurate time-stamping, integrate positioning sensors with sufficient and known measurement accuracy, affectively model the actual sensor performance, include a robust navigation kernel based on the equations of motion, and provide truly representative estimates of uncertainty with the PNT solution. The performance characteristics of the INS are essential to meeting mission requirements.

As operated for the 2014 AUV Bootcamp, the NOAA REMUS 600 system relied on surface GNSS fixes, as an underwater acoustic positioning capability was not part of the operations plan. For this scenario, THU is dominated by the component uncertainty contribution from the GNSS/IMU/DVL-based INS navigation solution. The AUV obtains GNSS solutions on the surface at the start of the mission. The AUV real-time navigation solution uncertainty can be modelled starting with the uncertainty of the surface GNSS fixes, and then allowing the horizontal uncertainty to increase as a function of the expected INS performance using bottom lock DVL velocity measurements integrated with inertial measurements. A simple model can then be developed using 0.6 meters distance root mean square (DMRS) for horizontal differential GNSS solution uncertainty, a speed of 3.5 knots in water depths where bottom lock is achieved from the surface to operating depth, expected INS performance of 0.1 % of distance travelled, and assuming the AUV is running in a straight line. [5] The result is shown in Figure 1, where the horizontal position uncertainty is treated as having a circular distribution, and is scaled to 95% confidence level (CL) to allow for comparison with the International Hydrographic Organization (IHO) order 1 guidelines for horizontal uncertainty.

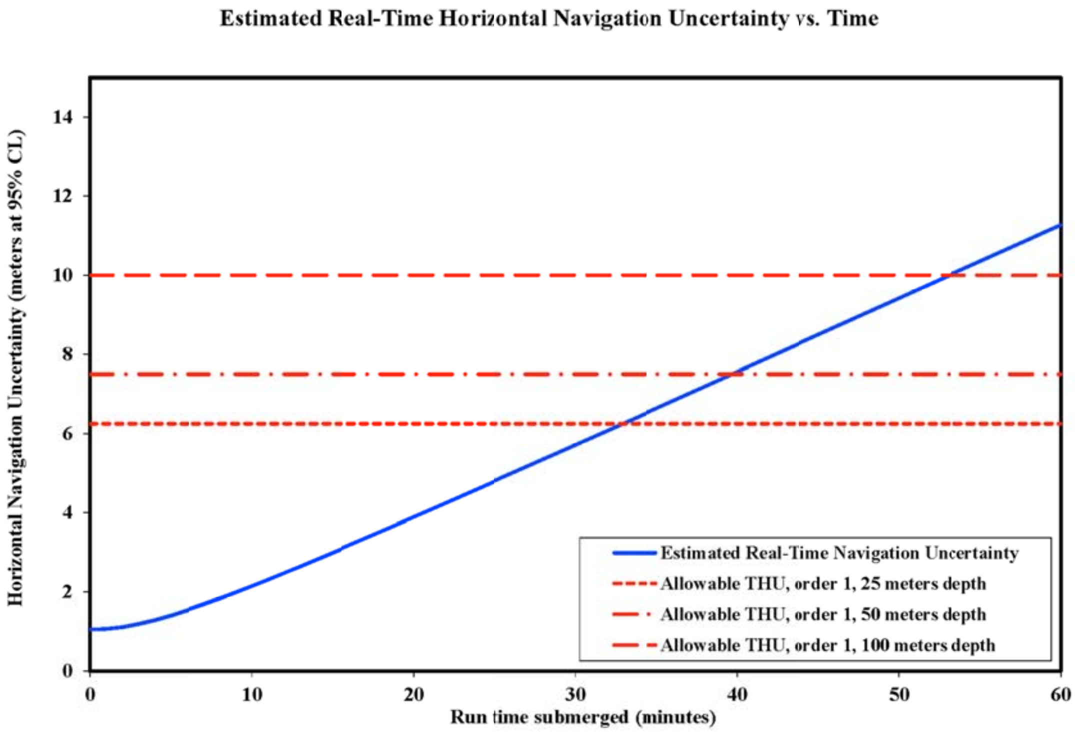

Figure 1 Estimated real-time THU, AUV submerged with DVL bounded inertial positioning.

This suggests that after approximately 33 minutes of survey operations, the navigation solution component uncertainty will reach the maximum allowable THU for the order 1 guideline for a total water depth of 25 meters. Of course, room in the uncertainty budget also must be allowed for other contributions. While this simple model suggests the significant operational constraint of needing to surface on approximately 30 minute intervals, it provides a useful starting point, and it helps define a potential shallow water worst-case scenario where the AUV runs in a straight line, but with DVL bottom-lock. This simplistic model is offered to provide some insight into potential real-time straight-line INS performance, but is not intended for use in actual uncertainty attribution.

The model shown in Figure 1 does not account for two factors that can be used to improve horizontal uncertainty. First, a significant percentage of the DVL error is directional and some cancelling of horizontal uncertainty occurs on reciprocal headings. Second, in post-processing a robust forwards-backwards smoothing approach can reduce the navigation solution uncertainty by propagating uncertainty reduction from GNSS and other measurements both forward and backward in time, resulting in a significant improvement in the positioning solution. The "shark-fin" uncertainty pattern predicted by the simple model shown in Figure 1 would then be reduced to an "M" pattern with significant reduction in the peak uncertainties. As compared to the 30-minute fix interval predicted by Figure 1, utilization of these two factors makes it possible to significantly extend the time the AUV can spend running on DVL aided inertial positioning alone.

In the REMUS 600, the Kongsberg NavP system provides a robust Kalman Filter (KF) based subsea navigation solution that integrates the available positioning measurements and produces an uncertainty attributed position, velocity, and orientation state vector. NavP characterizes the overall measurement performance of each sensor (the Novatel GNSS receiver, the RD Instruments 600 kHz DVL, the Honeywell IMU, the ParoScientific pressure sensor, and acoustic ranging systems) through the KF algorithm. Post processing using the Kongsberg NavLab package has the ability to further reduce navigation uncertainty, using a forward and backward multi-pass approach and a Rauch-Tung-Striebel smoother [5]. The mechanics of the implementation of the NavP and NavLab are described in [6].

The horizontal uncertainty predicted by NavP and NavLab is based on estimated uncertainties in the measurements of position, velocity, acceleration, and rotation rate made by the onboard sensors. For robustness, the component uncertainty values used by NavP and NavLab are conservative and largely hidden from AUV operators as their tuning can create unwanted navigation artifacts. The error state KF provides estimates of sensor errors where these are observable such as during vehicle dynamics and these can be used in the navigation solution. Nonetheless, it is incumbent for AUV operators and hydrographers to scrutinize the uncertainty attribution provided to NavP and NavLab in collaboration with the manufacturer to ensure the values reflect the achieved sensor performance and make sense in the context of the mission.

The SABER THU model starts with the time-varying horizontal uncertainty from NavLab, and interprets this value as accounting for the horizontal uncertainty of the AUV at each position update. The uncertainty in the AUV's position is then propagated to the sonar, and from the sonar to each sounding location. The THU at the sounding location is then a combination of the horizontal uncertainty of the AUV position and the other factors that contribute to computing the along-track and across-track distances to each sounding. These component uncertainties are either measured or estimated for an AUV platform in very much the same way as is done for a surface platform. The summation of all contributing components then leads to a THU value for each sounding.

Vertical Uncertainty

Estimation of the uncertainty in vertical positioning of the AUV requires additional consideration. In an attempt to clearly layout the calculations, the following paragraphs first describe the conversion from absolute pressure measured aboard the AUV to depth. Recipes are also given for implementing these calculations using freely available software implementing these algorithms. Finally a methodology for estimation of uncertainty in the vehicle's depth given these calculations is presented.

For real-time calculations, it is possible to use a "standard ocean" model for water density, or optionally to use a climatology model that provides average temperature and salinity for the area of operations. Vehicle depths from these real-time calculations are used for navigation and control and are also embedded directly in the sonar data during the mission. However to meet the uncertainty requirement necessary for hydrographic survey, post-processing of vertical positioning is required. [3] The post-processed calculation includes compensation for time-varying

[3]Merging of post-processed vehicle navigation can be done through many sonar data processing packages. In addition, Kongsberg provides tools to replace both the horizontal and vertical vehicle navigation embedded in the raw.all files with post-processed values, mitigating the confusion that can come with multiple sources of navigation.

atmospheric pressure, surface waves and swell effects, and varying salinity and temperature in the water column. The latter impacts both the pressure-to-depth conversion to account for the weight of the water above the vehicle and the sound-speed profile to account for ray path propagation of the multibeam observations. The pressure-to-depth calculation presented here is based on UNESCO adopted algorithms for fundamental properties of seawater.

Vertical Positioning of the AUV – Real-time

The primary navigation input used to determine the vertical position of the AUV in the water column is the absolute pressure measurement provided by a Paroscientific pressure sensor installed in the stern of the vehicle. The effect of atmospheric pressure must be removed as part of the conversion from pressure to depth. NavP uses a configurable, yet fixed value (typically 1 bar) for standard atmospheric pressure correction for real-time operations. An offset is typically observable when comparing the time series of pressure observations taken from the AUV when it is in air, with concurrently available barometric pressure observations. For the Bootcamp dataset, the Paroscientific pressure sensor data was less than reference atmospheric pressure by 0.01 bars on average when comparing data from multiple missions. An example is shown in Figure 2 for pre-mission data acquired on 06 August 2014. The first barometric pressure reference is from Wells, Maine, located about 20 miles northeast of the area of operations, and the second is from Isles of Shoals, located about 10 miles southeast of the area of AUV operations. This offset can either be applied directly within the Paroscientific pressure sensor by adding a 0.01 bar calibration factor, or the offset can be corrected post-mission. For the Bootcamp data, the 0.01 bar offset was corrected post-mission in NavLab by subtracting 0.01 bars from the recorded pressure sensor measurements. By nature of applying this calibration, it is also necessary to lever-arm correct the pressure sensor measurements to the location in the vehicle reference frame where the ambient pressure is sampled.

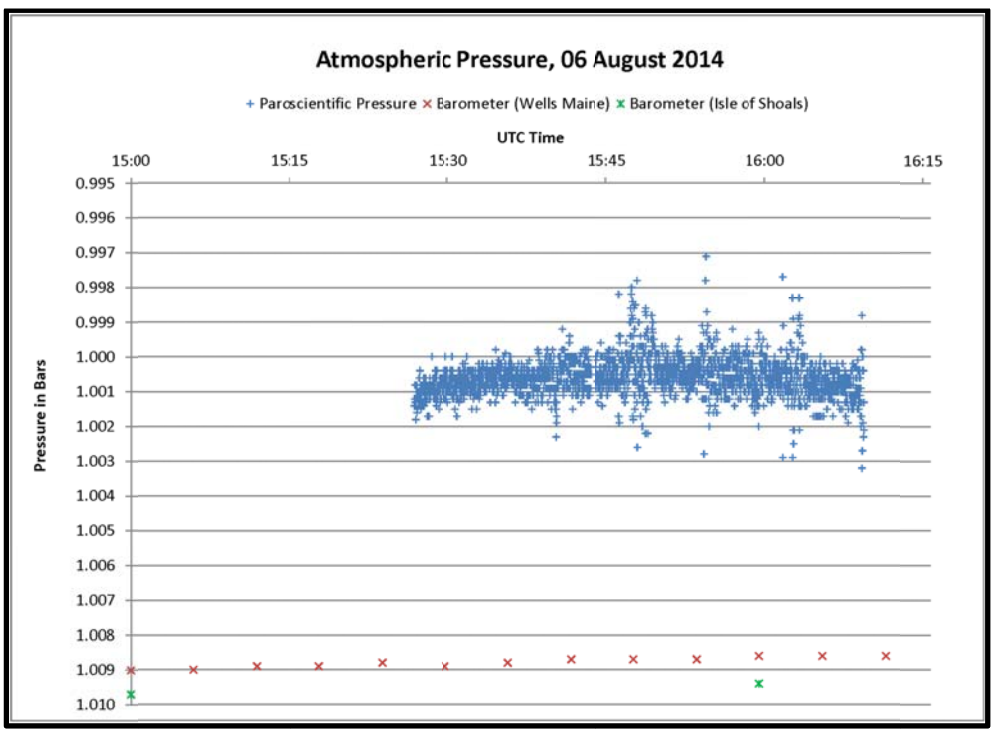

Figure 2 Static bias in Paroscientific pressure sensor data.

Hydrostatic pressure is then converted to depth in real time using the UNESCO 1983 equation popularized by an algorithm formalized in UNESCO's Algorithms for computation of fundamental properties of seawater [7] and reproduced in many programming languages. The vehicle uses latitude in addition to the hydrostatic pressure measurement and, depending on configuration settings, may assume a "standard ocean" (0°C and 35 PSU), or may use temperature and salinity from historical climatology. These pressure sensor derived depth values are lever-arm corrected and then integrated with inertial and DVL measurements in the NavP KF to obtain a filtered depth estimate in real-time. The real-time estimate is used for navigation and is recorded within the raw multibeam data files. While the raw multibeam data may be used immediately post-mission for initial bathymetry and imagery products, in general, a more careful post-processed depth estimate is required with full consideration for atmospheric pressure, changing ocean conditions and the uncertainty reduction provided by forward-backward smoothing.

Vertical Positioning of the AUV – Post Processing

As part of the NavLab post-processing, absolute pressure measurements made by the pressure sensor at the stern of the vehicle are translated to the location of the vehicle navigation reference point (co-located with the IMU), and integrated with the inertial measurements in a forward/backward process to generate the final smoothed navigation solution. The depth component of the position solution is output in meters. NavLab is configurable to produce the depth value using one of several options to facilitate straightforward integration with other packages. In its simplest form, NavLab uses a fixed water density, fixed gravity value, and atmospheric pressure of 1 bar. When reading the NavLab smoothed navigation file, it is then straightforward to invert the depth estimate for a smoothed time-series of the pressure. Reverting to AUV operating depth expressed in units of pressure pressure allows for correction of time-varying atmospheric pressure from a separately recorded reference barometer, and allows for a pressure to depth calculation using one or more temperature and salinity profiles obtained by the AUV or obtained from other platforms. A recent NavLab update also allows for output of a smoothed pressure file directly, which could then also be used as the starting point for refinement using the atmospheric pressure correction, and refinement of the pressure to depth corrections based on the observed Physical Oceanographic parameters. During AUV Bootcamp, physical oceanographic profiling was completed both by the AUV and from the watch boat used for AUV deployment, recovery and mission monitoring.

Conversion from the smoothed pressure to depth is accomplished in SABER using equation (25) on page 26 of UNESCO's Algorithms for computation of fundamental properties of seawater [7]. This is the classic UNESCO 1983 algorithm for pressure conversion to depth in the ocean, where the integration of the specific volume anomaly is included to account for the variability in water density as a function of the observed temperature and salinity profile over the AUV. The Thermodynamic Equation of State of Seawater (TEOS) [9] implements a more precise, set of calculations than defined by the UNESCO 1983 publication. The Gibbs SeaWater (GSW) Oceanographic Toolbox of TEOS-10 [9] provides a software library that can be used to support calculation of many oceanographic parameters, including a solution for pressure to depth conversions. While the GSW implementation is more precise than the UNESCO 1983-based calculations, the UNESO 1983 approach is sufficiently accurate for hydrography and bathymetry products as long as integration of the specific volume anomaly is included. Details of the steps required are specified in the Appendix.

For AUV platforms, the vertical location of the AUV is fully defined by the depth component of position; therefore, heave is not a consideration and the uncertainty contribution from heave is excluded from contributing to the AUV TVU. It is of course still necessary to use rigid-body rotations to account for lever arm (X,Y,Z) offsets to each sensor and using the AUV orientation. Surface waves and swell can present an operational challenge in that both the pressure variation from the surface wave and the orbital velocity field generated by surface waves impact the AUV during the mission. Proper integration in the Kongsberg KF allows the vertical location of the AUV to be accurately estimated even when operating in areas with surface waves and swell. Additional information is provided on this topic in Hagen and Bjørn's Vertical Position Estimation For Underwater Vehicles [8]. Nonetheless, an uncertainty estimate for residual effects of surface waves has been allowed as an entry in the uncertainty model. The static draft, loading draft, and dynamic draft parameters typical for surface ship platforms are excluded from contributing to the AUV-based TVU.

Vertical Position Uncertainty

Estimation of the uncertainty in the depth of the vehicle requires consideration of the uncertainty in each contributing factor: absolute pressure measured aboard the vehicle and atmospheric pressure measured at the surface during the survey, uncertainty in the vertical profile of temperature and salinity used in calculation of the specific volume anomaly described above, uncertainty in the local gravity vector, and finally uncertainty in the inertial accelerations and gyro measurement with which the pressure-derived depths are blended in the KF solution. These components are summed as variances as shown in Equation 1.

$$\sigma_{d_{AUV\ POSITION}} = \sqrt{\sigma^2_{d_{AUV\ PRESS.}} + \sigma^2_{d_{INERTIAL}} + \sigma^2_{d_{NAV.\ LEVER\ ARMS}} + \sigma^2_{d_{ATTITUDE}} + \ldots + \sigma^2_{d_{BAR.PRESS.}} + \sigma^2_{d_{WATERCOLUMN}} + \sigma^2_{d_{GRAV.}}} \qquad (1)$$

Similar to methods used for horizontal positioning uncertainty, the SABER TVU model uses NavLab's estimate of vertical uncertainty. The KF solution produced by NavLab results from a blend of the manufacturer's specification for uncertainty for the vehicle's pressure sensor, along with that of the inertial and gyro measurements. The time-varying estimate of AUV depth uncertainty output from NavLab accounts for uncorrected biases and random uncertainty in the pressure measurement ($\sigma^2_{d_{AUV\ PRESS.}}$), the uncertainties of the IMU data ($\sigma^2_{d_{INERTIAL}}$), the lever arms locating each navigation sensor, the lever arm uncertainties, and the attitude uncertainties ($\sigma^2_{d_{ATTITUDE}}$). The NavLab depth uncertainty value thereby accounts for the first four components in Equation 1.

Uncertainty in the watercolumn temperature and salinity come from two sources, namely, the sensors' inherent accuracy, and the aliased environmental variability that occurs in the water column both spatially and temporally. The vertical profile data may come from conductivity temperature and depth CTD casts made during the survey or from sensors on board the AUV itself. In the latter case, vertical profiles of temperature and salinity may be extracted from any depth excursion made by the vehicle. At a minimum, generally two such sets of profiles can be extracted, one from the initial dive and a second from the final return to surface. The difference in the temperature and salinity measurements at each depth interval between successive pairs of CTD casts serves as a rough measure of the spatial and temporal variability of the environment.

Environmental variability is generally larger than sensor accuracy and as such the uncertainty of the vertical temperature and salinity data is modeled having an uncertainty corresponding to instrument accuracy at the time the profile measurements are made, growing linearly in time until the next profile is measured, reaching a maximum uncertainty level corresponding to the absolute difference between the original profile and the subsequent one. In this way the modeled uncertainty in temperature and salinity at each depth in the profile is saw-toothed over time, growing to match observed changes in the data and resetting to instrument uncertainty at the time of each profile measurement. Inherent in this model are many assumptions, including that sufficient samples of the water column have been taken, and that the dynamics experienced by the vehicle changes linearly with time between samples.

The errors described here are systematic biases rather than stochastic measurement error. As such, rather than propagating the uncertainty of the temperature and salinity profiles through the pressure-to-depth calculation through a Monte Carlo simulation, as one might do if the errors were random, the uncertainty is more appropriately estimated by bounding the maximum bias in depth of the AUV that would result given the modeled biases in each profile. To do so theoretical, minimum and maximum temperature profiles are generated as the measured temperature minus or plus 1-sigma error, respectively. Similar profiles can be created for salinity. These can then be combined to produce a minimum and maximum error bound for each depth by inserting these maximum-bias profiles into the pressure-to-depth calculation described above. When doing so one must choose the minimum temperature and maximum salinity profiles to produce a maximum positive depth error and the maximum temperature and minimum salinity profiles to produce a maximum negative depth error. In this way positive and negative depth error bounds due to uncertainty in the vertical temperature and salinity profiles are produced as a function of depth of the vehicle and provide a lookup table into which the AUV's depth time series may be interpolated for the temperature and salinity vertical profile uncertainty contribution. This may then be combined with uncertainty from other sources in a root-square sum to obtain the full depth uncertainty estimate shown in Equation 1.

Uncertainty in the pressure-to-depth conversion due to the local gravity anomaly was estimated by comparing depth calculations made using both the UNESCO gravity model and actual marine gravity measurements obtained from the National Geophysical Data Center (NGDC). In the vicinity of subduction zones around the major trench systems, the effect of gravity anomalies was estimated to be as large as 0.02 meters. However, for the Bootcamp area of operations, the effect of gravity anomalies is estimated to be insignificant.

Uncertainty in the depths of each sounding is a combination of vertical uncertainty in the AUV position, uncertainty due to lever arms to the MBES arrays, vehicle attitude, sound speed at the MBES transducer array, sound velocity profile (SVP), and in the MBES bottom detect as shown in Equation 2. See Hare's Depth and Position Error Budgets for Multi-Beam Echosounding [1] for details.

$$\sigma_{d_{total}} = \sqrt{\sigma^2_{d_{AUV\ POSITION}} + \sigma^2_{d_{MBES\ LEVER\ ARMS}} + \sigma^2_{d_{ATTITUDE}} + \sigma^2_{d_{SS\ TRANS.}} + \sigma^2_{d_{SVP}} + \sigma^2_{d_{MBES}}} \tag{2}$$

Table 1 provides component uncertainties for the parameters contributing to the AUV uncertainty model and described in the above text. These parameter values define the TPU model inputs corresponding to the results presented in the next subsequent sections. The cells shaded in grey in Table 1 are the component uncertainty values that comprise the NavLab measurement uncertainty model. These values are listed here for reference, but have been included already in the horizontal and vertical AUV position uncertainty provided by NavLab.

Component	Manufacturer	Model	Operational Mode	Uncertainty Estimate	Confidence Interval	Notes
Pressure sensor	Paroscientific	9000	N/A	0.07 meters	RMS	Uncertainty is 0.01 % of full scale (1000 PSI) , 689.475 decibar, or approximately 689.475 m
CTD sensor	Neil Brown	G-CTD	Conductivity	0.01 mS/cm	RMS	
			Temperature	0.001°C	RMS	
CTD sensor	YSI	CastAway				Deployed from launch and recovery boat.
			Temperature	0.05°C	RMS	
			Pressure	0.25% of FS	RMS	FS = 100 decibar
			Salinity (Derived)	0.1 (PSS-78)	RMS	
			Sound Speed (Derived)	0.15 m/s	RMS	
GNSS receiver	NovAtel	OEMV-3	Single Point L1	1.5m	DRMS	
			Single Point L1/L2	1.2m	DRMS	
			SBAS	0.6m	DRMS	Satellite Based Augmentation Service (SBAS)
NavP, NavLab (Used with Honeywell HG9900 IMU)	Kongsberg					
			roll	0.005°	1-sigma	
			pitch	0.005°	1-sigma	
			heading	0.02° * sec(lat)	1-sigma	
Atmospheric pressure sensor	Unknown	Unknown	N/A	1 mbar		Atmospheric pressure was taken from any of several public sources. Measurement accuracy was estimated from typical barometric sensor

Component	Manufacturer	Model	Operational Mode	Uncertainty Estimate	Confidence Interval	Notes
						specifications for research grade weather stations.
Tide zoning	NA	NA	NA	0.1 meters	RMS	
Tide measurement	Unknown	Unknown	NA	0.01 meters	RMS	
Lever Arm Offsets	NA	NA	NA	0.01 meters	RMS	
Roll Bias	NA	NA	NA	0.01°	RMS	
Pitch Bias	NA	NA	NA	0.1°	RMS	
Heading Bias	NA	NA	NA	0.1°	RMS	
Gravity anomaly	NA	NA	NA	0.00 meters	RMS	
Navigation latency Bias	NA	NA	NA	0.0 sec.	RMS	
Navigation latency uncertainty	NA	NA	NA	0.001	RMS	
Attitude latency Bias	NA	NA	NA	0.0 sec.	RMS	
Attitude latency uncertainty	NA	NA	NA	0.001	RMS	
Sonar latency Bias	NA	NA	NA	0.0	RMS	
EM3002 latency Bias	NA	NA	NA	0.001sec.	RMS	
Wave height removal	NA	NA	NA	0.01 m	RMS	
Transducer face sound speed uncertainty	NA	NA	NA	0.25 m/s	RMS	
SVP measurement uncertainty	NA	NA	NA	0.75 m/s	RMS	
Spatial and temporal T, S variability	NA	NA	NA	Varies	RMS	Determined by comparison of SVPs through the mission

Table 1 Component uncertainty contributions.

Reference Bathymetry Surface

A reference bathymetry dataset was provided by UNH's Center for Coastal and Ocean Mapping (CCOM). Sounding data were acquired approximately three months prior to AUV Bootcamp in May 2014 using an Edgetech 6205 multiphase echo sounder (MPES). Horizontal and vertical control for this survey was provided by post-processed kinematic (PPK) GNSS solutions generated using Applanix POSPac software. The Ellipsoid to Mean-Lower-Low-Water (MLLW) separation was based on a single-point value of -29.32 meters defined over one of the benchmarks for tide gauge 8423898 installed at Fort Point, NH, approximately 0.5 km from the survey area. [10] The sounding data were processed through CARIS HIPS to generation of a 0.5 meter node-spacing CUBE BASE surface and output as a Bathymetry Attributed Grid (BAG). The RMS of the hypothesis standard deviation layer across the surface is 0.1 m with 95% of values falling below 0.19 m. The BAG grid was used in SABER as the reference surface for junction analysis. Figure 3 shows an overview of the reference bathymetry surface with sun shading from the north. The survey transect lines were run in north-south orientation with a line spacing that produced approximately 100% coverage overlap.

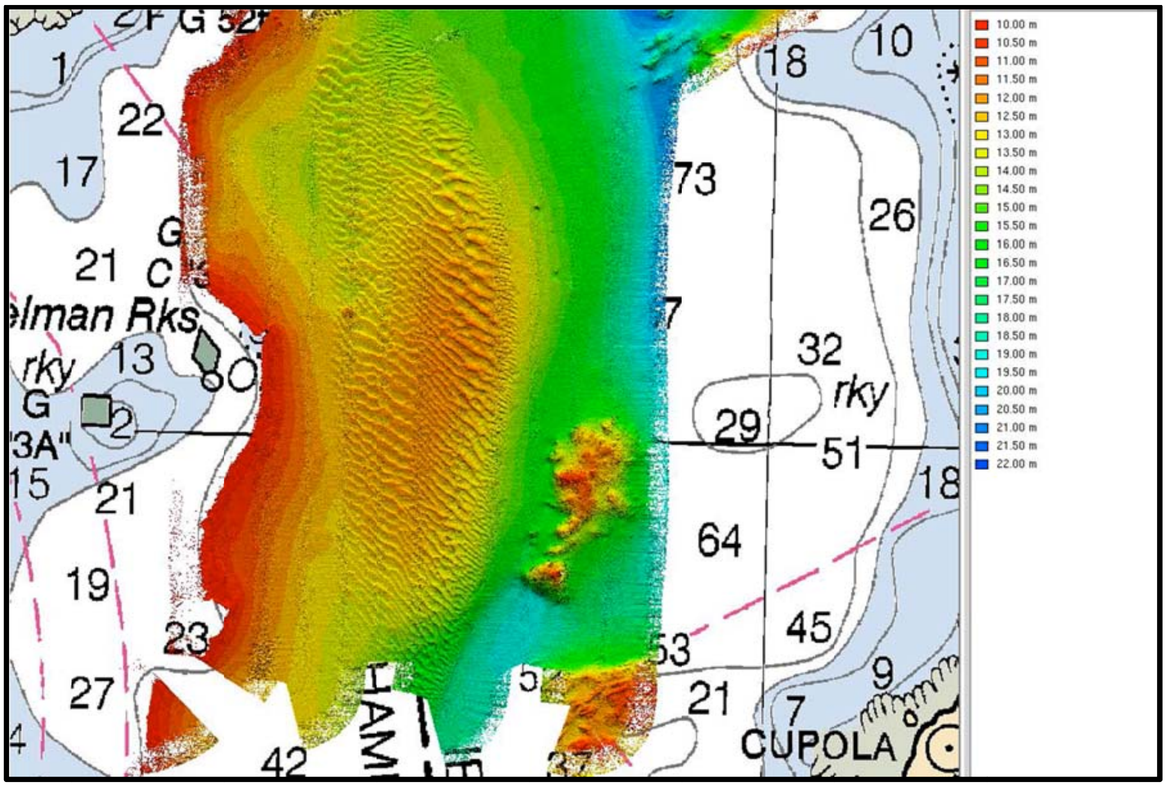

Figure 3 Sun shaded image of reference bathymetry surface.

AUV Bathymetry and Uncertainty

The AUV mission completed on 06 August 2014 consisted of nine north-south oriented transects at 20 meter line spacing. All nine transects where run first in fixed altitude mode and then repeated in fixed depth mode. The AUV was programmed to obtain GNSS fixes at the start of the mission, in the middle of the mission after completing the fixed altitude lines, and again at the end of the mission. SABER was used to process the data acquired from the nine transects completed in fixed altitude mode. The lines run in fixed depth mode are not reviewed within the scope of this paper. The temperature and conductivity data from this mission were extracted and processed to generate profiles of temperature, salinity and sound speed. Two profiles were generated where the AUV completed depth excursions. The first profile was extracted shortly after the start of the mission at 14:07 universal time coordinated UTC (cast 1), at the southern extent of the planned survey transects. The second profile was extracted at a start time of 15:21 UTC (cast 2) in the location where the AUV completed running the planned transects in fixed altitude mode. While separated in time by 1 hour and 14 minutes, these two profiles were taken within 100 meters of each other. Both profiles generated from the AUV had a maximum sampling depth of 11 meters.

Three CTDs were taken from the surface boat at: 14:43 UTC (cast 3), 14:55 UTC (cast 4), and 16:31 UTC (cast 5). All five of these profiles were taken in the general area of AUV coverage for 06 August 2014. The maximum water depth in the area of AUV coverage is 20 meters. Unfortunately, none of these profiles covered the full water column to 20 meters. Both of the AUV-acquired profiles (casts 1 and 2) were extended in depth from 11 meters to 20 meters by replicating the deepest salinity observation and the deepest temperature observation. Sound speed at 20 meters was then calculated using the replicated temperature, replicated salinity, and the pressure value consistent with 20 meters depth. The processed results of all five profiles are shown in Figure 4. The high tidal dynamics of the area explain the differences between these profiles.

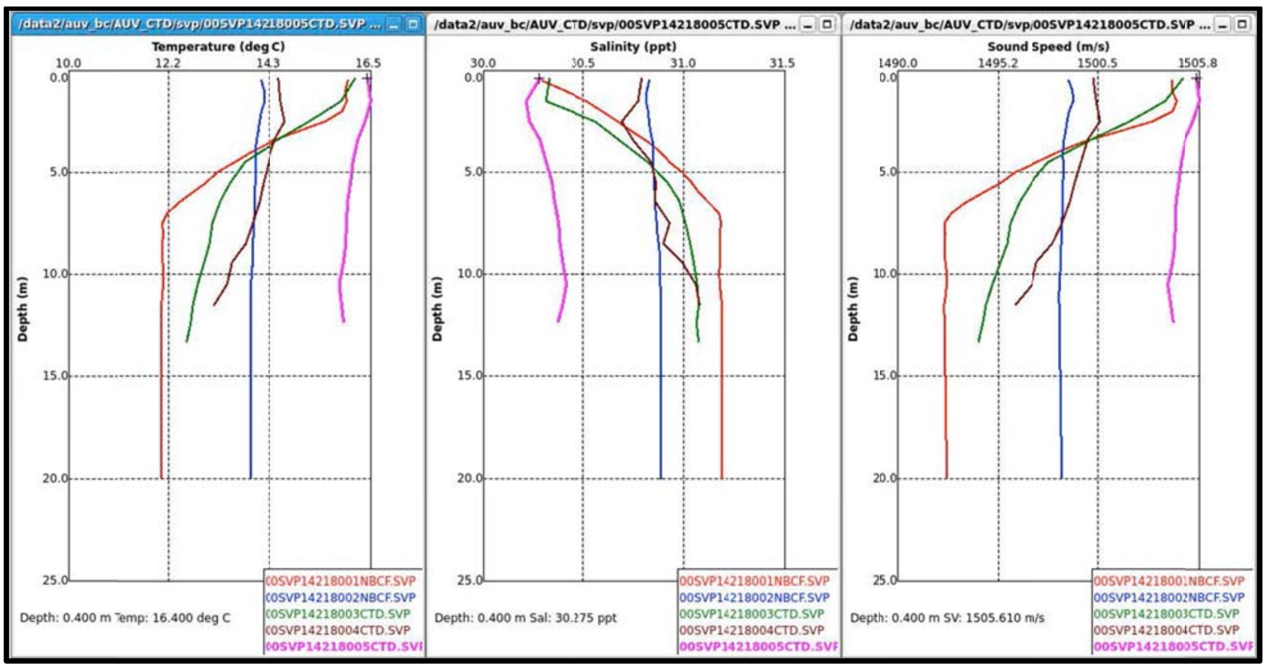

Figure 4 AUV acquired physical oceanographic profiles.

Using the processes described above, pressure to depth conversions were run through all five of these profiles. At a surface relative pressure of 11.5 decibars, (the deepest value of the shallowest profile) a maximum of only 0.02 meters in variability of the computed depth across the five profiles was found. A fixed value of 0.02 meters was used to account for the spatial and temporal variability of the weight of water above the AUV, one of the two components of $\sigma^2_{d_{WATERCOLUMN}}$ from Equation 1. For this mission, the spatial and temporal variability of the water mass above the vehicle is not a dominant contribution to the uncertainty model, in part due shallow operating depths.

NavLab processing was completed and the final 3-D AUV position and uncertainty solution was generated. The horizontal position uncertainty and the vertical position uncertainty are shown in Figure 5, for the timeframe covering the fixed altitude survey transects. GNSS position fixes were acquired and used in the navigation solution when the AUV was on the surface at the start of the mission near 14:00 UTC, and gain when the AUV surfaced at approximately 15:25 UTC. As seen in Figure 5, the horizontal navigation uncertainty is well constrained by the forward-backward processing that ties the uncertainty down across the elapsed time between GNSS fixes, producing a smooth uncertainty over these extents, and leaving the largest uncertainty estimate near the mid-point in time between the GNSS fixes.

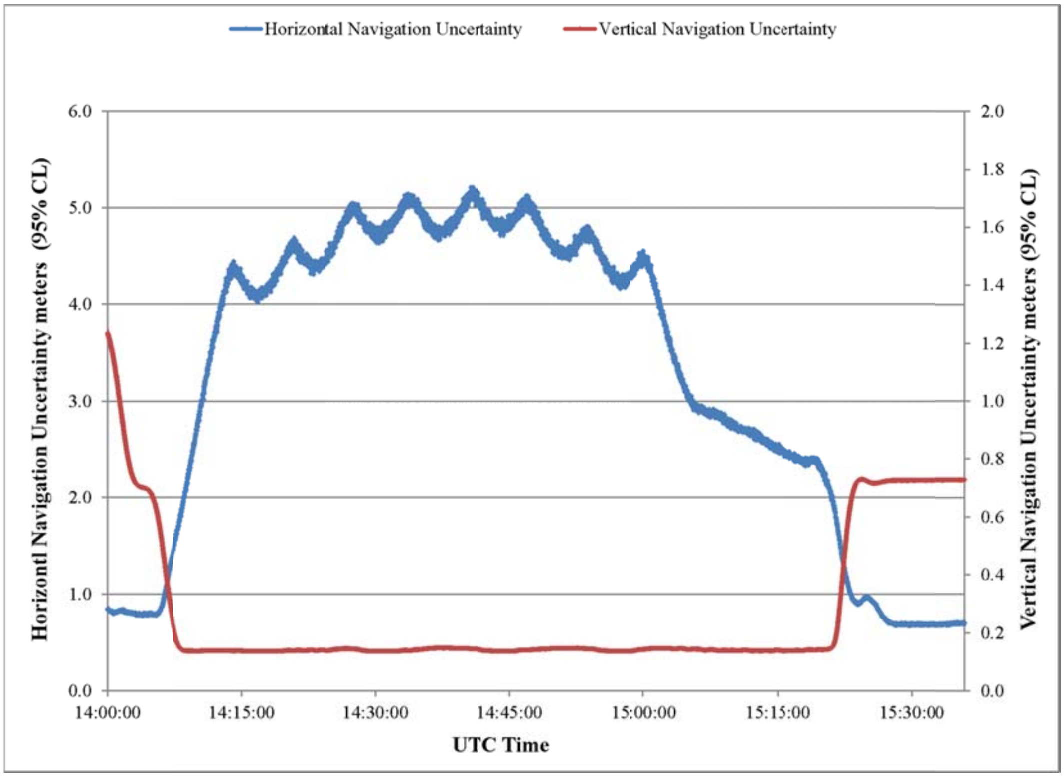

Figure 5 NavLab horizontal uncertainty and NavLab vertical uncertainty.

When the bivariate distribution of latitude and longitude is isotropic, meaning their standard deviations are equal, a scaling factor of 2.45 times the standard deviation of one component is used to compute the 95% CL. [11] Likewise, the root sum square (RSS) of two equal-valued components would be scaled by a factor of 1.74 to obtain 95% CL [12]. The horizontal and vertical navigation uncertainties are scaled to 95% CL in Figure 5 since the THU is largely controlled by the AUV navigation uncertainty and it is useful to review this in context with the allowable THU. When the AUV is submerged, the latitude and longitude standard deviations will have an elliptical distribution, so scaling from the one-sigma values output from NavLab to 95% CL is not a straightforward multiplication. The scaling applied in Figure 5 was arrived at empirically for each position by creating a distribution of points having the statistical uncertainty in x and y equal to that output from NavLab and then determining the 95th percentile radial distance. Relative to the shallowest depth of 11 meters from the area covered, the allowable order 1 horizontal uncertainty is 5.55 meters at 95% CL. At the maximum AUV navigation uncertainty of 5.2 meters (95% CL), there is remaining horizontal uncertainty budget of 0.35 meters for all additional contributions from the sonar measurements, attitude data, lever arms, and sound speed, in order to remain within the IHO order 1 guideline. When the sound speed profile below the AUV is adequately sampled, and all other horizontal uncertainty contributions are well controlled, it is then feasible for the majority of the EM3002 soundings from this sample dataset to have THU values within the allowable limit for order 1 guidelines.

The ramp-up in horizontal uncertainty near the start of the mission has a slope noticeably steeper than estimated by the simple model presented in Figure 1. Indeed, positional errors as measured by post-mission fixes and in-mission acquisition of repeat-measurement survey targets often indicate that NavLab overestimates the AUV position uncertainty. If the position uncertainty values output from NavLab are overly conservative, this could result in less than optimal survey efficiently by elimination of data that exceed the allowable THU. While it may be safer to be conservative than aggressive, future work is planned to better understand the uncertainty estimates output from NavLab and to work towards ensuring that these are a truly representative characterization of the position solution. For the present work however, THU assessment is based on the NavLab reported values.

In SABER, the EM3002 raw.all files are converted to generic sensor format (GSF), and the NavLab results are merged into the bathymetry files. During this process, the AUV position (latitude, longitude, depth), heading, roll, pitch and time-varying navigation uncertainty values are updated in the GSF files. As described above, the NavLab depth solution is converted to pressure to allow for removal of the time-varying atmospheric pressure, and to allow for use of the in-situ sampled temperature and salinity profiles in the conversion to establish the AUV operating depth in meters. Given that the navigation and orientation data have been updated with the NavLab position solution, and given that the EM3002 was operated with a default SVP during acquisition, it is necessary to do a full swath recalculation of the platform relative across-track, along-track, and depth below the AUV. The full swath recalculation starts from the raw sonar travel-time measurements, and uses the full time series attitude data, position data, lever arm offsets, installation offsets, patch test results and the SVP for the refraction calculations. For the results presented here, the full swath recalculation is done using the processing algorithm in SABER. The AUV bathymetry data presented here were generated using SVP cast 2, the profile shown in blue in Figure 4, for both the pressure to depth conversion process and for the refraction calculations. The bathymetric value for each sounding is a combination of the EM3002 altitude value and the final AUV depth. Water level corrections were applied using the verified tides from NOAA gauge 8423898 located at Fort Point, New Hampshire. Given proximity to Fort Pt. the survey area was treated as being in the same tide zone as the gauge itself, so the observed water levels were applied directly, without applying any zone mapping parameters.

The TPU model was then run on the GSF files to compute the THU and the TVU estimates for each sounding. This approach starts from the horizontal position uncertainty provided by NavLab and then combines all additional horizontal uncertainty estimates to arrive at a THU for each sounding in the GSF file. The current approach in SABER assumes equal distribution between latitude uncertainty and longitude uncertainty, improving this assumption for AUV-acquired data is planned for a future version. Similarly, the vertical position uncertainty provided by NavLab is combined with all other uncertainty components that contribute to the vertical uncertainty.

A 0.5 meter node spacing CUBE bathymetric model was then generated. The number of soundings contributing to each selected hypothesis ranges from approximately 25 observations for areas of single coverage to approximately 50 for areas of overlapping coverage. While there are occurrences of EM3002 soundings that are inconsistent with the CUBE surface, no data cleaning has been completed. The results are shown in Figure 6 and Figure 7. Figure 6 shows two images of the AUV generated bathymetry surface with sun shading from the north and with sun shading from the west. Figure 7 shows the standard deviation of all soundings contributing to the selected hypothesis for each node. The increase in standard deviation in the across-track direction visible in Figure 6 is consistent with the artifacts visible in the west-shading image in Figure 6 and results from a combination of horizontal positioning uncertainty and the under-sampling of the physical oceanography resulting in a refraction variance. The horizontal navigation uncertainty is maximum when the AUV is in the center of the area, and covering some of the largest sand waves. Here, the combination of the AUV horizontal uncertainty and the large slope in the seafloor results in the higher standard deviation values shown in Figure 7. Also notable in Figure 7 are two localized areas of high standard deviation in the south-east corner of the area, labelled as areas 1 and 2 in Figure 7. The high standard deviation in area 1 is attributable to a timeframe when the AUV experienced 20 degrees positive pitch followed by 20 degrees negative pitch. These pitch extremes exceed the pitch steering capability of the EM3002 resulting in poor signal-to-noise ratio and poor bottom tracking. In general, the bathymetry around conditions such as this would need manual editing. The high standard deviation in area 2 is attributable to horizontal position uncertainty in the vicinity of high seafloor slope.

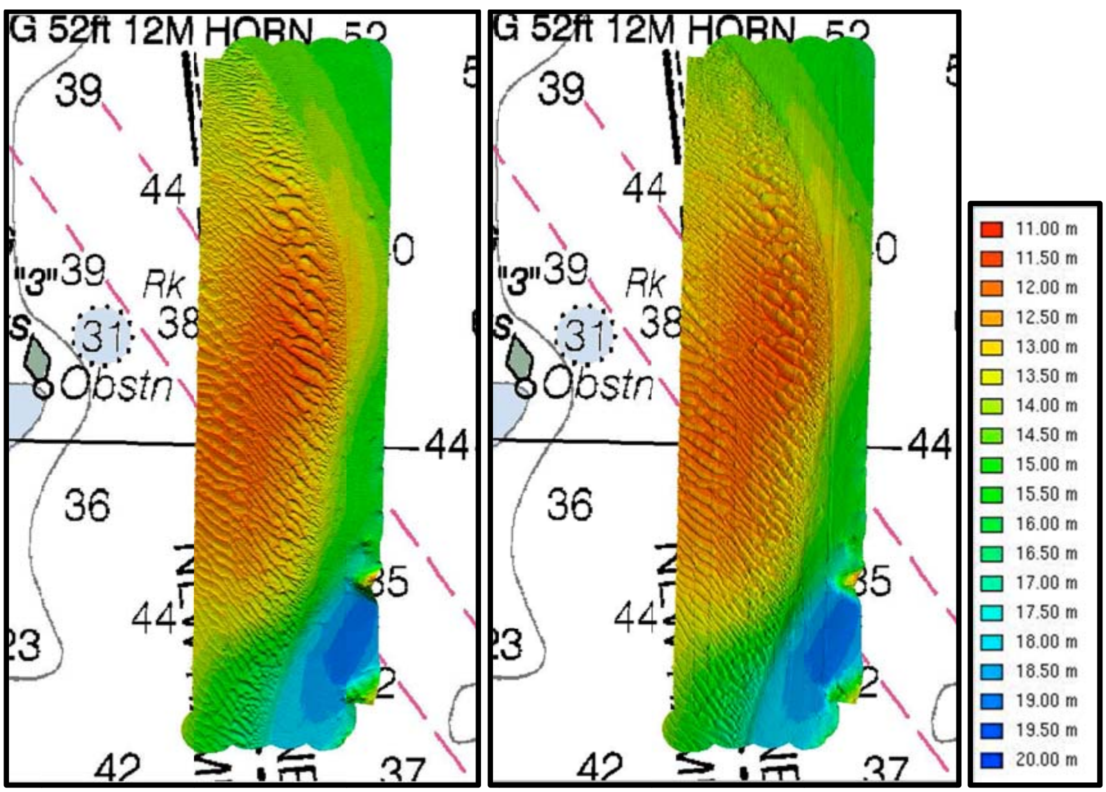

Figure 6 CUBE grid surface of EM3002 data acquired from the AUV. Image on left is sun shaded from the north, image on the right is sun shaded from the west.

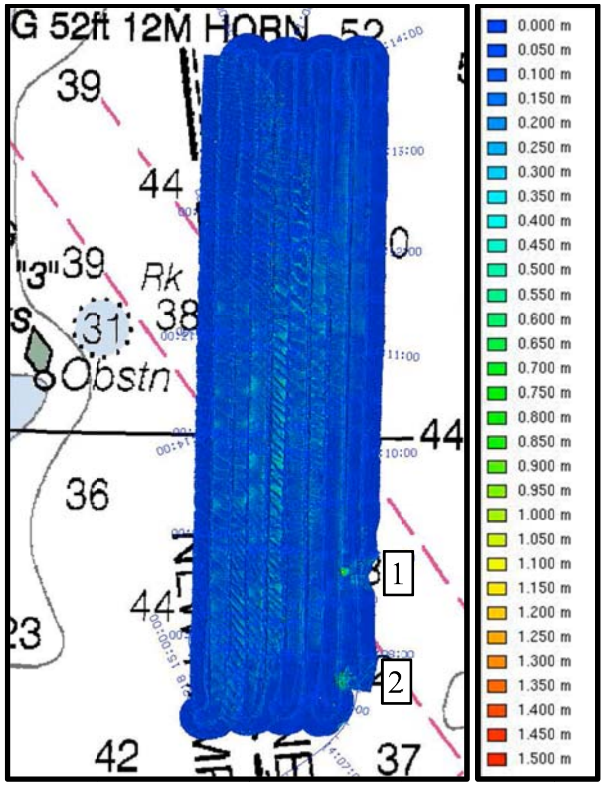

Figure 7 CUBE Node Standard deviation of depth for EM3002 data acquired by the AUV.

A difference grid was produced by bin-for-bin subtracting the AUV bathymetry surface from the CCOM reference surface. The result is shown in Figure 8. The variability of nearly +/- 1.0 meter in the area of the sand waves is attributable to high local slope of the seafloor, magnifying the combined effects of positional errors in the surfaces and migration of the bed forms themselves as the elapsed timeframe between the surveys is approximately three months. Notably, little difference is seen over stationary rock outcrops in the south east of the survey and because sand waves in this area have been known to migrate 0.2 m - 0.6 m in just 7 days [13], most of the difference shown here is believed to result from sand wave migration. Nonetheless, AUV positional uncertainty is highest over the sand wave field and therefore contributes to the observed differences.

The frequency distribution of depth differences is shown in Figure 9. Here, 95% of the differences are less than 0.38 meters. The mean difference is approximately 0.07 meters, with the AUV bathymetry surface shallower than the reference. If the area of sand waves is excluded from the grid difference statistics, then 95% of the differences are less than 0.19 meters and mean difference is 0.08 meters with the AUV surface shallower.

The level of agreement between the two surveys is well within both their respective TVU and the allowable maximum vertical uncertainty for an order 1 survey. The THU values for the soundings near the peak navigation uncertainty at 14:40 UTC are generally less than the maximum order 1 allowed uncertain of 5.55 meters. The AUV remained submerged for almost 1.5 hours and with the post-processed horizontal positioning uncertainty remaining less than the allowable IHO order 1 guideline for the survey area minimum depth. This time duration is approximately three times longer than the maximum duration estimated by the straight-line, real-time navigation uncertainty model shown in Figure 1, clearly demonstrating the significant improvement realized from post-processing the navigation and from limiting survey transect line length.

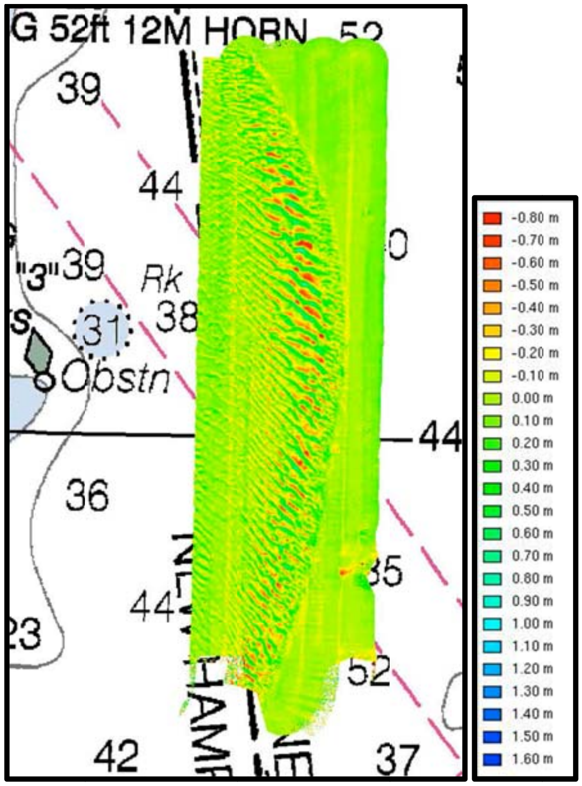

Figure 8 Difference grid obtained when AUV bathymetry is subtracted from reference surface.

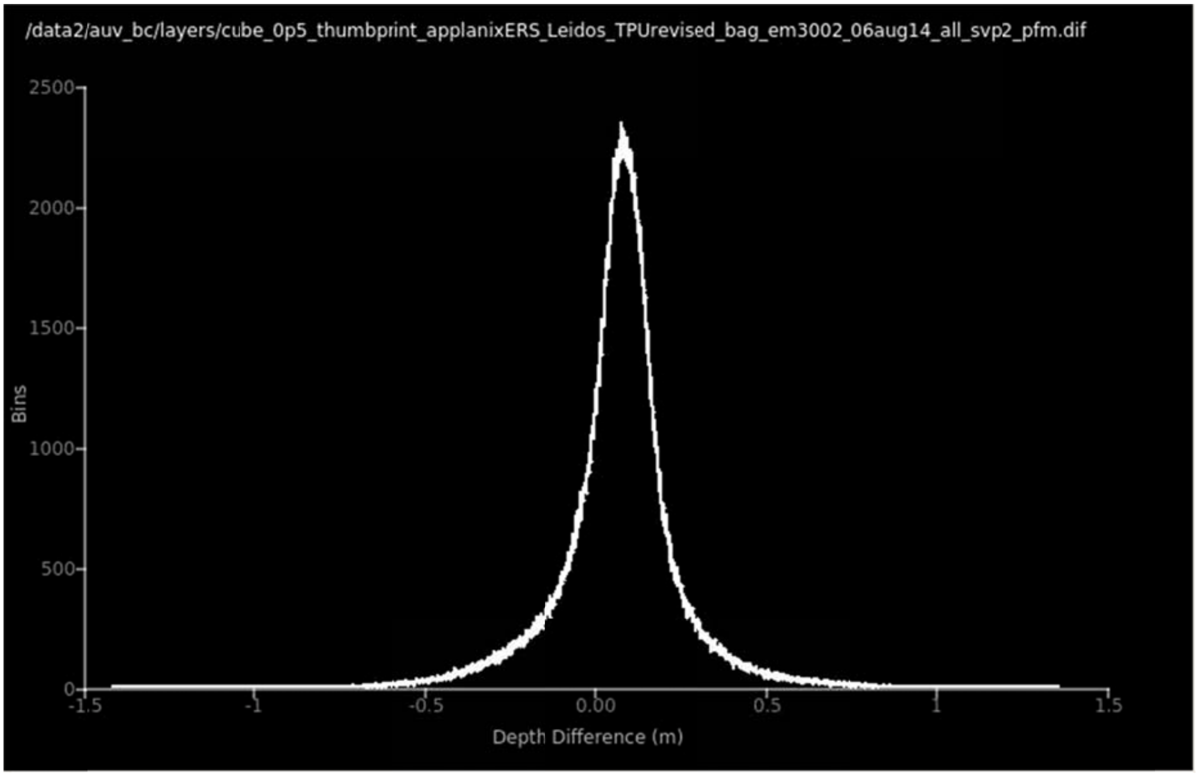

Figure 9 Frequency distribution of depth differences.

Conclusions

Autonomous underwater vehicles provide a unique set of capabilities to the hydrographer. Their autonomy can provide for increased survey efficiency. Their ability to map at a constant altitude no matter the water depth allows them to create higher resolution bathymetric data sets than possible from surface vessels. When necessary, their stealth allows them to operate undetected from the surface. However, careful operational and post-processing considerations must be made to achieve hydrographic standards for uncertainty.

AUV systems benefit from integration of SBAS GNSS positioning, as position uncertainty only grows while submerged. Use of clock and ephemeris GNSS corrections is generally not practical given the convergence time requirements for these solutions. Because drift in the inertial solution is so greatly constrained by DVL measurements, when at all possible, missions should begin in waters sufficiently shallow such that DVL lock on the seafloor can be obtained while on the surface. Even if the vehicle must transit several kilometers to the survey area, it is generally advantageous to start a mission with DVL bottom lock. Particular attention should be paid to the process of calibrating the alignment between the DVL and IMU. While beyond the scope of this paper, errors in this calibration can quickly become the largest source of uncertainty growth when unaccounted for. Navigation uncertainty growth is checked with frequent turns, allowing the KF solution to “observe” unaccounted for alignment biases and largely removing their effect on reciprocal lines. Therefore survey plans should consist of small patches, with transect line length limited by the allowable horizontal uncertainty required by the products to be produced from the mission data. Uncertainty in the navigation solution must be monitored, ideally by the AUV itself, such that the vehicle can return to the surface for GNSS fixes should the position uncertainty grow too large. Alternatives to GNSS position fixing are possible using acoustic ranging systems, e.g., single beacon navigation [14]. When such capabilities are included in the mission configuration, it is possible for the AUV to remain submerged for its entire energy capacity.

Great value is realized in post-processing navigation through a Kalman smoother type operation. For many missions, such an operation will significantly increase the time the AUV may remain submerged without exceeding positional uncertainty limits. To implement post-processing of this type requires an inertial system capable of logging all measurements at the full data rate and careful scrutiny of measurement uncertainty models for each subsystem.

As demonstrated here, achieving IHO order 1 compliant hydrographic data products is achievable with careful planning of AUV operations and post-processing of AUV navigation and bathymetry data. The TPU model presented here is consistent with industry standard models for surface ship acquired datasets, and includes the considerations unique to seafloor mapping using an AUV.

Acknowledgements

This work would not have been possible without the support of and contributions from UNH/CCOM, the University of Delaware, NOAA, Kongsberg, Hydroid and the participants of AUV Bootcamp 2014. Specific thanks to Øyvind Hegrenæs for his expertise in NavLab and his support in processing the AUV navigation. Thanks to Steve Brodet of Hydroid and to Øyvind Hegrenæs of Kongsberg Maritime for their review and feedback on this work. This work is supported in part by NOAA Grant NA10NOS4000073. Recognition is also extended to NAVOCEANO for their support and guidance and whose AUV operations are leading the way forward.

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Appendix, Pressure conversion to depth in the ocean

The classical structure of the pressure-to-depth calculation equates the geopotential due to the earth's gravitational pull as a function of depth with that due to the pressure exerted by a mass of water. The effect of the mass of water is split into the effect of water at standard ocean conditions and that due to the specific volume anomaly, which itself is called the *geopotential anomaly*. The task at hand is to calculate the geopotential anomaly, which requires integration of the specific volume anomaly vertically through the water column from the surface to the pressure of interest, in which the specific volume anomaly is calculated from salinity and temperature measurements made vertically down through the water column. These measurements may be obtained from conductivity, temperature and depth (pressure) (CTD) casts obtained during the survey or by a synthetic vertical profile of measurements obtained from the vehicle itself during its dive and return from survey depth. [Both methods were used over the course of AUV Hydrographic Bootcamp with negligible difference, although missions were generally limited to under 3 hours in a relatively stable environment.] The calculation itself is facilitated by algorithms specified in [Fofonoff and Saunders] (UNESCO 1983) or [TEOS-10] (UNESCO 2010), and function calls to software libraries implementing these algorithms.

Specifically, the conversion from pressure-to-depth using Fofonoff algorithms (UNESCO 1983) is given by the following recipe:

1) Calculate the depth of the AUV, Zo(t), due from pressure measurements assuming "standard" ocean conditions, where P(t) is the hydrostatic pressure measured by the vehicle during the survey and LAT is the nominal latitude.

   Zo(t) = SW_DPTH(P(t),LAT));

2) Calculate the "geopotential anomaly", GA, at each measured pressure, P, in the CTD cast, due to deviations from "standard" ocean conditions. This term is calculated using the "GPAN()" function provided in [REF] from the CTD cast data ,where S is salinity in PSU, T is temperature in degrees Celsius, and P are the pressures at which the salinity and temperature measurements were made in decibar.

   GA = GPAN(S,T,P);

1) Interpolate the geopotential anomaly calculated above to the hydrostatic pressure time series, P(t), recorded during the survey.

   GA(t) = interp1(P, GA, P(t));

3) Add the effect of the standard ocean and the effect of geopotential anomaly.

   Z(t) = Zo(t) + GA(t) / 9.8;

Using the newer Thermodynamic Equation of State of Seawater (UNESCO 2010), one may use the following recipe:

2) Given a CTD cast at (LON,LAT), in which salinity, S, is measured in PSU and Temperature, T, is measured in degrees Celsius at depths having pressures, P, first convert these measurements to "Absolute Salinity" and "Conservative Temperature".

   SA = gsw_SA_from_SP(S, P, LON,LAT);
   CT = gsw_CT_from_T(SA, T, P);

3) Calculate the "geopotential anomaly" due to deviations from "standard" ocean conditions for the pressures of each CTD measurement. Note that within the TEOS10 library, geopotential anomaly is referred to as the "Geostrophic Dynamic Height" or alternatively the "dynamic height anomaly".

   GA = gsw_geo_strf_dyn_height(SA, CT, P, 0);

4) Interpolate the geopotential anomaly calculated above to the hydrostatic pressure time series, P(t), recorded during the survey.

   GA(t) = interp(P, GA, P(t));

5) Calculate the final depth, including the effect from the standard ocean and variations from it. This is done with a single function call, passing both the pressure time series, P(t), latitude, LAT, and the geopotential anomaly, GA(t).

   Z = gsw_z_from_p(P(t), LAT, GA(t));

Conversion from Pressure to Depth

Consider the following equation for hydrostatic pressure P, due to a liquid of uniform density, ρ, under a constant force of gravity with acceleration, g, at a depth, z.

$$P = \rho g z$$

Reorganization the equation it can be expressed as a balance of geopotentials, where $\frac{1}{\rho} = V$, is the specific volume anomaly.

$$gz = \frac{P}{\rho}$$

$$gz = PV$$

Thus far the force of gravity has been considered constant with depth and the specific volume anomaly constant with pressure. However they are not and as such the geopotential balance can be expressed in integral form as shown below.

$$\int_0^z g(z)\,dz = \int_0^P V(P)\,dP$$

The LHS is approximated such that gravity is given as a latitude dependent term plus linear variation of gravity with depth. The RHS is broken into calculation of the geopotential due to conditions of a standard ocean and that due to conditions that vary from that of a standard ocean (the "geopotential anomaly"), where S is Salinity and T is temperature.

$$\left[g[\phi] + \frac{1}{2}\gamma z\right] z = \int_0^P V(35\ PSU, 0\ C, P)\,dP + \int_0^P [V(S,T,P) - V(35,0,P)]\,dP$$

When the two RHS integrals have been evaluated, the resulting equation may be solved for depth as a function of pressure. UNESCO 1983 and UNESCO 2010 take slightly different approaches with generally negligible differences. Specifically, UNESCO 1983 replaces the integral of the specific volume under standard ocean conditions with a 4th degree polynomial numerical approximation, and further approximates depth within the brackets on the LHS by pressure in decibar. UNESCO 2010 evaluates the integral of the specific volume anomaly using the Gibbs function equation of state, and evaluates the resulting second-order equation in depth using the quadratic equation solution.

$$\left[g[\phi] + \frac{1}{2}\gamma z\right] z = G_o + G_a$$

$$z = -\frac{g[\phi]}{\gamma} + \frac{\sqrt{g[\phi]^2 + 4\frac{1}{2}\gamma(G_o + G_a)}}{\gamma}$$