Short article

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Estimation of total vertical uncertainty for the bathymetry acquired by autonomous underwater vehicle in deep water†

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Abstract

Total vertical uncertainty (TVU) for the bathymetry acquired by multibeam echo sounder deployed on Autonomous Underwater Vehicle (AUV) in deep water was estimated. The existing uncertainty model for hydrographic survey using survey vessel was applied to AUV for estimation. Estimated TVU are between 0.27 m and 0.35 m for AUV depth 475 m and altitude 25 m, and between 0.34 m and 0.55 m for AUV depth 950 m and altitude 50 m. With the estimation method described in this paper, the uncertainty can be estimated for any AUV depth and altitude, regardless of vehicle's platform.

1 Introduction

In recent years, Autonomous Underwater Vehicle (AUV) is becoming a major tool for underwater survey and research in the world. AUV has a big advantage for bathymetric survey because it can acquire higher resolution bathymetry than survey vessel by bringing the echo sounder closer to seafloor. This advantage is especially enhanced in deep water survey. The high-resolution bathymetry helps to find unrevealed morphological features and geological structures in seafloor.

Japan Coast Guard (JCG) starts operation of AUV to enhance the survey and research in Japan's territorial seas and exclusive economic zones in 2013, with the main purpose of acquiring high-resolution bathymetry in deep water. Total Vertical Uncertainty (TVU) (IHO, 2008) is important attribute information for evaluation and use of bathymetric data.

The estimation method of TVU for AUV is different from that for survey vessel. This is because survey vessel directly measures bathymetry by using echo sounder, while AUV measures vehicle's depth with its pressure sensor, as well as the distance between the AUV and the seafloor by echo sounder. As depth measurement is affected by variation of barometric pressure and pressure-depth conversion model, the uncertainty specific to AUV survey needs to be incorporated into total vertical uncertainty.

Jalving (1999) incorporated these error sources from the external environment and estimated the depth accuracy in seabed mapping with AUV. The estimated accuracy was 0.13 m for AUV depth 300 m, altitude 50 m and beam angle 30 degrees. The estimated values may become one reference for

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our AUV survey, but will change depending on vehicle's platform such as echo sounder and motion sensor, and also on operating depth. Therefore, the flexible uncertainty estimation model specific to JCG's AUV is required. In this paper, TVU for AUV survey is computed quantitatively by applying the standard uncertainty model for hydrographic survey using survey vessel.

2 Total vertical uncertainty model for AUV survey

Reduced depth to reference datum is given by the following equation (Fig. 1),

$$d = d_{AUV} + d_{Depth} - d_{WL} \quad (1)$$

where d is reduced depth to reference datum (final bathymetry), d_{AUV} is measured bathymetry beneath AUV, d_{Depth} is measured depth above AUV, d_{WL} is measured water level above reference datum, which is affected by tide and wave.

These components are independent with each other, so the total vertical uncertainty is given by applying the method of propagation of uncertainty to equation (1),

$$\sigma_d{}^2 = \sigma_{d_{AUV}}{}^2 + \sigma_{d_{Depth}}{}^2 + \sigma_{d_{WL}}{}^2 \quad (2)$$

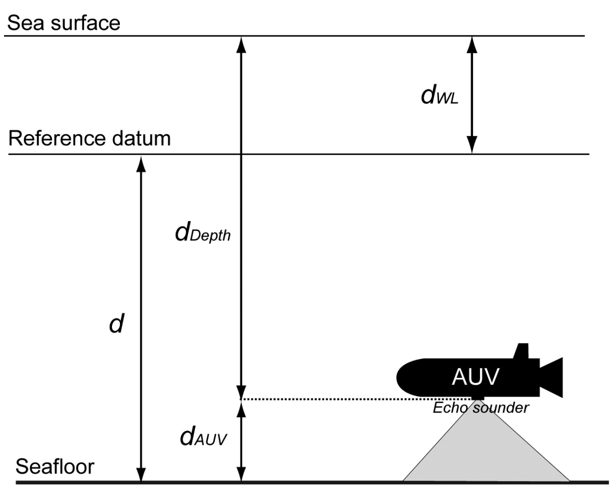

Fig. 1 Schematic image for bathymetry acquired by AUV.

where the symbol σ means the uncertainty for each component. It is noted that TVU is a priori uncertainty of each sounding, which is theoretically computed. It is different from a posteriori uncertainty such as standard deviation of multiple soundings as a result of actual survey.

2.1 Uncertainty for measured depth by AUV ($\sigma_{d_{AUV}}$)

The uncertainty model called as HGM model (Hare et al., 1995) is used here. This is a model developed for the uncertainty estimation mainly for hydrographic survey using multibeam echo sounder (MBES) on survey vessel. It is the most commonly used uncertainty model in hydrographic survey and also in ocean mapping. Most of the equations used in this paper were from HGM model.

The measured depth uncertainty $\sigma_{d_{AUV}}$ is given by,

$$\sigma_{d_{AUV}} = \sqrt{\sigma_{d1}{}^2 + \sigma_{d2}{}^2 + \sigma_{d3}{}^2 + \sigma_{d4}{}^2 + \sigma_{d5}{}^2} \quad (3)$$

where σ_{d1} is range uncertainty for echo sounder, σ_{d2} is beam angle and roll uncertainty, σ_{d3} is pitch uncertainty, σ_{d4} is depth measurement limitation for beamwidth and σ_{d5} is heave measurement uncertainty. The details of these terms are explained below.

2.1.1 Range uncertainty for echo sounder (σ_{d1})

Range uncertainty for echo sounder σ_{d1} is given by,

$$\sigma_{d1} = \sqrt{(\cos P \cos \theta)^2 \sigma_r{}^2} \quad (4)$$

where P is pitch angle, θ is beam angle including roll angle R. σ_r is range measurement uncertainty, which is broken down further,

$$\sigma_r = \sqrt{\sigma_{r_{meas}}^2 + \left(\frac{r_{meas}}{v_p}\right)\sigma_{v_p}{}^2} \quad (5)$$

where $\sigma_{r_{meas}}$ is range measurement uncertainty affected by sampling resolution and pulse length. r_{meas} is measured range, v_p is sound speed profile, σ_{v_p} is uncertainty for sound speed profile.

The model of range measurement uncertainty $\sigma_{r_{meas}}$ for the Kongsberg Simrad EM1000 MBES (Hammerstad, 2001) is applied here. The EM1000 has a frequency of 95 kHz and is suitable for shallow and mid-water survey. In most cases, AUV uses shallow type MBES, so the application of EM 1000 range measurement uncertainty model is appropriate. Here, the MBES is assumed to be deployed on the bottom of the vehicle flatly. The range measurement uncertainty is given by,

$$\sigma_{r_{meas}} = \sqrt{\left(\frac{\Delta r_s}{2}\right)^2 + \left(\frac{v \cdot t}{4}\right)^2} \tag{6}$$

where Δr_s is range sampling resolution, v is sound speed at seafloor and t is pulse length.

2.1.2 Beam angle and roll uncertainty (σ_{d2})

Beam angle and roll uncertainty σ_{d2} is given by,

$$\sigma_{d2} = \sqrt{(r \sin\theta \cos P)^2 \sigma_\theta^2} \tag{7}$$

where r is the range which is the geometric distance from the echo sounder to the center of the beam on seafloor. σ_θ is beam angle uncertainty including roll measurement uncertainty, which is broken down further,

$$\sigma_\theta = \sqrt{\sigma_{\theta_{meas}}{}^2 + \sigma_{\theta_{vp}}{}^2 + \sigma_{\theta_{vs}}{}^2 + \sigma_{R_{meas}}{}^2 + \sigma_{\Delta R_{align}}{}^2} \tag{8}$$

where $\sigma_{\theta_{meas}}$ is beam angle measurement uncertainty, $\sigma_{\theta_{vp}}$ is beam angle uncertainty due to sound speed profile, $\sigma_{\theta_{vs}}$ is beam angle uncertainty due to surface sound speed, $\sigma_{R_{meas}}$ is measurement uncertainty for roll angle and $\sigma_{\Delta R_{align}}$ is uncertainty for the correction of roll angle misalignment. Each component is further broken down bellow.

$\sigma_{\theta_{meas}}$, beam angle measurement uncertainty, depends on the type of bottom detection method, amplitude detection or phase detection. This is given by,

$$\sigma_{\theta_{meas}}(amplitude) = \frac{\phi_y}{12} \tag{9}$$

$$\sigma_{\theta_{meas}}(phase) = \frac{0.2\phi_y}{\sqrt{n_p}} \tag{10}$$

$$n_p = \frac{r\phi_y \tan\theta}{\Delta r_p}$$

where ϕ_y is across-track beamwidth, n_p is the number of phase samples used for phase detection, θ is beam angle of echo sounder, here not including roll angle, and Δr_p is range sampling resolution for phase. In this paper, phase detection is used when beam angle θ is over ± 15 degrees.

$\sigma_{\theta_{vp}}$, which is beam angle uncertainty due to sound speed profile, is given by,

$$\sigma_{\theta_{vp}} = \frac{\tan\theta}{2v_p}\sigma_{vp} \tag{11}$$

$\sigma_{\theta_{vs}}$, which is beam angle uncertainty due to surface sound speed, is given by,

$$\sigma_{\theta_{vs}} = \frac{\tan\theta}{v_s}\sigma_{vs} \tag{12}$$

where v_s is surface sound speed and σ_{vs} is uncertainty for surface sound speed.

$\sigma_{R_{meas}}$ is roll angle measurement uncertainty and $\sigma_{R_{\Delta align}}$ is uncertainty for the correction of angle misalignment. $\sigma_{R_{\Delta align}}$ is obtained as the standard deviation of multiple patch test results.

2.1.3 Pitch uncertainty (σ_{d3})

Pitch angle uncertainty σ_{d3} is given by,

$$\sigma_{d3} = \sqrt{(r \cos\theta \sin P)^2 \sigma_P^2} \tag{13}$$

$$\sigma_P = \sqrt{\sigma_{P_{meas}}{}^2 + \sigma_{\Delta P_{align}}{}^2} \tag{14}$$

where σ_P is pitch angle uncertainty, $\sigma_{P_{meas}}$ is pitch angle measurement uncertainty and $\sigma_{\Delta P_{align}}$ is uncertainty for the correction of angle misalignment.

2.1.4 Depth measurement limitation (σ_{d4})

Depth measurement limitation for beamwidth σ_{d4} is given by,

$$\sigma_{d4} = d\left[1-\cos\left(\frac{\phi_x}{2}\right)\right] \quad (15)$$

where ϕ_x is along-track beamwidth.

2.1.5 Heave uncertainty (σ_{d5})

Heave uncertainty σ_{d5} is separated into two components, heave measurement uncertainty σ_{Hmeas} and induced-heave uncertainty $\sigma_{H_{ind}}$,

$$\sigma_{d5} = \sqrt{\sigma_{Hmeas}{}^2 + \sigma_{H_{ind}}{}^2} \quad (16)$$

Substitution of equation (4) to (16) into equation (3) gives measured depth uncertainty $\sigma_{d_{AUV}}$.

2.2 Uncertainty for measured depth by depth sensor ($\sigma_{d_{Depth}}$)

Uncertainty for measured depth by depth sensor is given by,

$$\sigma_{d_{Depth}} = \sqrt{\sigma_{dmeas}{}^2 + \sigma_{dconv}{}^2 + \sigma_{d_{baro}}{}^2} \quad (17)$$

where σ_{dmeas} is uncertainty for pressure measurement, σ_{dconv} is uncertainty for pressure-depth conversion model and $\sigma_{d_{baro}}$ is uncertainty for variation of barometric pressure. The vehicle measures pressure and converts it to depth using pressure-depth conversion model (e.g. Fofonoff and Millard (1983)). The model uses an assumed profile for salinity and temperature. This profile will change with time during AUV survey and the difference between the assumed profile and real one causes the uncertainty through the variation of density. During survey, variation of barometric pressure above sea surface also causes depth uncertainty. Wave and swell also affects depth uncertainty, however, the effect can be negligible for deep water.

2.3 Uncertainty for water level measurement ($\sigma_{d_{WL}}$)

Water level measurement uncertainty is divided into two components, measurement uncertainty at water level gauge σ_{WLmeas} and spatial and temporal prediction (zoning) uncertainty σ_{WLzone}. It is given by,

$$\sigma_{d_{WL}} = \sqrt{\sigma_{WLmeas}{}^2 + \sigma_{WLzone}{}^2} \quad (19)$$

Substitution of equation (3), (17) and (19) into equation (2) gives TVU for AUV.

3 Results

3.1 Parameters used for TVU computation

Table 1 shows the parameters used for TVU computation. Most parameters are from the sensor specifications deployed on JCG's AUV.

TVU was computed as the function of beam angle from $\theta = -60°$ to $60°$. The following two scenarios were considered,

Scenario 1: Depth 500 m (AUV depth 475 m and AUV altitude 25 m)

Scenario 2: Depth 1000 m (AUV depth 950 m and AUV altitude 50 m)

For the computation, the following assumptions were made in this paper,

1) Induced-heave is set to zero.

Since the offset between the MBES and the motion sensor for AUV is short enough, induced-heave is considered to be small and uncertainty for induced-heave $\sigma_{H_{ind}}$ can be negligible.

2) Constant value is used for the uncertainty for variation of barometric pressure.

The averaged maximum pressure variation in 24 hours was 3.5 hPa from the vessel's log of JCG's S/V *Kaiyo* cruise from July 14, 2012 to August 7, 2012 in the coastal areas of Japan. Effect of pressure variation on depth measurement can be estimated by using hydrostatic equation,

$$dz = \frac{dp}{\rho g} = \frac{350Pa}{1030kg/m^3 \cdot 9.8m/s^2} \approx 0.03$$

$$\sigma_{d_{baro}} = 0.03 \ (\mathrm{m})$$

Table 1 Parameters used for TVU computation (uncertainty is expressed as 1 sigma value).

Variable	Symbol	Value (unit)
Beam angle	θ	- 60 to 60 (deg)
Pitch for echo sounder	P	2 (deg)
Roll for echo sounder	R	2 (deg)
Pitch measurement uncertainty	$\sigma_{P_{meas}}$	0.01 (deg)
Roll measurement uncertainty	$\sigma_{R_{meas}}$	0.01 (deg)
Pitch misalignment uncertainty	$\sigma_{\Delta P_{align}}$	0.05 (deg)
Roll misalignment uncertainty	$\sigma_{\Delta R_{align}}$	0.05 (deg)
Beamwidth	ψ_x , ψ_y	1.0 (deg)
Range sampling resolution	Δr_s	0.02 (m)
Range sampling resolution for phase	Δr_p	0.02 (m)
Pulse length	t	0.05 (ms)
Sound speed profile	v_p	1500 (m/s)
Sound speed profile uncertainty	σ_{v_p}	3 (m/s)
Surface sound speed	v_s	1530 (m/s)
Surface sound speed uncertainty	σ_{v_s}	1 (m/s)
Sound speed at sea floor	v	1500 (m/s) for depth 500 m 1480 (m/s) for depth 1000 m
Heave measurement uncertainty	$\sigma_{H_{meas}}$	0.05 (m)
Induced-heave uncertainty	$\sigma_{H_{ind}}$	0 (m)
Uncertainty for pressure measurement	$\sigma_{d_{meas}}$	0.01 % of AUV depth (m)
Uncertainty for pressure-depth conversion	$\sigma_{d_{conv}}$	0.10 (m)*1
Uncertainty for barometric pressure	$\sigma_{d_{baro}}$	0.03 (m)
Uncertainty for water level measurement	$\sigma_{WL_{meas}}$	0.01 (m)
Uncertainty for water level zoning	$\sigma_{WL_{zone}}$	0.05 (m)

*1 Fofonoff and Millard (1983)

0.03 m is used as a fixed value for uncertainty for barometric pressure in this report.

3.2 Computed TVU

Table 2 and Fig. 2 show the results of TVU computation. The results are expressed as 1.96 sigma value.

The results show that TVU is the smallest around beam angle ±15 degrees, where bottom detection method changes between amplitude detection and phase detection. As beam angle gets larger, TVU becomes larger because of the longer range from echo sounder to seafloor.

TVU for beam angle +60 degrees was larger than that for −60 degrees. This is because roll angle for echo sounder is set to +2 degrees in this computation. Large beam angles cause long range and TVU gets larger generally. The effect of echo sounder's tilting is well incorporated into the result.

The AUV altitude for scenario 2 (altitude 50 m) is higher than that of scenario 1 (altitude 25 m). Because of high altitude in scenario 2, the range gets longer and the uncertainty for measured

Table 2 Computed TVU for scenario 1 and scenario 2.

Scenario 1. AUV depth 475 m and altitude 25 m (unit is meter)

	-60°	-45°	-30°	-15°	0°	15°	30°	45°	60°
$\sigma_{d_{AUV}}$	0.23	0.15	0.13	0.12	0.13	0.12	0.13	0.15	0.25
$\sigma_{d_{Depth}}$	0.22								
$\sigma_{d_{WL}}$	0.10								
σ_d	0.34	0.29	0.28	0.27	0.28	0.27	0.28	0.29	0.35

Scenario 2. AUV depth 950 m and altitude 50 m (unit is meter)

	-60°	-45°	-30°	-15°	0°	15°	30°	45°	60°
$\sigma_{d_{AUV}}$	0.42	0.24	0.18	0.16	0.20	0.16	0.19	0.25	0.47
$\sigma_{d_{Depth}}$	0.28								
$\sigma_{d_{WL}}$	0.10								
σ_d	0.51	0.38	0.35	0.34	0.36	0.34	0.35	0.39	0.55

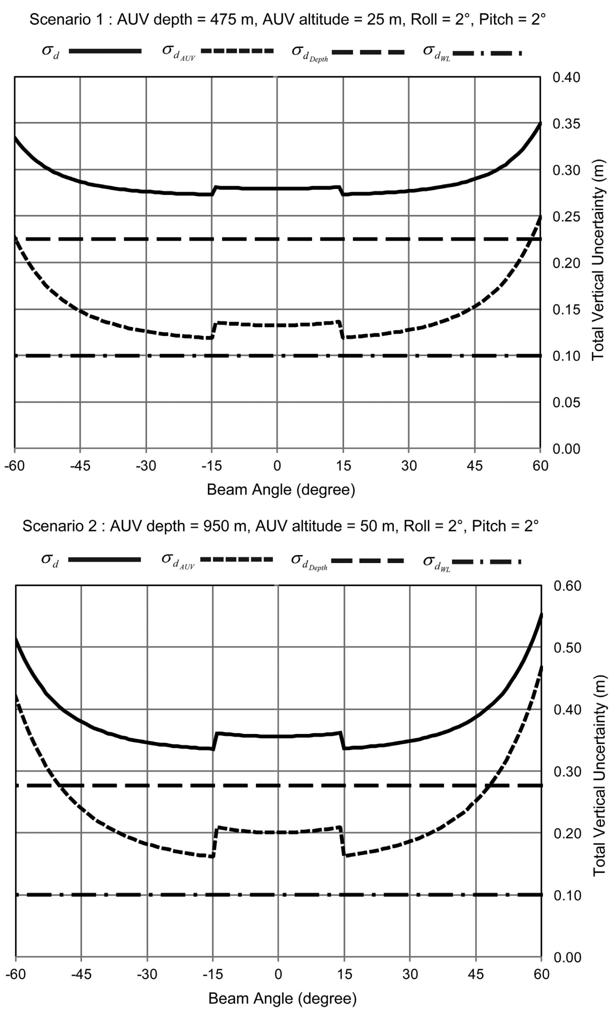

Fig. 2 Total Vertical Uncertainty (TVU) for scenario 1 (upper) and scenario 2 (lower). Horizontal axis is beam angle (degree) and vertical axis is computed TVU (m).

depth by AUV $\sigma_{d_{AUV}}$ becomes larger than that in scenario 2. The uncertainty associated with the measured depth by depth sensor and water level measurement was constant across the swath.

4 Summary

Total vertical uncertainty (TVU) for the bathymetry acquired by AUV was estimated for two scenarios by applying the existing uncertainty estimation model for hydrographic survey using survey vessel. Estimated TVU under some assumptions are between 0.27 m and 0.35 m for scenario 1 (AUV depth 475 m and altitude 25 m), and between 0.34 m and 0.55 m for scenario 2 (AUV depth 950 m and altitude 50 m). TVU are the smallest at MBES beam angle ±15 degrees and becomes large for outer beam angles. With the estimation method described in this paper, the uncertainty can be estimated for any AUV depth and altitude, regardless of vehicle's platform.

The accuracy of depth sensor is necessary to be tested and evaluated in the future work. When AUV is operated in deep water, depth sensor accuracy has a significant impact on TVU. For example, 0.01% accuracy produces 0.1 m vertical uncertainty at depth 1000 m. If the practical sensor accuracy is 0.1%, it produces 1 m uncertainty, which will get larger than the vertical uncertainty for measured depth by AUV. Therefore, better understanding for depth sensor accuracy is critically important for estimation of TVU.

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深海域において AUV で取得する
水深の鉛直総伝搬不確かさの推定

南　宏樹

要　旨

AUV に搭載したマルチビーム音響測深機で取得される水深の鉛直総伝搬不確かさを深海域において推定した．不確かさの推定には，測量船を用いた水路測量で利用される既存の不確かさ推定モデルを AUV に適用した．計算された鉛直総伝搬不確かさは，AUV 深度 475 m，AUV 高度 25 m という条件で，0.27 m から 0.35 m となった．また AUV 深度 950 m，AUV 高度 50 m という条件では，0.34 m から 0.55 m となった．AUV のプラットフォーム（測深機やモーションセンサー）

に関わらず，本報告で述べた方法により，AUVの任意の水深および高度についての不確かさの推定が可能である．