Depthimeter – Precise vessel depth for bathymetry

Brian S. Bourgeois and Andrew B. Martinez

Abstract—
This paper describes the design, operation and field testing of the depthimeter. The depthimeter merges heave and acoustically derived vessel depth to form estimates of instantaneous vessel depth and instantaneous sea surface height, both relative to mean sea level. Results from sea trials held in December 1997 demonstrate successful operation of the system.

Keywords— **Navigation, bathymetry, heave compensation, depth measurement, wave height measurement.**

I. Introduction

THIS paper describes the depthimeter, a system that integrates the output of an up-looking acoustic ranger with a heave sensor to produce a precise measurement of full-spectrum vessel altitude and instantaneous sea surface height, both relative to mean sea level. In sea trials, depthimeter corrected bathymetry has met IHO standards for a special hydrographic survey [1] which requires a constant depth error of no greater than 0.25 m.

The depthimeter was developed to provide precise depth compensation for the ORCA vessel. ORCA (Oceanographic Remotely Controlled Automaton) [2] is an untethered, air-breathing, remotely controlled semi-submersible equipped with a Simrad EM950/1000 multibeam sonar for bathymetric surveying. Distance to the water surface is found using an uplooking acoustic ranger, the Tritech ST500-6 with a range of 0.3 to 50 m and a resolution of 1.2 cm. The 10 m actively stabilized ORCA vessel travels only a few meters below the ocean surface, typically beneath the waves; this provides a stable platform for bathymetry measurements and allows the ORCA to collect bathymetric data of the same quality and quantity as ships that are 60 m or greater.

For all bathymetric survey vessels, sonar ranges must be corrected for the offset between the sonar head and mean sea level, which is subsequently corrected for tide. For both surface and subsurface craft, this offset is the sum of the vertical distance from the sonar head to mean sea level plus the vessel heave. The vertical distance is expected to vary for subsurface craft, but surface ships also experience changes due to alterations in liquid loading and squat effects in shallow water.

Heave is typically measured using an inertial system, whose measurements are derived by double integration of the output of a vertical accelerometer, resulting in two unknown constants of integration. The navigation system high-pass filters the estimated heave, removing low frequencies and effectively setting these constants of integration equal to zero. The consequence of this approach is noted by Clarke et al. [3]: when the absolute vessel elevation changes, the inertial heave does not record the low frequency portion of that change. For slow changes, no evidence of the change will appear in the inertial heave. For fast changes, this results in long transients in the inertial heave. Simply using heave plus vertical offset as vessel elevation ignores the effect of these long-term transients and can result in bathymetry errors. In this paper, the missing low frequency portion of the heave is defined to be the vessel mean path.

It is shown that an up-looking acoustic ranger can be used to estimate mean path. Output of the acoustic ranger can be viewed as instantaneous distance from the acoustic sensor to the sea surface. This includes not only instantaneous depth, but a significant component due to instantaneous wave height. Two conditions must be met for the range data to be used to estimate the mean path component that is missing in the heave data: the component due to wave height must be eliminated and the estimate of mean path must be precisely matched to the missing component in the heave. Precise matching is essential to completely compensate for transients produced by high-pass filtering the heave data. A low-pass filter can be designed that meets both conditions. In addition to extracting a reasonable estimate of mean path, instantaneous vessel depth and wave height, with respect to mean sea level, can also be produced.

II. Design of Estimation Filter

As a convention, all vertical positions are taken to be positive upward relative to mean sea level. Depth is normally considered to be positive downward, so altitude, which is positive upward and the negative of depth, is used to denote the vertical positioning. The up-looking acoustic ranger returns the instantaneous range to the surface. Since range is a distance, and not a position, it is always positive or zero.

The range, $r(t)$, is assumed to consist of two components:

$$r(t) = w(t) - z(t) \tag{1}$$

where $z(t)$ is the instantaneous vessel altitude and $w(t)$ is the instantaneous water surface height with respect to mean sea level. The measurement error in the range is neglected in this and the following computations.

The mean path, $m(t)$, is defined as that part of the altitude not present in the heave. Therefore, the heave $h(t)$ is the position of the vessel relative to its mean path,

$$h(t) = z(t) - m(t). \tag{2}$$

As with the range, measurement error in heave is neglected in the following derivations. The heave is produced by the

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inertial navigation system by double integration and high-pass filtering of vertical acceleration. Since the mean path contains those components of altitude missing in the heave, the mean path contains only very low frequencies. For surface craft in calm seas, this usually produces reasonable results; for submersibles this results in long transients in the heave when changing depth.

An estimate of altitude is found by merging range and heave. Since heave is vessel motion about mean path, it is missing only the low frequency mean path components of altitude. These components are present in the acoustic ranger output, but range also contains a significant component due to wave action and heave. Unfortunately, wave height and altitude are significantly correlated, and this correlation is not known. Thus traditional least squares estimation techniques are not applicable. However, it can be assumed that the surface waves have negligible components at frequencies near zero. Therefore, the range is low-pass filtered with a filter designed to be complimentary to the high-pass heave filter, and the resulting low frequency part of the range is an estimate of the vessel mean path. Design of this filter is critical, as the estimated mean path should exactly replace those low frequency components of altitude missing in the heave and exactly cancel transients introduced by the heave filter.

The heave filter, $P(s)$, in a typical inertial navigation system performs both a double integration and high-pass filtering operation on the vertical accelerometer output. It can be viewed as the cascade of two filters, a double integrator, $1/s^2$, and a high-pass filter, $G(s)$. That is, $P(s) = G(s)/s^2$. By separating the operations of integration and filtering, we can view the heave as the altitude high-pass filtered with $G(s)$. In terms of Fourier transforms,

$$H(s) = G(s)Z(s)$$

where $H(s)$ and $Z(s)$ are the Fourier transforms of heave and altitude respectively. The mean path $M(s)$ is the missing component of altitude, thus using the definition in Eq. 2,

$$M(s) = Z(s) - H(s) = (1 - G(s))Z(s) = L(s)Z(s)$$

where $L(s) = 1 - G(s)$ is defined as the low-pass filter complementary to $G(s)$. The low-pass filter $L(s)$ is dependent on the heave filter used in the navigation system, and it is an extremely narrow-band low-pass filter.

Given $L(s)$, range and heave, both altitude and instantaneous wave height can be estimated. If the low frequency portion of the range is assumed to consist entirely of mean path – or equivalently the wave height $W(s)$ is assumed to have negligible low frequency content – then an estimate of the mean path, $\hat{M}(s)$ is given by the low-pass filtered range,

$$\hat{M}(s) = -L(s)R(s) \quad (3)$$

This follows by noting that $L(s)W(s) \approx 0$ and therefore

$$-L(s)R(s) = L(s)(Z(s) - W(s)) \approx L(s)Z(s) = M(s)$$

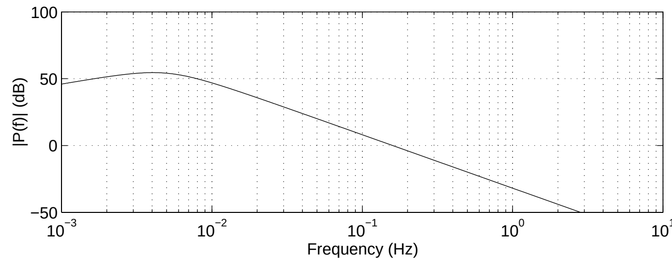

Fig. 1. Frequency response of analog heave filter, $P(s)$.

Given heave and range, altitude can be estimated using the estimated mean path and Eq. 2:

$$\hat{z}(t) = h(t) + \hat{m}(t) \quad (4)$$

Finally, using the definition of range in Eq. 1, the surface wave height can be found by adding the estimated altitude to the range,

$$\hat{w}(t) = r(t) + \hat{z}(t) \quad (5)$$

III. Application to POS/MV system

The analog version of the POS/MV[4] heave filter has transfer function

$$P(s) = \frac{s}{(s + \omega_0)(s^2 + 2\xi\omega_0 s + \omega_0^2)}$$

This filter has two free parameters, the corner frequency, ω_0, and the damping coefficient, ξ. The corner filter is related to a time constant by $\omega_0 = 2\pi/\tau_0$ The default values of these parameters are $\xi = 1/\sqrt{2}$ and $\tau_0 = 200$ seconds (or $\omega_0 = \pi/100$).

The frequency response of this filter is shown in Fig. 1. Note that this filter combines two functions, double integration and high-pass filtering. The filter response rolls off at 40 dB/decade above the corner frequency ω_0 resulting in double integration of the accelerometer data above this frequency. Below ω_0, the response rolls off at 20 dB/decade effectively removing these frequencies from the output. The damping factor ξ is used to produce the clean corner at the corner frequency.

The heave filter can be written as the cascade of two filters, a double integrator, $1/s^2$, and a high-pass filter, $G(s)$. Multiplying $P(s)$ by s^2 gives the transform of the high-pass filter $G(s)$:

$$G(s) = \frac{s^3}{(s + \omega_0)(s^2 + 2\xi\omega_0 s + \omega_0^2)}$$

The frequency response of the analog high-pass filter $G(s)$ is shown in Fig. 2.

The high-pass filter effectively removes low frequency components in the heave, and it has another less desirable effect. Abrupt changes in altitude, which are common in AUV's, produce long transients in the output heave. In Fig. 3 the step response of this filter illustrates the effect of a step change in operating altitude on the heave. Note that the transient is significant for more than 100 seconds.

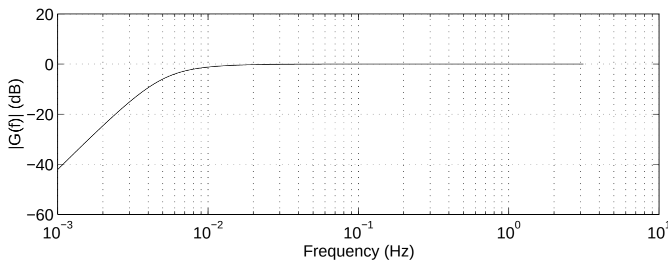

Fig. 2. Frequency response of high-pass part of analog heave filter, $G(s)$.

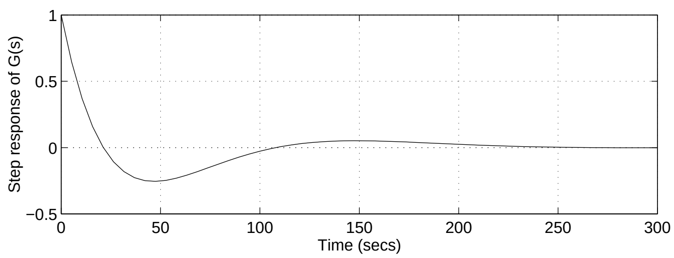

Fig. 3. Step response of high-pass part of analog heave filter.

It is imperative that any method of heave correction also removes transients. It will be shown that this has been accomplished by the careful matching of the estimation filter to the heave filter as derived above.

The complimentary low-pass filter, $L(s)$ can easily be found from its definition above, and a digital version produced using the mapping $s = (1 - z^{-1})/T$. (This is the same mapping used to produce the digital version of the heave filter used in the POS/MV.)

The resulting low-pass digital filter has transfer function

$$L(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3}}$$

The numerator coefficients are functions of ω_0, ξ, and sampling frequency, f_s. Defining the digital corner frequency,$\theta_0 = \omega_0/f_s$, the numerator coefficients are given by

$$\begin{aligned} b_0 &= (\theta_0 + \theta_0^2)(2\xi + 1) + \theta_0^3 \\ b_1 &= -(2\theta_0 + \theta_0^2)(2\xi + 1) \\ b_2 &= \theta_0(2\xi + 1) \end{aligned}$$

The denominator coefficients are found from the numerator coefficients by

$$\begin{aligned} a_1 &= b_0 - 3.0 \\ a_2 &= b_1 + 3.0 \\ a_3 &= b_2 - 1.0 \end{aligned}$$

Values of the numerator coefficients are given in Table I for a damping coefficient of $\xi = 1/\sqrt{2}$, a cutoff frequency of $\omega_0 = \pi/100$, and a sampling frequency of $f_s = 5$. Since the filter response is somewhat sensitive to coefficient round-off, it is recommended that the coefficients be used at the maximum precision possible.

b_0	0.01526450856491123
b_1	-0.03043321169819411
b_2	0.01516895118349632

TABLE I
Digital filter coefficients for $\xi = 1/\sqrt{2}$, $f_s = 5$, and $\omega_0 = \pi/100$.

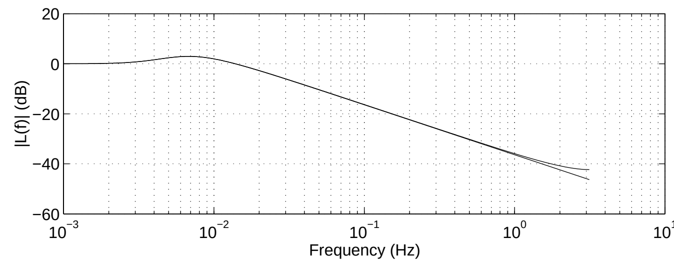

Fig. 4. Frequency response of complimentary low-pass filter.

The frequency responses of the analog and digital versions of this filter are plotted in Fig. 4. Both are low-pass filters with cutoff determined by ω_0 and a small peak resulting from the damping coefficient. The two filters are virtually identical below 1 Hz, and the difference above is negligible due to the attenuation at higher frequencies.

Using the coefficients found above, the low-pass filter can be implemented directly as a difference equation

$$m(n) = -\left[\sum_{k=0}^{2} b_k a(n-k) + \sum_{k=1}^{3} a_k m(n-k)\right] \qquad (6)$$

or the filter can be re-arranged to reduce the number of memory registers or operations.

The processing consists of these steps:

1. Correct bad data points in the range and heave, correct both for roll and pitch and synchronize and resample data streams if necessary.
2. Low-pass filter the range using the filter in Equation 6 to produce mean path.
3. Add mean path to heave to produce altitude as in Eq. 4.

$$\hat{z}(n) = h(n) + \hat{m}(n)$$

4. Add the estimated altitude to range to produce wave height as in Eq. 5.

$$\hat{w}(n) = r(n) + \hat{z}(n)$$

IV. Trial Results

A sea trial of the depthimeter subsystem of the ORCA was performed on 9-12 December 1997. While extensive testing of the system was performed over this period, two survey lines collected on 10 December are presented here to illustrate its performance under static and dynamic conditions. Data consist of two lines taken over the same west-east track with light seas. Line 7 was taken at a fixed command depth of 3 m. This track establishes a steady-state operation of the system and is used as a baseline for

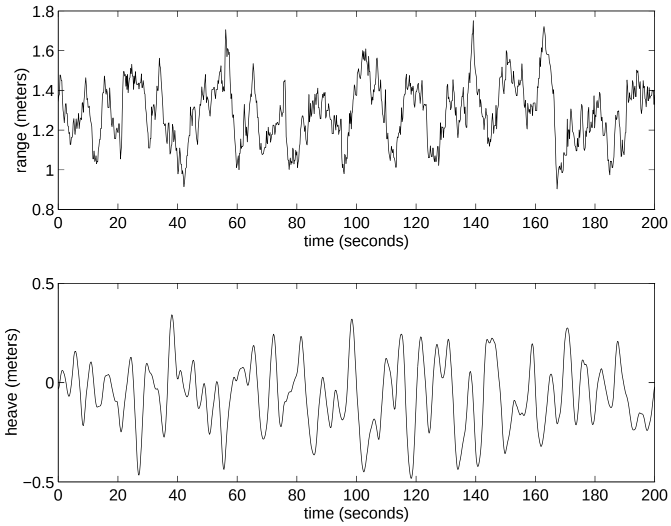

Fig. 5. Line 7 – Corrected range and heave.

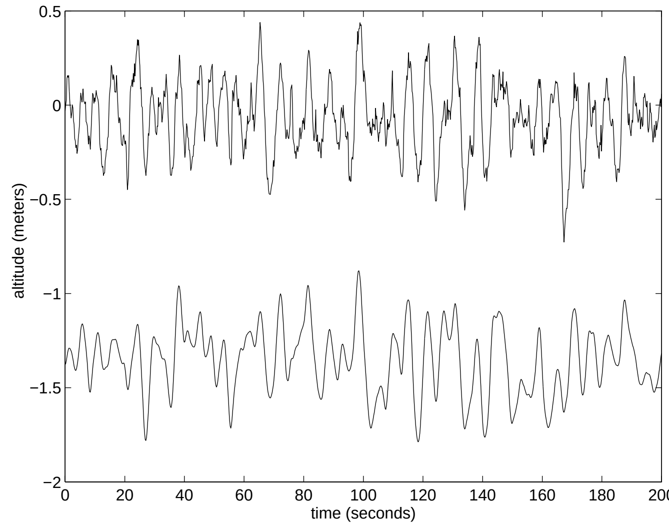

Fig. 6. Line 7 – Vessel altitude and surface height.

the dynamic test. Line 9 includes a change in command depth to test the dynamic behavior of the depthimeter. Since the acoustic ranger is mounted on top of the ORCA, there is a constant difference between the command depth and the depth as measured by the depthimeter. Furthermore, the command depth is based on pressure depth and is not consistent or very accurate. Throughout the trials it was found that a 1 m change in command depth did not actually result in a 1 m change in depth.

Some preprocessing of the data was performed. Missing values in the range data were found and replaced by linear interpolation of neighboring values. The heave data was resampled from 10 to 5 samples per second and synchronized with the range data.

A. Steady State Operation

Raw heave and range for line 7 were corrected for missing samples and are shown in Fig. 5. The resulting estimates of altitude and wave height are shown in Fig. 6. In this and the following lines, correlation between surface waves and vessel altitude can be clearly seen. The vessel was at a command depth of 3 meters for the entire line and the estimated altitude is a fairly constant 1.3 m. Recall that this altitude estimate is referenced to the sensor depth, and command depth is referenced to a different point on the vessel.

B. Dynamic Operation

While line 7 demonstrates the steady-state behavior of the depthimeter, performance under dynamic circumstances is more interesting. In line 9, the same path was traveled with a change in command depth part way through the line.

Corrected heave and range for line 9 is plotted in Fig. 7. The transition from a command depth of 4 to 3 meters is seen in the range about 40 seconds into the line. It is particularly interesting to note the long transient this

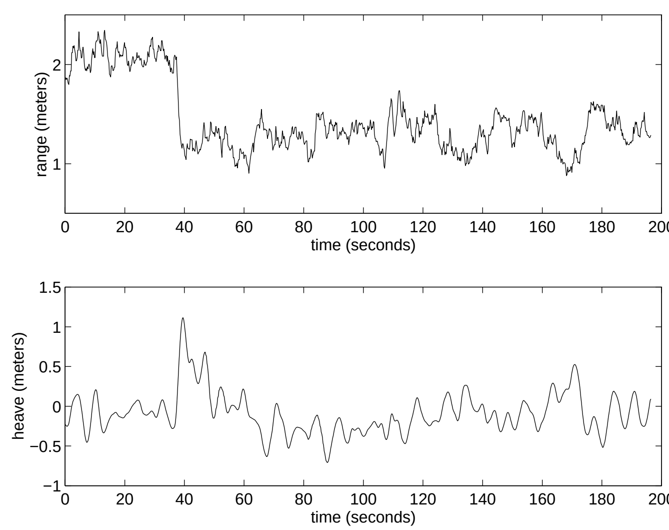

Fig. 7. Line 9 – Corrected range and heave.

change produces in the heave. This is the expected result of high-pass filtering a step function as illustrated in Fig, 3, and this transient is precisely what makes it impossible to use heave alone as a correction to command depth in a dynamic situation.

Fig. 8 shows the estimated altitude and wave height. Note that the transient observed in the heave is not evident in the resulting altitude. The depth change from 2 to 1.3 m is consistent with the depths estimated in other portions of the sea trial for the same command depths.

Using the Simrad swath bathymetry data from each line for comparison, a total system estimated vertical error of 6.5cm RMS was achieved in 12m of water for both constant depth and varying depth scenarios.

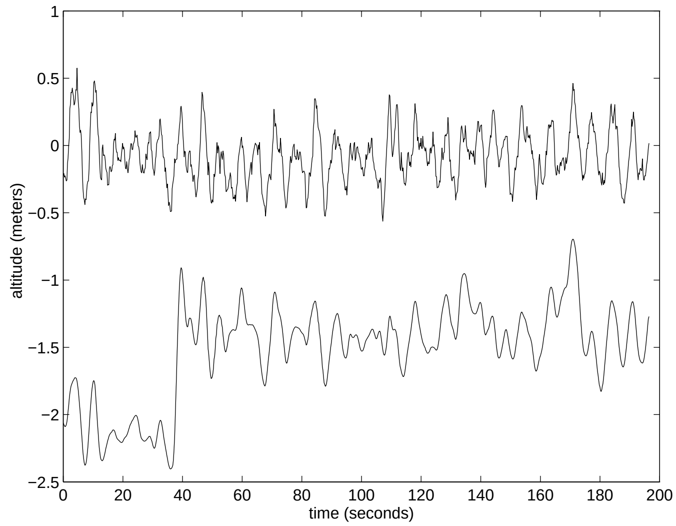

Fig. 8. Line 9 – Vessel altitude and surface height.

V. Conclusions

This paper outlines the design of a depthimeter employed to augment an inertial navigation system on a vessel, and field testing of the depthimeter on the ORCA. By carefully matching a low-pass filter to the heave filter in the inertial system, a consistent and accurate estimate of vessel depth was achieved. The depthimeter was especially effective in situations where the vessel rapidly changed depth.

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