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DEPTHIMETER

BACKGROUND OF THE INVENTION

Field of the Invention

This invention pertains generally to a device for determining the draft of a surface vessel or the depth of a submerged vehicle and more particularly to the accurate measurement of these quantities relative to mean sea level.

Description of the Related Prior Art

A surface vehicles draft is traditionally measured by observing the position of the waterline on hull draft markings. However, it is not feasible to accurately estimate draft in this way when there is wave action. Also, this measurement cannot be accomplished while the vehicle is underway. Another method for measuring draft of a vehicle is by estimation through computation by accounting for the loading of fuel, water and cargo on the vehicle. This is not accurate and does not compensate for squat and lift effects when the vehicle is moving. Squat and lift cause changes in a vehicles draft as a function of vehicle speed, water current and water depth and cannot be accurately computed.

When in close proximity to a shore having a kinematic Global Positioning System (GPS) which measures vehicle position with respect to a GPS reference point, the draft is computed by adjusting the GPS reference point for the tide level at the vehicle's position. Accurate tide level

requires placement of a tide sensor in the proximity of the vehicle. Because of the requirements for off-board sensors, this approach is not generally practical for a transiting vehicle.

In submerged vehicles, depth is traditionally measured by a pressure sensor. With this method of measurement errors occur due to head pressure effects and fluid flow over a moving vehicle; pressure effects due to wave action when the vehicle is near the surface; vertical current components in the water through which the vehicle is moving; and changes in the water density due to temperature or salinity changes.

An acoustic ranging device can be used to determine the travel time of an acoustic pulse, and thus the distance, from the vehicle to the water's surface. For near surface applications the measured range signal is contaminated by surface wave action. Measurement of vertical displacement can also be achieved for a subsurface vehicle using a pressure depth sensor, but the same errors are experienced as discussed above for measuring vehicle depth.

The measurement of vertical displacement for a surface or subsurface vehicle is traditionally accomplished using a heave sensor. A typical heave sensor uses accelerometers to measure the vertical acceleration of the vehicle in order to generate heave. The state of the art heave for sensors, is shown in U.S. Patent No. 4,986,121; APPARATUS FOR MEASURING THE VERTICAL MOTION OF A FLOATING PLATFORM; Luscombe; January 22, 1991; U.S. Patent No. 4,697,253; SONAR HEAVE COMPENSATION SYSTEM; Lind et al.; September 29, 1987; and U.S. Patent No. 4,104,608; HEAVEMETER; Melling et al.; August 1, 1978. These devices compute heave by double integrating measured vertical acceleration of the

vehicle to obtain vertical displacement (heave). Due to the double integration there are two unknown constants of integration and the average value of this signal is thus meaningless and is removed in the heave sensor using a high pass filter. Due to the employment of the high pass filter in a heave sensor , the output cannot be correctly interpreted as vertical displacement after abrupt changes in the vehicle's mean path. The result is a signal that is the heave of the vehicle about an unknown mean path; a heave of zero indicates no vertical displacement from this path. This method of measuring vertical displacement is effective in cases where the mean path of a vehicle does not change or changes very slowly with time. With a heave sensor, knowledge of the vertical position of a vehicle with respect to an earth reference frame requires addition of the heave to draft or depth.

Due to the employment of a high pass filter in the heave sensor, however, the heave signal cannot be used as the vertical displacement of the vehicle after abrupt changes in the vehicle's mean path. **Figure 1** shows the unit step response of a typical heave system high pass filter, denoted G(s). In **Figure 1**, the the sensor is moved 1 unit upward at time zero and left in that position, representing the new mean path. It is evident in **Figure 1** that this change in mean path results in a long transient (several minutes) that represents an error in vertical displacement from the new mean path. Changes in a surface vehicles mean path, i.e., draft, may occur due to a change in loading or due to squat and lift effects. Changes of a submerged vehicle's mean path, i.e:, depth, may occur due to a change in the command depth.

SUMMARY OF THE INVENTION

The object of this invention is to provide a device for accurately measuring a surface vehicles draft relative to mean sea level.

Another objective of this invention is to provide a device for accurately measuring a submerged vehicle's depth relative to mean sea level.

Another objective of the invention is to provide a device for accurately measuring the vertical displacement of a vehicle relative to mean sea level.

These and other objectives are achieved by the depthimeter comprising a mean path compensator, a heave sensor, and a combiner. The mean path compensator comprises a ranging device which measures the instantaneous distance from a fixed point on the vehicle to the ocean surface as a function of time; a range compensator to compensate for signal dropouts in the ranging devices data, for sensor offset angle, and vehicle pitch and roll, thereby providing a signal that includes the vehicles vertical motion and the vertical motion of a sea surface; and a low-pass filter within the mean path compensator that eliminates the component of the resulting signal due to the motion of the sea surface and the high frequency component of the vehicle vertical motion, thereby producing a signal that is the mean path of the vehicle, relative to mean sea level. The heave sensor uses accelerometers to measure the vertical acceleration of the vehicle which is double integrated and filtered to produce heave. The combiner merges the mean path signal from the mean path compensator and a heave signal generated by the heave sensor to

generate a signal that is a surface vehicle's draft relative to mean sea level or a submerged vehicle's depth relative to mean sea level, and is also the vehicle's vertical displacement relative to mean sea level.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a unit step response of a typical heave system high pass filter.

Figure 2 a block diagram of a depthimeter

Figure 3 shows a block diagram of a heave sensor.

Figure 4 shows a block diagram of a mean path compensator.

Figure 5 shows a depthimeter for surface vehicle application.

Figure 6 shows a ranging device footprint and beam width.

Figure 7 shows a block diagram of a range compensator.

Figure 8 shows a block diagram of a combiner.

Figure 9 shows a depthimeter for a submerged vehicle application.

DESCRIPTION OF THE PREFERRED EMBODIMENT

For the purposes of this specification, like elements performing like functions are assigned the same reference number throughout the specification.

In a preferred embodiment, the depthimeter **10**, as shown in **Figure 2**, is used for the determination of the draft of a surface vehicle and for the determination of vertical displacement of the vehicle relative to mean sea level.

Figure 2 is a top-level functional block diagram of the depthimeter **10**. The depthimeter **10** may be implemented as a digital or an analog system, preferably, a digital system. In this embodiment, the parameters measured by the depthimeter **10** are range from a fixed point on the vehicle to the water's surface and vehicle's vertical acceleration.

In this embodiment, as shown in **Figure 2**, the depthimeter **10** is comprised of a mean path compensator (MPC) **12**, a heave sensor **14** and a combiner **16**. The mean path compensator **12** measures the range to the water surface **18** and generates a signal that is the mean path of the vehicle relative to mean sea level **22**. This signal **22** may be time varying if the vehicle's draft changes with time. The mean path compensator **12** eliminates the component due to wave height and high frequency vehicle vertical motion from the range measurement, and the estimate of mean path is precisely matched to the missing component in the heave to completely compensate for transients in the heave. The heave sensor **14** measures the vehicle's vertical acceleration **24** and generates a signal **26** that is the heave of the vehicle. The heave signal **26** does not contain information about the mean path of the vehicle. The combiner **16** takes the heave signal **26** and the mean path signal **22** and generates a signal that is the vehicle's draft as well as the vehicle's vertical displacement relative to mean sea level **28**.

The heave sensor **14**, as shown in **Figure 3,** is a commercial item, such as a Model POS/MV 320, manufactured by Applied Analytics of Markham, Ontario, Canada. or equivalent, and may be either an analog or digital device. A typical heave sensor **14** comprises an accelerometer package **32**, a double integrator **34** and a high-pass filter **36**. The heave sensor **14**

measures the vertical acceleration **24** of a vehicle. The output of the heave sensor **14** is a vehicle's heave **26**, the vertical displacement of the vehicle about its mean path. A vehicle's heave being defined as that component of the vehicle's vertical displacement, with respect to a fixed vertical reference point, that is absent in the vehicle's mean path. The heave signal **26** does not contain information about the mean path of the vehicle **64**. The accelerometer package **32** directly measures the vertical acceleration **38** of the vehicle, to obtain the vertical displacement **42** the double integrator **34** double integrates the vertical acceleration **38** signal . Due to the double integration there are two unknown constants of integration and the average value of this signal **38** is thus meaningless and is removed in the heave sensor **14** using a high-pass filter **36**. The result is a heave signal **26** that is the vertical displacement of the vehicle about an unknown mean path. A heave of zero indicates no vertical displacement from this mean path. This technique of measuring vertical displacement is effective in cases where the mean path of a vehicle does not change or changes very slowly with time. Knowledge of the vertical position of a vehicle with respect to an earth reference requires addition of the heave **26** to draft. Due to the employment of the high-pass filter **36** in the heave sensor **14**, however, the heave signal **26** cannot be used as the vertical displacement of the vehicle after abrupt changes in the vehicle's mean path. As previously noted, the unit response of a typical heave system **14** high-pass filter **36**, denoted G(s), is shown in **Figure 1**. In this figure, the heave sensor **14** is moved one unit upward at time zero and left at that position, representing a new mean path. This change in mean path results in a long transient (several minutes) that represents an error in vertical displacement

from the new mean path. Changes in a surface vehicle's mean path may occur due to changes in loading or due to squat and lift effects.

If the heave sensor **14** is not collocated with the ranging device **44**, the heave measured at the position of the heave sensor **14** may not be the same as the position of the ranging device **44**. If this is the case, then the heave data must be translated, using measured vehicle pitch and roll, to compute the heave of the vehicle **52** at the location of the ranging device. This may require an additional sensor, a vertical reference unit, for the measurement off vehicle **52** pitch and roll. If the POS/MV 320 system is utilized, it also measures vehicle **52** pitch and roll. Given measured pitch and roll, translation of the heave measurement is well known to those skilled in the art.

The mean path compensator (MPC) **12**, as shown in **Figure 4**, measures the instantaneous distance from a fixed point on the vehicle to the ocean surface as a function of time. The output **22** of the MPC **12** is the mean path of the vehicle relative to mean sea level. The MPC **12**, preferably, is a digital device, however, it may be an analog device. The MPC **12** comprises a ranging device or sensor **44**, a range compensator **46** and a low-pass filter **48**.

The ranging device **44** is used to measure r_{meas} **56**, the instantaneous range from a fixed point on the vehicle to the ocean surface as a function of time. Measurement of range is accomplished by measuring the time required for a transmitted pulse to travel from the device **44** to the surface and back to the device **44**; the pulse would typically be acoustic for the ranges discussed herein. This device **44**, preferably, is a combination of analog and digital components, but it may be all analog or all digital. The measured range signal contains two components --

the instantaneous vertical displacement of the vehicle relative to mean sea level and referenced to the vertical position of the ranging device, and the vertical motion of the sea surface (wave height).

As shown in **Figure 5**, the ranging device **44** measures the range from its position on the vehicle **52** to the ocean surface **54**; r_{meas}**56**. The ranging device **44** for a surface vehicle **52** is a device such as a Level Metrics 2002, manufactured by UltraSound Solutions of Albany, NY. This range measurement is corrected to produce the vertical distance to the sea surface, r_s, by applying the range device mounting angle, θ, which is the vertical offset of the ranging device **44**. If the vehicle **52** pitch and roll are large, then the measured range, r_{meas} **56**, must be corrected for vehicle **52** pitch and roll. This correction is well known to those skilled in the art.

For bow mounting of the ranging device **44** on a surface vehicle **52** it must be oriented so that its beam strikes the water's surface, or instantaneous sea level relative mean sea level **66** clear of the vehicle's **52** wake. The wake of the vehicle **52** would cause an erroneous offset in the measured range **56**. Typically this requirement will exclude mounting on the sides or the stern of the vehicle **52**. In the bow mounting the ranging device **44** may be placed on a rigid structure extending far enough beyond the bow to avoid wake contamination. The mounting of the ranging device **44** must be rigid to the hull of the vehicle **52**. Any independent motion or vibration of the ranging device **44** with respect to the vehicle's **52** hull mount may result in contamination of the measured range signal **56**. The mounting of the ranging device **44** must be such that the angle, θ, of the ranging device **44** with respect to the vehicle's vertical reference is

measurable. Since it is desired to measure the vertical distance from the ranging device **44** to the sea surface **54**, any angular offset of the ranging device **44** from vertical must be known so that the measured non-vertical range can be corrected to produce the vertical range, r_s. Angular offset is determined analytically at the time the ranging device **44** is installed on the vehicle **52** by actual measurement of the angle offset.

Selection of a ranging device **44** for a particular implementation involves several considerations. For ranging devices **44**, the beam is usually directional, resulting in a finite angular beam width. A ranging device's **44** beam typically has a footprint that is circular when projected onto a flat surface perpendicular to the direction of the beam, and this is illustrated in **Figure 6**. The size of the beam's footprint **78** is a function of the beam width **74** and the range to the surface **76**. The footprint's diameter **72** is given by the formula

$$D = 2*R*\tan(BW/2)$$

where D id the footprint diameter **72**, R, is the range to the water surface **76**, and BW is the angular beam width **74**. A beam width **74** in the range of 5-30 degrees is likely to be adequate for most implementations.

When selecting a beam width **74**, the following considerations should be addressed. If the beam width **74** is too narrow the beam may reflect off the water's surface in the opposite direction, and the ranging device **44** would be unable to produce a valid range **76**. This condition will be accentuated in very calm water. In general, a wider beam width will not adversely impact the depthimeter's **10** operation. A wider beam effectively low pass filters the measured range

data, but since this signal is subsequently low pass filtered in the MPC **12** there are no negative consequences. If the beam is very wide, then the vehicle's **52** bow wake or the vehicle's **52** hull could fall within the beam and contaminate the measured range signal **76**.

The effective range of a ranging device **44** must be sufficient considering the size and bow configuration of the vehicle **52**, the placement of the ranging device **44** on the vehicle **52**, and the anticipated wave heights. The resolution and accuracy of the ranging device **44** dictates in part the overall accuracy of the depthimeter **10**. An accuracy of 5 cm or less is likely adequate for most implementations. The resolution should be smaller than the accuracy, 1 cm or less.

Aliasing is an adverse phenomenon that occurs due to improper sampling of a signal and is well known to those skilled in the art. When aliasing occurs, high frequencies in the original signal are erroneously produced as low frequencies in the sampled signal; the effect is undetectable and uncorrectable in the sampled signal. In using a ranging device **44**, aliasing of the measured range **76** can be prevented by ensuring that the footprints **78** from consecutive pulses overlap. For a maximum relative wave speed and the nominal range of the ranging device **44** from the water's surface **54**, the footprint **78** overlap can be increased by increasing the ranging device's **44** beam width **74**, or by increasing the pulse repetition rate. The maximum relative wave speed is given by the sum of the maximum assumed vehicle speed and the maximum assumed wave speed. Ranging devices **44** will typically have fixed beam widths **74**, governed by the physical transducer construction, but may have variable pulse repetition rates. For example,. consider an implementation where the maximum relative wave speed is assumed

to be 10 meters/sec (20 knots), the ranging device **44** is mounted 4 meters above the water's surface **54**, and the ranging device **44** has a 10 degree beam width. For this implementation a sampling rate of 15 samples/second is required to ensure beam footprint **74** overlap.

The range compensator **46**, as shown in **Figure 7**, has two functions: first it corrects for data dropouts and secondly it corrects for the error in the measured range due to non-vertical orientations of the ranging device **44**. The range compensator **46** receives the range measurement **18** from the ranging device **44**, r_{meas}, and outputs **58** the vertical range **18**, r_s, from the ranging device **44** to the ocean surface **54**. The range compensator **46** is composed of a dropout compensator **82** and a vertical offset compensator **84**.

The dropout compensator **82** receives the range measurement **18**, r_{meas}, from the ranging device **44** and generates an output **86** free of data dropouts. Since the beam of the ranging device **44** may reflect off of the ocean surface **54** away from the sensor **44**, particularly for smooth surfaces, data dropouts may occur. This problem may occur more often if the ranging device **44** has a fairly small beam width. To compensate for this, interpolation is used between adjacent good data points from the ranging device **44** to estimate the missing points. Interpolation of sampled data is well known to those skilled in the art.

The vertical offset compensator **84** receives the dropout compensated signal **86** from the dropout compensator **82** and vehicle pitch and roll **88** from an external, sensor (not shown), such as a Model POS/MV 320, manufactured by Applied Analytics of Markham, Ontario, Canada or equivalent. The vertical offset compensator **84** outputs **58** a vertical range, r_s, from the ranging

device **44** to the ocean surface **54**. The vertical offset compensator **84** corrects the error in range measured by the ranging device **44** for any offsets of the ranging device **44** from vertical. Offsets from the vertical may be due to the ranging device **44** mounting angle θ resulting in a constant offset angle from vertical. Offsets from the vertical may also be due to vehicle **52** pitch and roll which will change with time. Compensation of a measured distance for an offset angle is well known to those skilled in the art.

The corrected range output signal **58** contains two components; first the instantaneous vertical displacement of the vehicle **52** relative to mean sea level **68** and secondly the vertical motion of the sea surface **54** (wave height). One consequence of the low pass filter **48** is that those portions of the signal due to the vertical motion of the sea surface **54** are removed. A second consequence of the low pass filter **48** is that those portions of the signal **58** due to the instantaneous vertical displacement of the vehicle that exactly match the signal **26** from the heave sensor **14** are removed. This is accomplished by using a low pass filter **48** that is the complement of the high pass filter **36** used in the heave sensor **14**. As a result of the low pass filter **48**, the output **22** of the MPC **12** contains exactly those components of the vehicle's **52** vertical motion that are missing in the output **26** of the heave sensor **14**. By adding the output **22** of the MPC **12** and the output **26** of the heave sensor **14**, as is done in the combiner **16**, the final output **28** of the depthimeter **10** is free from the transients seen in the output **26** of the heave sensor **14** due to sudden changes in the vehicle's mean path **64**.

For a heave sensor **14**, as show **Figure 3**, the parameters of a high pass filter **36** are,

typically, adjustable. If those parameters are changed, the coefficients of the low pass filter **48** in the MPC **12** must also be changed to ensure the low pass filter **48** is still the complement of the high pass filter **36**. The implementation of a filter in a system and the design of a low pass filter **48** that is the complement of a specified high pass filter **36** is well known to those skilled in the art.

Appendix A is a section of software written in Matlab® used to develop and test the depthimeter **10** using previously collected range and heave data. The software, which was written for the submerged vehicle application, includes implementation of the range compensator **46** and low pass filter **48**. The software also includes a section that is used to compute the filter parameters of the low pass filter **48** given the parameters of the high pass filter **36**. Although Matlab® was utilized in the development of this software program, C is the preferred language, however any scientific programming language may be utilized for similar programs.

The combiner **16**, as shown in **Figure 8**, is composed of two resamplers **94** and **96**, a time synchronizer **98** and a pair of adders **102** and **104** in cascade. The combiner **16** receives the estimated mean path **22** from the MPC **12** and the vehicle heave **26** from the heave sensor **14**. The output **28** of the combiner **16** is a signal that is the vehicle's **52** draft as a function of time, relative to mean sea level **68**. This output **28** signal is also the vehicle's vertical displacement, relative to mean sea level **68**, as a function of time. Preferably, the combiner is a digital device, however, an analog device may be used.

The resamplers **94** and **96** perform sampling of the estimated mean path data **22** and

heave data **26**, if necessary, to ensure these two data streams **22** and **26** are at the same sampling rates. The two data streams **22** and **26** must have the same sampling rates to allow subsequent time synchronization and addition of the resulting signals. This operation is not necessary if the mean path data **22** and the heave data **26** are originally sampled at the same rate. The inputs **22** and **26** to the samplers **94** and **96** are sampled at an arbitrary sampling rate (samples/second). For implementation with the depthimeter **10**, the specified sampling rate is preferably 10 samples/second. Such resampling is well known to those skilled in the art.

The time synchronizer **98** synchronizes the estimated mean path data stream **106** and the vehicle **52** heave data stream **108** for subsequent addition in the adders **102** and **104** to produce a synchronized mean path data stream **112** and synchronized heave data stream **114**. This operation is required so that the addition operation will add the synchronized heave data samples **114** and the synchronized mean path data samples **112** that correspond to the same instants in time. This operation is not necessary if the estimated mean path data **22** and the heave data **26** are originally sampled at the same instants of time. The inputs **106** and **108** to the time synchronizer **98** are the resampled estimated mean path **106** and resampled vehicle heave **108**. Time synchronization of data signals is well known to those skilled in the art.

The first adder **102** adds the resampled and time synchronized estimated mean path **112** and the resampled and time synchronized vehicle heave **114** at each instant in time. The result of this addition operation is a signal **116** that is the vehicle's **52** vertical displacement relative to mean sea level **68**, referenced to the vertical position of the ranging device **44**.

The second adder **104** adds the vehicle's vertical displacement relative to mean sea level **68** , referenced to the position of the ranging device **44**, and K_o **72**, the ranging device **44** to keel **69** offset. K_o is obtained from actual measurement or design drawings of the vehicle **52**. For this operation, the additive inverse of K_o, i.e., $-K_o$, is added for the proper offset correction. The result of this addition operation is a signal **28** that is the vehicle's vertical displacement relative to mean sea level **68**, referenced to the vehicle's keel **69**. This signal **28** is also the vehicle's **52** draft. Addition of sampled signals and a constant value, $-K_o$, is well known to those skilled in the art.

In another preferred embodiment, the depthimeter **10**, as shown in **Figure 2**, is used for the determination of the depth of a sub-surface vehicle and for the determination of vertical displacement of the vehicle with respect to mean sea level, as shown in **Figure 9**. For the sub-surface embodiment of the depthimeter **10**, the output **28** of the depthimeter **10**, shown in **Figure 2**, is a signal that is the vehicle's **22** depth **118** as a function of time, relative to mean sea level **68**. The output **31** is also the vehicle's **122** vertical displacement relative to mean sea level **66**, as a function of time. The parameters measured by the depthimeter **10** in this embodiment are range **124**, r_{meas}, from a fixed point on the vehicle to the water's surface or instantaneous sea level relative to mean sea level **66** and the vehicle's **112** vertical acceleration. Measurement of r_{meas} **124** is accomplished by a ranging device **44** mounted on the hull of the vehicle **122**. There are two significant components to r_{meas} **124** , first is the instantaneous vertical displacement of the vehicle **122** and the second is the instantaneous sea level relative to mean sea level **68**. The

instantaneous vertical displacement is a point on the instantaneous path of the vehicle **62**, which varies about the mean path of the vehicle **64**. The mean path of the vehicle **64** is referenced to the vertical position of the ranging device **44**, but may be referenced to any other fixed vertical position on the vehicle **122**. The mean sea level **68** is the mean of the instantaneous sea level **62** over time. Vehicle **122** vertical acceleration is the vertical component of the acceleration experienced by the vehicle **122** as it travels along the instantaneous path **62**. Depth **118** is defined as the vertical distance between the vehicle's depth reference point **126** and the mean sea level **68**. Depth of a sub-surface vehicle **122** may change with time due to changes in the commanded depth of the vehicle **122**.

As in the surface vehicle **52** embodiment, the depthimeter **10** is composed of a mean path compensator **12** (MPC), a heave sensor **14** and a combiner **16**, as shown in **Figure 2**. The MPC **12** measures the range to the water surface **124** and generates a signal **22** that is the mean path of the vehicle relative to mean sea level **68**. This signal may be time varying if the vehicle's **122** depth changes with time.

The heave sensor **14**, as shown in **Figure 3**, measures the vehicle's **122** vertical acceleration and generates a signal **26** that is the heave of the vehicle **122**. Heave, in this embodiment, is the vertical displacement of the vehicle **122** from the mean path of the vehicle **64** to the instantaneous path of the vehicle **62**; but heave can equally be defined as that component of the vehicle's **122** vertical displacement, with respect to a fixed vertical reference point, that is absent in the vehicle's mean path **64**. The heave signal **26** does not contain

information about the mean path of the vehicle **64** and cannot be used as the vertical displacement of the vehicle **122** after abrupt changes in the vehicle's mean path **64**. Changes in a sub-surface vehicle's **122** mean path **64**, i.e., depth, may occur due to changes in the command depth.

If the heave sensor **14** is not collocated with the ranging device **44**, the heave measured at the position of the heave sensor **14** may not be the same as the position of the ranging device **44**. If this is the case, then the heave data must be translated, using measured vehicle pitch and roll, to compute the heave of the vehicle **122** at the location of the ranging device. This may require an additional sensor, a vertical reference unit, for the measurement off vehicle **122**pitch and roll. If the POS/MV 320 system is utilized, it also measures vehicle **122** pitch and roll. Given measured pitch and roll, translation of the heave measurement is well known to those skilled in the art.

The MPC **12** is similar to that previously described and shown in **Figure 4**, containing a ranging device **44**, range compensator **46** and a low pass filter **48**. The ranging device **44** is used to measure r_{meas} **124**, the instantaneous rage from a fixed point on the vehicle **122** to the ocean surface **66** as a function of time. Measurement of range is accomplished by measuring the time required for a transmitted pulse to travel from the device **44** to the surface **66** and back to the device **44**; the pulse would typically be acoustic for the ranges considered in this embodiment. The measured range signal **56** contains two components; first is the instantaneous vertical displacement of the vehicle **122** relative to mean sea level **68** and referenced to the vertical

position of the ranging device **44**, and secondly, the vertical motion of the sea surface **66** (wave height). A typical ranging device **44** for use in this application is a ST500 Precision Altimeter, manufactured by Tritech International Ltd. of Aberdeen, Scotland, United Kingdom, however any other suitable device may be utilized.

In the sub-surface embodiment the following mounting considerations for the ranging device **44** must be applied. First, if the sub-surface vehicle **122** travels near the surface of the water **66**, then the vehicle **122** may leave a wake. The ranging device **44** must be oriented so that its beam strikes the water's surface **66** clear of the vehicle's **122** wake; the wake could cause an erroneous offset in the measured range. Typically this could be accomplished by mounting the ranging device **44** far forward of the vehicle **122**. A second consideration is that the mounting of the ranging device **44** must be rigid to the hull of the vehicle **122**. Any independent motion or vibration of the ranging device **44** with respect to the hull of the vehicle **122** hull mount may result in contamination of the measured range signal **56**. Finally, the mounting of the ranging device **44** must be such that the angle, θ (in actual degrees), of the ranging device **44** with respect to the vehicle's **122** vertical reference is measurable. Since it is desired to measure the vertical distance, r_s, from the ranging device **44** to the sea surface **66**, any angular offset of the ranging device **44** from the vertical must be known so that the measured non-vertical range, r_{meas}, can be corrected to produce the vertical range, r_s.

In selecting a ranging device **44** for the sub-surface installation the following considerations are involved. First, for ranging devices **44**, the beam is usually directional,

resulting in a finite angular beam width. The ranging device's **44** beam typically has a footprint **78** as discussed previously, and as depicted in **Figure 6**, but inverted, that is circular when projected onto a flat surface perpendicular to the direction of the beam. The size of the beam's footprint **78** is a function of the beam width **74** and the range to the surface **76**. A beam width **74** in the range of 5-30 degrees is likely adequate for most implementations. (The beam width of a Tritech ST500 ranging device is 6 degrees.) However, the following considerations must be applied to beam width **74**: first, if the beam width **74** is too narrow, the beam may reflect off the water's surface **66** in the opposite direction, and the ranging device **44** would be unable to produce a valid range. Secondly, in general, the wider beam will not adversely impact the depthimeter's **10** operation. A wider beam again effectively low pass filters the measured range data, as in the previous embodiment. If the beam is very wide, then the vehicle's **122** bow wake, or protrusions from the vehicle's **122** hull could fall within the beam and contaminate the measured range signal.

A second consideration for the ranging device **44** is that the effective range of the ranging device **44** must be sufficient considering the anticipated depth of the vehicle **122** below the surface **66** and the anticipated wave heights **128**. In a third consideration, the resolution and accuracy of the ranging device **44** dictates in part the overall accuracy of the depthimeter **10**. An accuracy of 5 cm or less is likely sufficient for most implementations. The resolution should be smaller than the accuracy, 1 cm or less. In a third, and last, consideration for the ranging device **44**, is the pulse repetition rate which has previously been discussed.

The range compensator **46**,as in **Figure 7**, and combiner **16**,as in **Figure 8**, perform as previously discussed. However, the output of the second adder **104** in the combiner **16** adds the vehicle's **122** vertical displacement relative to mean sea level, referenced to the vertical position of the ranging device **44**., and K_o, the ranging device **44** to depth reference point offset. The resulting output **28** of this addition operation is a signal that is the vehicle's **122** vertical displacement referenced to the vehicle's **122** depth reference point **126**. This signal **28** is also the vehicle's **122** depth **118** relative to mean sea level **68**.

The depthimeter **10** bypasses the problems associated with the use of pressure sensors and corrects for the errors induced by wave action to produce accurate measurement of vehicle **52** and **122** draft or depth with respect to mean sea level **68**. The depthimeter **10** compensates for the errors in vertical displacement from the heave sensor **14** by generating a vertical displacement signal that is referenced directly to mean sea level **68** instead of an unknown mean path. Since the draft of a surface vehicle **52** or the depth of a sub-surface vehicle **122** signal produced by the depthimeter **10** is a non-constant function of time, this signal is also the vertical displacement of the vehicle **52** or **122** referenced to mean sea level **68**.

Although the invention has been described in relation to an exemplary embodiment thereof, it will be understood by those skilled in the art that still other variations and modifications can be affected in the preferred embodiment without detracting from the scope and spirit of the invention.

ABSTRACT

The depthimeter comprises a heave sensor, a mean path compensator and a combiner. The mean path compensator comprises a ranging device which measures the instantaneous distance of the vehicle from a fixed point on the vehicle to ocean surface as a function of time; a range compensator to compensate for signal dropouts in the ranging devices data, for sensor offset angle, and vehicle pitch and roll, thereby providing a signal that contains the vehicles vertical motion and the vertical motion of the sea surface. A low-pass filter within the mean path compensator eliminates the components of the resulting signal due to the motion of the sea surface and the high frequency components of the vehicle's vertical motion, thereby producing a signal that is the mean path of the vehicle, referenced to mean sea level. The combiner merges the mean path signal from the mean path compensator and a heave signal generated by the heave sensor to generate a signal that is a surface vehicle's draft relative to mean sea level or a submerged vehicle's depth relative to mean sea level. This signal is also the vehicle's vertical displacement with time relative to mean sea level.

APPENDIX A

```
function meandepth = afilter(altitude,d)
%AFILTER  filter altimeter data with dropouts
%            This filter is designed to estimate mean path of
%            the ORCA to exactly compliment the heave as measured
%            by the POS/MV
%
%     Syntax:
%            meandepth = afilter(altitude)
%     Input:
%            altitude   input data   dropout: -1,  valid range 0 to 5
%            d          initial value of depth used on short sequences
%                       to alleviate transients
%     Output:
%            meandepth  mean depth of ORCA  (positive upward)

% ABM  12/10/97

% filter coefficients  (double precision required)
b =  [  0.0152645085649112; -0.0304332116981941; 0.0151689511834963  ];
a = b + [ -3.0; 3.0; -1.0 ];

%  find beginning of good data in altitude
start=1;
while (altitude(start)<0 | altitude(start)>5)
   start=start+1;
end

%  replace initial data point with first good value
altitude(1)=altitude(start);

%  if user didn't provide initial depth, make one up
if nargin<2, d=altitude(start); and

%  compute initial values of states using initial depth
```

```
x = d/sum(b)*ones(3,1);

% setup storage
meandepth=zeros(size(altitude));

% now do filtering
for i=1;length(altitude)
  if  (altitude(i)<0 | altitude(i)>5)
   % hold last value
  else
   % update states
   x0 = altitude(i) - a'*x;
   x(3) = x(2); x(2) = x(1) =x0;
   % compute output
   d = b'*x;
  end
  meandepth(i)=-d;
end
```

```
% MATLAB script to generate digital filter parameters
% for altimeter to :
% analog filter

% HP*Integrator^2
%                          s
% G(s) = ---------------------------------
%         s^3 + g1*s^2 + g2*s + g3

xi=1/sqrt(2);
%xi = 0.707
w0=2*pi/200

g1 = w0*(2*xi+1);
g2 = (w0^2)*(2*xi+1);
g3 = w0^3;

% Interagator
%          1
% I(s) = ------
```

```
%          s^2

% HP

%                          s^3
% H(s) = ------------------------------------
%          s^3 + g1*s^2 + g2*s + g3

Aa = [1;g1;g2;g3];
Ba = [1;0;0;0];

% Complementary LP
%                              g1*s^2 + g2*s + g3
% L(s) = 1 - H(s) = ------------------------------------
%                    s^3 + g1*s^2 + g2*s + g3

Ba = Aa-Ba;

% digital filter

fs=5;

% Let s = fs*(1-z^{-1})
% Then
% g1*s^2 + g2*2 + g3 ->
%    (g1*fs^2+g2*fs+g3) + (-2*g1*fs^2-g2*fs)*z^-1 + (g1*fs^2)*z^-2
%    = B(z)

B = [g1*fs^2+g2*fs+g3;-(2*g1fs^2+g2*fs);g1*fs^2];
% and
% s^3 -> fs^3*(1 - 3*z^-1 + 3*z^-2 - z^3)
% and so

A = fs^s3*[1;-3;3;-1] + [0;B];

% normalize
B = B/A(1);
A + A/A(1);

% test
```

```
theta = logspace(-3,pi,1000)';
H = freqz(B,A,theta);
Ha = freqs(Ba,Aa,theta*fs);
semilogx(thets,0*log10(abs([H Ha])));
```

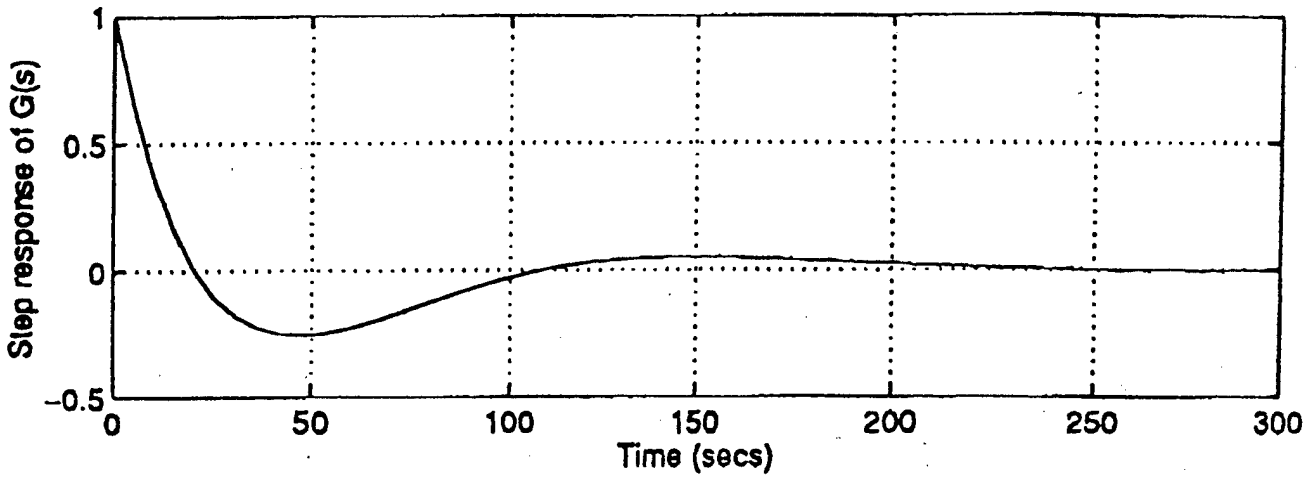

Figure 1

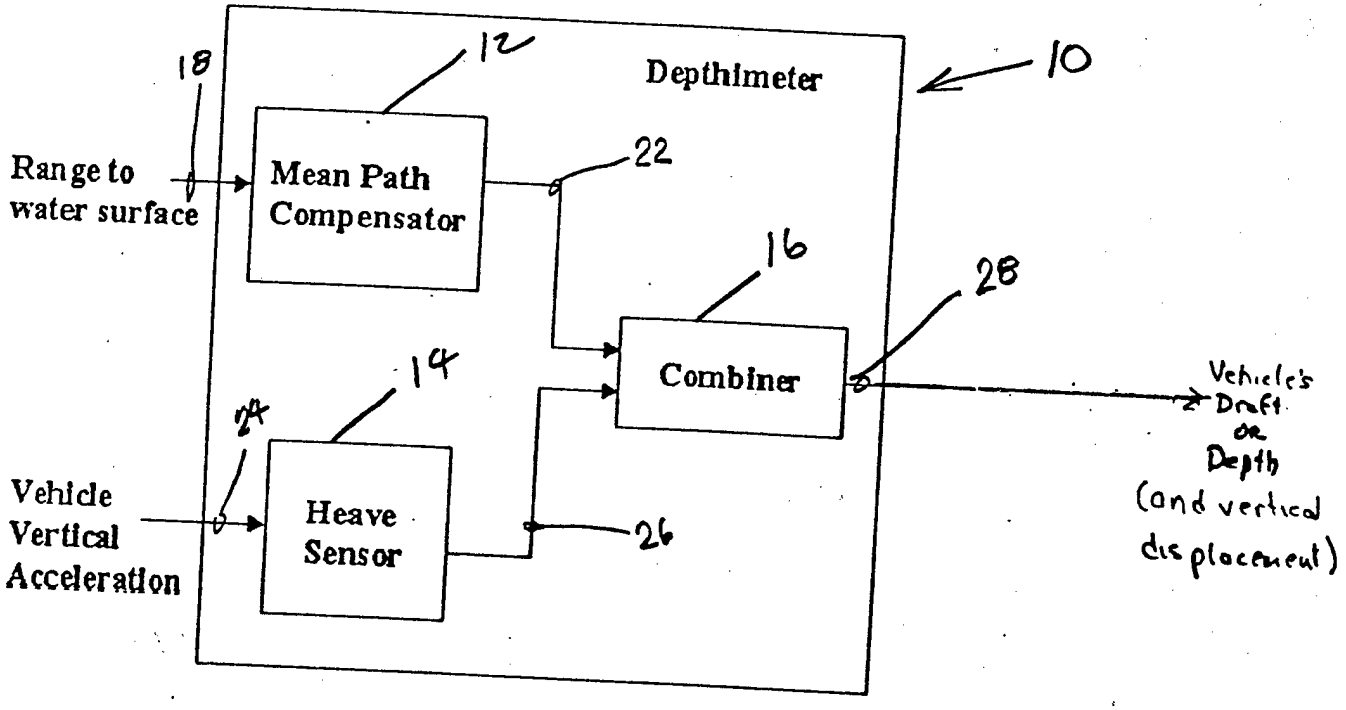

Figure 2

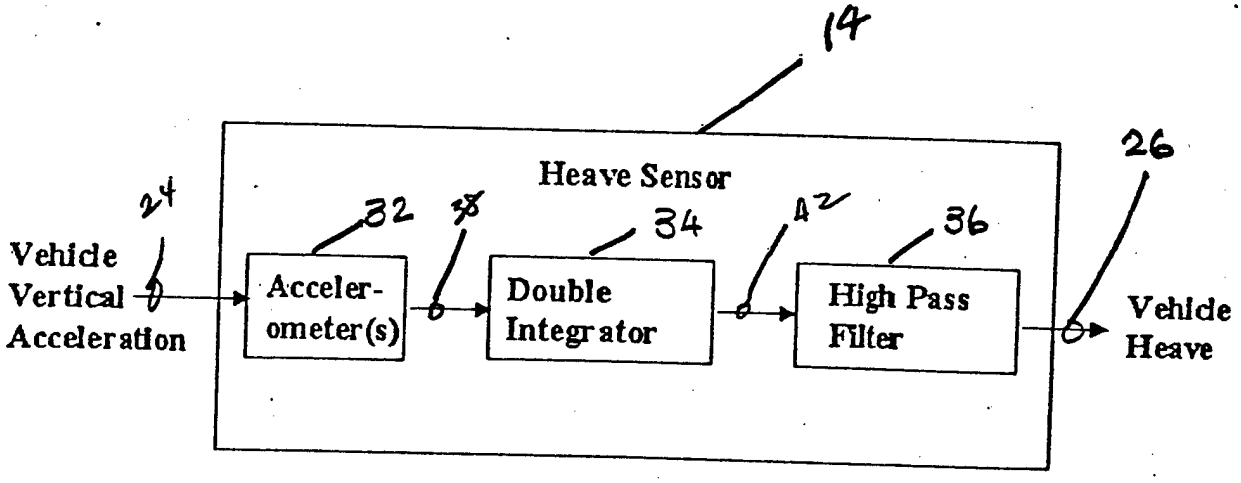

Figure 3

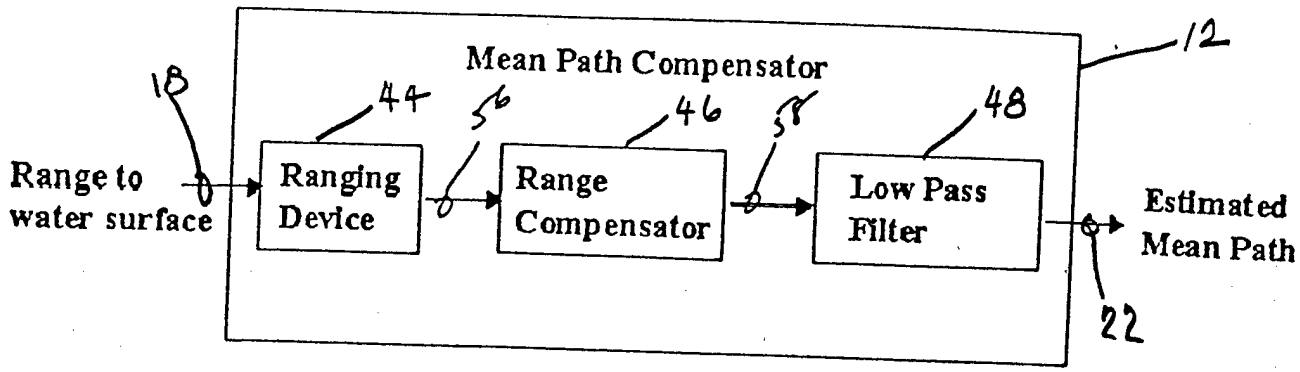

FIGURE 4

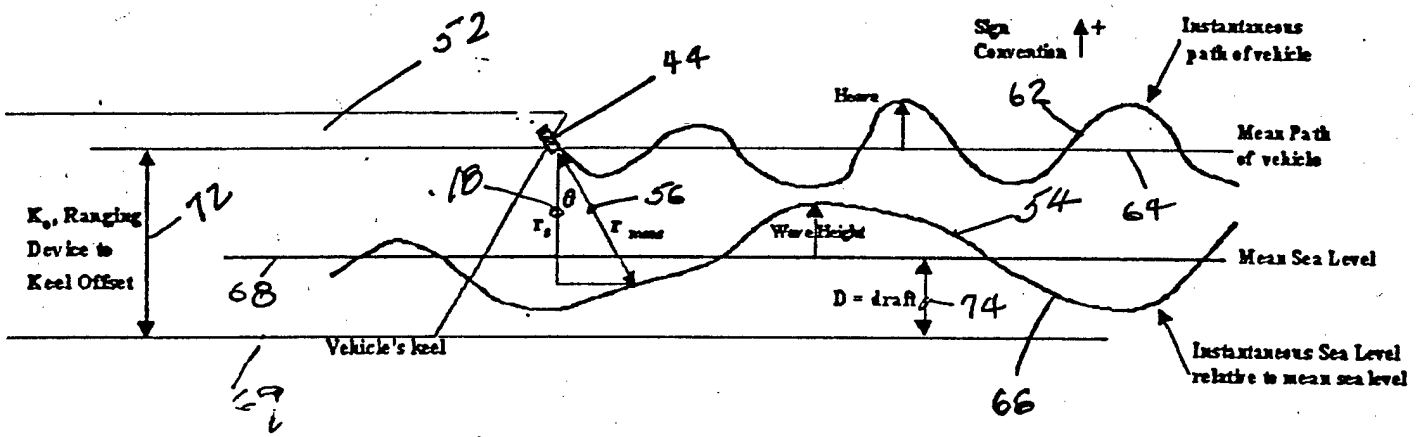

FIGURE 5

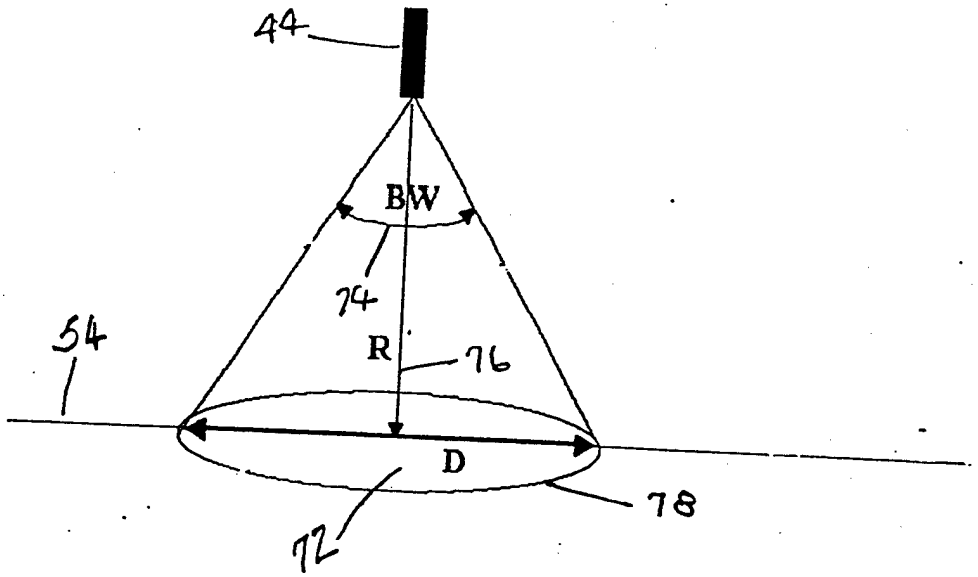

Figure 6

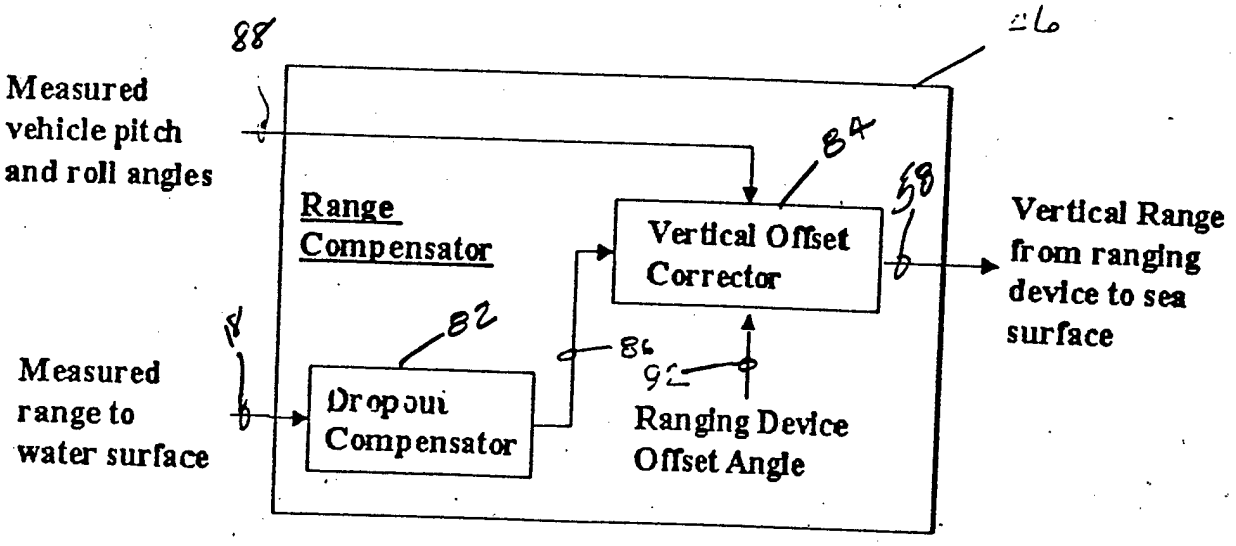

Figure 7

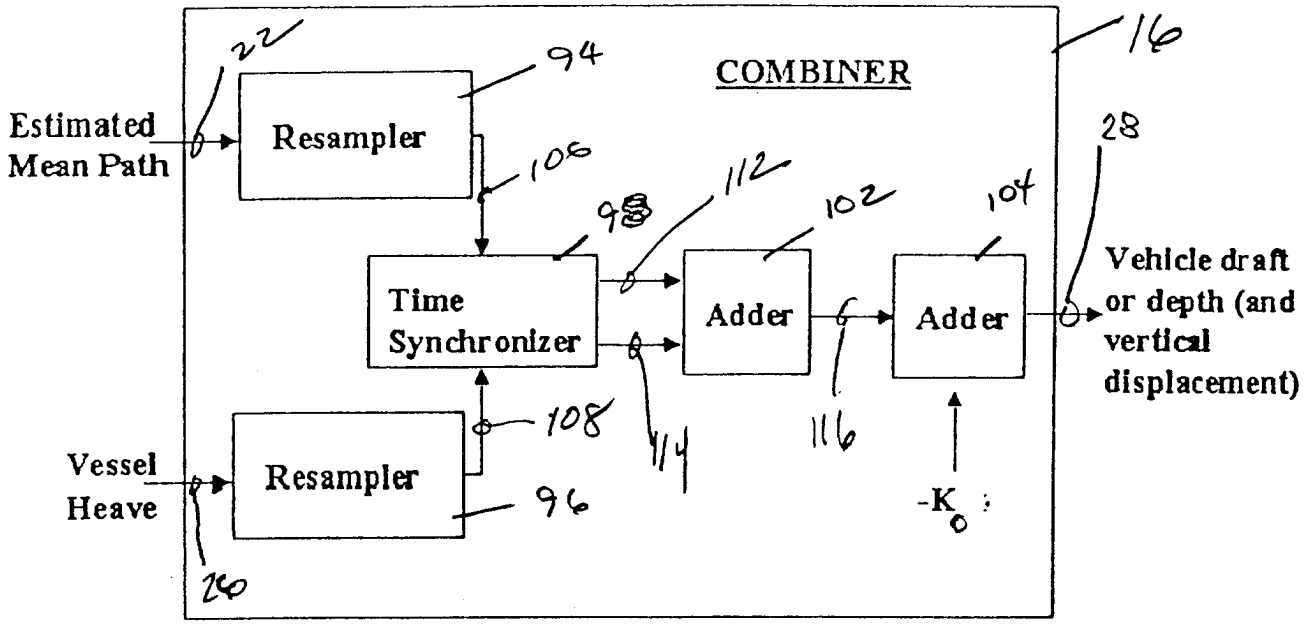
COMBINER
16
22
94
Estimated Mean Path
Resampler
106
98
112
102
104
28
Time Synchronizer
Adder
Adder
Vehicle draft or depth (and vertical displacement)
108
114
116
Vessel Heave
Resampler
96
$-K_0$
20

Figure 8