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LOCALIZATION OF A SUBMERGED TOW VEHICLE (LOST)

BACKGROUND OF THE INVENTION

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Field of the Invention

This invention pertains generally to a device for accurate estimation of an underwater towed vehicle's position, and more particularly to the making of an estimate of an underwater towed vehicle's position independent of off-board sensors and horizontal range from the towing vehicle.

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Description of the Prior Art

Underwater towed vehicles are in common use for surveying and location of objects in the ocean due to their relatively low operational cost. To be useful however, the position of the towed vehicle must be known so that the data collected by the towed vehicle's sensors may be geo-rectified. Due to currents in the water and the cantilever in the towing cable, a towed vehicle's position relative to the towing vessel is not easily determined. Since the ocean is opaque to high-frequency electromagnetic signals, the global positioning system (GPS) cannot be used for tow vehicle position.

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Current methods for determining the position of a towed vehicle include the lay-back model (See, **Figure 1**), the long-base line (LBL) (See, **Figure 2**), the short base line (SBL) (See, **Figure 3**), and the inverted SBL systems. With the lay-back model method the towed vehicle is assumed to be directly behind the towing vehicle and the lay-back (distance from the towing

5 vehicle) is assumed to be a fixed multiple of the tow vehicle's depth. Alternatively, the amount of cable paid out is assumed to be the slant range to the tow vehicle. The latter method does not take into account the cable's cantilever. Neither method takes into account the effects of local currents on the cables' shape and position. The accuracy of these methods will in general not support precise positioning of the towed vehicle.

10 The LBL method uses a series of acoustic transponders to localize the tow-vehicle by measuring the time delays between the tow-vehicle and the transponders. These transponders may be bottom mounted or located on the surface, such as shown in U.S. Patent No. 5,119,341. While these systems are very accurate, their deployment is a time consuming and expensive operation. Furthermore, the LBL method requires that the system be redeployed to each
15 operational area.

The SBL method uses time delay and measured arrival angle of an acoustic signal from the tow-vehicle to the towing vehicle to compute position. These systems are fairly accurate but their resolution is range dependent. Typically, in order to achieve sufficient accuracy, a SBL system is deployed over the tow-vehicle, requiring a second surface craft – an obvious economic
20 disadvantage.

With the inverted SBL method, the directional acoustic receiver is mounted on the towed vehicle instead of the towing vehicle. As a consequence the range dependent accuracy of this system is a problem for very deep tows. SBL and inverted SBL systems cannot be readily used in applications with helicopter towed systems.

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5 **SUMMARY OF THE INVENTION**

The object of this invention is to provide a system and method for accurate determination of an underwater towed vehicle's position.

Another object of the invention is to provide a system with a position accuracy that is not dependent upon the horizontal range of the towed vehicle from its host.

10 Another object of the invention is to provide a system where no off-board sensors are required and the system needs not be re-deployed in each new operation area.

Another object of the invention is to provide a system that is cheaper than existing systems.

15 These and other objectives are achieved with a device for localization of a submerged towed vehicle (LOST) that provides a technique for accurately determining the position of an underwater vehicle towed by a surface craft or a helicopter. The LOST system comprises a state updater, a maximum likelihood estimator, a constrained adaptive tracker and a slant range corrector. The state updater generates a prediction of the towed vehicle's position using a previous estimate and the towing vehicle's course and speed (i.e., dead reckoning). The
20 maximum likelihood estimator utilizes the output of the state updater, along with the measured ocean depth at the current position of the towed vehicle and bathymetry data for the area to compute the most likely position of the towed vehicle based on ocean depth. The constrained adaptive tracker constrains the output of the maximum likelihood estimator by applying limits to the towed vehicle's velocity and acceleration. The slant range corrector forces the position
25 estimate from the constrained adaptive tracker to have the proper slant range between the towed

5 vehicle and a known reference point.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a cable layback method of the prior art.

Figure 2 shows a long baseline approach of the prior art.

10 **Figure 3** shows a short baseline approach of the prior art.

Figure 4 shows an overview of the implementation of a device for localization of a submerged tow vehicle (LOST) system.

Figure 5a shows a side view of the LOST system.

Figure 5b shows a top view of the LOST system

15 **Figure 6** shows a block diagram of the LOST system.

DESCRIPTION OF THE PREFERRED EMBODIMENT

In order to provide an alternative, low-cost, and accurate method to tow vehicle
20 localization, the localization of a submerged tow vehicle (LOST) system **10**, as shown in **Figure**
4, has been developed for the use in conjunction with certain applications. In applications where
high resolution bathymetry data is available, a technique exists for the measurement of ocean
depth **14** at the position of the towed vehicle **12**, and a technique exists for the measurement of
the slant range **18** to a known reference point, then terrain matching provides another means of
25 tow vehicle **12** localization.

5 The LOST system **10** provides accurate position estimates of towed vehicles **12** towed by
either a surface ship **22** or a helicopter (not shown). The primary difference between the two
techniques of towing the tow vehicle **12** is in the method that the required data is collected. The
system **10** then follows the same implementation once the data has been collected. The LOST
system **10** is implemented as a digital system. The LOST system **10** requires several input
10 parameters; these are (1) geo-rectified, high resolution bathymetry **16** for the operational area
obtained from a towing vehicle **22** utilizing multibeam swath bathymetry, utilizing past recorded
historical data or data recorded after the deployment of the tow vehicle; (2) the depth **24** of the
towed vehicle **12** through the use of a pressure sensor or with an uplooking acoustic ranging
device; (3) altitude **26** of the towed vehicle **12** over the ocean floor **25** at the position of the
15 towed vehicle **12** which can be measured by an acoustic ranging device, (4) the tow vehicle's **12**
velocity over the bottom **25** (both course and speed) utilizing an inertial navigation system
(INS), acoustic Doppler velocity log, or an acoustic correlation velocity log; (5) the slant range
18 between the towed vehicle **12** and a known reference point with an acoustic ranging device
mounted on the towing vehicle or another vehicle, also an acoustic ranging device mounted on a
20 buoy or some bottom mounted system whose position is known, as shown in U.S. Patent No.
6,028,823, may be used ; and (6) the position and velocity of the towing vehicle **22** obtained from
a global positioning system (GPS) satellite system or other navigation system. The LOST
system's **10** output is the estimated geo-referenced position of the towed vehicle **12**.

25 The outputs and inputs to the LOST system **10** for position are typically in the form of (x,
y, z) triplets where x is latitude or northings, in meters, y is longitude or eastings, in meters, and z

5 is depth (or altitude) measured in meters. For all calculations, the LOST system **10** uses an internal coordinate system, whose orthogonal axes are shown in **Figure 4**, which are composed of cross track **27**, as shown in **Figure 5b**, along track **28**, as shown in **Figure 5b**, and depth **32** directions, as shown in **Figure 5a**. **Figure 5a** and **5b** shows the along track and cross track distances of the towed vehicle **12** with respect to the towing vehicle **22**. The along track distance is the projection of the vector between the tow vehicle **12** and the towing vehicle **22** onto the towing vehicle's track **28**. The cross track distance **27** is the component of that vector perpendicular to the towing vehicle's track **28**. Coordinate transformations are needed throughout the LOST system **10** to transfer between earth coordinates and the LOST **10** coordinate system; the position and course of the towing vehicle **22** are needed for these transformations. Transforming a position between coordinate systems is well known to those skilled in the art.

There are several methods for collecting each of the six inputs needed by the LOST system **10**. The first input, high resolution bathymetry, is collected from any system capable of collecting accurate (x, y, z) data points with high spatial density, before, during, or after the deployment of the tow vehicle **12**. The ocean depth **14** is typically computed by combining tow vehicle depth **24**, which is measured with a pressure sensor or a system such as a depthimeter (See, U.S. Patent Application, Serial No. 09/399,474, entitled DEPTHIMETER, filed September 20, 1999), and the tow vehicle altitude **26** above the sea floor **25**, which can be measured with an acoustic ranging device. The velocity over the ground of the tow vehicle **12** can be measured directly on the towed vehicle **12** using an inertial navigation system (INS), a velocity log (VL), or

5 a combined INS/VL system. Velocity through the water can be also measured and used as an
estimate of the towed vehicle's 12 velocity over the bottom 25 however, this does not take into
account the effect of currents. If a velocity measurement is not directly available on the towed
vehicle 12, the velocity of the towing vehicle 22 can be used as the estimate. The slant range 18
between the tow vehicle 12 and a known reference point can be obtained with an acoustic
10 ranging device. The known reference point may be the towing vehicle 22, in the case of a surface
ship, but it may also be a buoy or a bottom mounted transponder system. The slant range 18 can
also be obtained, albeit less accurately, using a cable lay-back model. A cable lay-back model
typically uses a rule-of-thumb to determine how far the tow vehicle 12 is behind the towing
vehicle 22 based on the length of cable deployed and/or the depth of the tow vehicle 12.

15 The LOST system 10, as shown in **Figure 6**, is composed of four modules. These are the
state updater (SU) 34, a maximum likelihood estimator (MLE) 36, a constrained adaptive tracker
(CAT) 38, and a slant range corrector (SRC) 42.

The state updater 34 takes as input the previous best estimate of the tow vehicle position
44 (either from the LOST system 10 or from an initialization routine) and the tow vehicle's
20 velocity 46 and outputs a predicted position 48 at time t, $P_p(t)$, for the tow vehicle 12 based on
this information. The state updater 34 predicts the tow vehicle's position 48 based on the
previous estimate of its position 44 and an estimate of its velocity over the sea floor 46. The
prediction, $P_p(t)$ 48, is calculated by projecting the previous position estimate 44 forward using
the tow vehicle's estimated velocity 46. This is shown by the equation:

25
$$P_p(t) = P_e(t-1) + vt \quad (1)$$

5 where:

$P_p(t)$ is the predicted position at time t

$P_e(t-1)$ is the position estimate output of the LOST system at time $t-1$

v is the tow vehicle's estimated velocity

10 The SU 34 has the effect of changing the along the track component of the tow vehicle's
12 estimated position from the previous estimate but leaves the cross track component of the
position unchanged, when the towing vehicle's velocity is used as the tow vehicle's velocity 44.
For system initialization, $P_e(t-1)$ 44 must be given an initial seed value. This initial seed value
may be obtained numerous ways, but essentially amounts to providing the best estimate of the
tow vehicle's position 44. Referring again to Figure 5b, for example, a cable lay-back model
15 can be used to estimate the along track distance 28 of the tow vehicle 12 and the cross track
distance 27 can be assumed to be zero.

The maximum likelihood estimator (MLE) 36 takes as input the towed vehicle's ocean
depth measurements 52 measured at the tow vehicle's actual position, the bathymetry 56 and
 $P_p(t)$ 48 and outputs the MLE's estimate of position, MLE(t) 54.

20 The MLE 36 computes a maximum likelihood estimate of tow vehicle position 54 using a
point-matching algorithm. The algorithm utilizes an input of the bathymetry data 56 and the
towed vehicle's measured ocean depth 52 and evaluates the likelihood function, $\lambda(x, y, z)$, at the
tow vehicle predicted position 48 and each of the (x, y, z) bathymetry 56 points within the MLE
36 search area. The MLE 36 search area is a region that is expected to include the actual position
25 of the tow vehicle and is centered at the predicted position 48, $P_p(t)$. The size of the search area

5 is a trade-off between convergence speed and computational cost. A large area allows faster convergence since it is more likely that the tow vehicle will be located within that area, but it requires more time to compute the likelihood function's values.

The likelihood, $\lambda(x, y, z)$, is the probability that the ocean depth **52** measured at the actual position of the tow vehicle corresponds to a particular (x, y, z) bathymetry point. In the design of this algorithm, it is assumed that the position errors in (x, y, z) are jointly Gaussian, and that the error in x and y are similar. This yields a likelihood function of the form

$$\lambda(x, y, z) = ((\Delta x)^2 + (\Delta y)^2) / 2(\sigma_x)^2 + (\Delta z)^2 / 2(\sigma_z)^2 \quad (2)$$

where:

σ is the standard deviation of Gaussian model, and σ_x , σ_y and σ_z are the standard deviations in the x , y , and z directions respectively. As mentioned above, it is assumed that the errors in the x and y coordinates are similar, so $\sigma_x = \sigma_y$.

Δx is the predicted tow vehicle x position minus the bathymetry x position

Δy is the predicted tow vehicle y position minus the bathymetry y position

Δz is the ocean depth (z) measured at the position of the tow vehicle minus the depth

value for the current bathymetry (x, y, z) data point being considered.

For ease of calculation Eq. (2) can be rewritten as

$$\lambda(x, y, z) = ((\Delta x)^2 + (\Delta y)^2) + k(\Delta z)^2 \quad (3)$$

where k is defined as the ratio σ_x / σ_z . The effect of k is to scale Δz , which in turn determines to what extent the depth measurement, versus the tow vehicle's predicted position, influences the likelihood of the position being considered. The proper value for this ratio is dependent on the

5 character of the terrain over which the LOST system 10, as shown in **Figure 4**, is operating as well as the accuracies of the systems being used to collect the various measurements. In general, larger values of k are used for rough terrain, and smaller values are used when data inaccuracies are suspected. A nominal value for k is in the range of 100-1000.

10 The minimum value of $\lambda(x, y, z)$ corresponds to the most likely (x, y, z) position of the tow vehicle 12. Computing the minimum of a function is well known to those skilled in the art. The resulting minimum is called MLE(t) 54, as shown in **Figure 6**, and is passed to the constrained adaptive tracker (CAT) 38 system. The MLE 36 updates both the cross track and the along track estimates of tow vehicle 12 position.

15 The constrained adaptive tracker (CAT) 38 takes as input $P_e(t-1)$ 44 and MLE(t) 54 and outputs CAT(t) 62. The CAT 38 constrains MLE(t) 54 by forcing the cross track component of the tow vehicle's estimated position 44 to behave in a realistic manner. It does this by applying nonlinear constraints on both the velocity and the acceleration of the cross track component of the tow vehicle's estimated position 44. This is accomplished by using difference equations and applying a threshold to the first and second derivatives of the tow vehicle's position 44. The
20 difference equations used are:

$$e = f_{ct}(MLE(t)) - f_{ct}(P_e(t-1)) \quad (4)$$

$$d(t) = f_a(2ue) \quad (5)$$

$$w(t) = f_v((1-u)w(t-1) + d\Delta t) \quad (6)$$

$$cross(t) = f_{ct}(P_e(t-1) + w(t)\Delta t) \quad (7)$$

25 where:

- 5 e is the difference between the predicted and MLE cross track positions
- $f_{ct}()$ is a function that computes the cross track position given an (x, y) position
- $d(t)$ is the estimated tow vehicle's cross track acceleration at time t
- $f_a()$ is a function that thresholds the acceleration; the threshold value is set according to
the dynamics of the tow vehicle.
- 10 u is an adaptive constant; a nominal value for u is 0.001 - 0.01
- $w(t)$ is the estimated tow vehicle's cross track velocity at time t
- $f_v()$ is a function that thresholds the velocity; the threshold value is set according to the
dynamics of the tow vehicle
- cross(t) is the estimated cross track position at time t
- 15 Δt is the amount of time between system updates.

Computing cross track component for a defined coordinate system, given a point referenced to a different coordinate system is well known to those skilled in the art. (function f_{ct} above).

Thresholding a value is well known to those skilled in the art (function f_a and function f_v above).

The functions f_a and f_v serve to limit the estimated values of the tow vehicle's velocity and
20 acceleration to reasonable quantities, which prevents the LOST system 10 from generating a new
position estimate that is too far from the previous position. The resulting value of cross(t) is the
cross track component of the CATs 38 estimated position 62, CAT(t). CAT 38 keeps MLE's 36
estimated along track position as its own estimate of along track position.

The slant range corrector (SRC) 42 takes as input CAT(t) 62, the position of the known
25 reference point 64, and the measured slant range 66 from the tow vehicle 12 to that reference

5 point, and outputs $P_e(t)$ 68, the LOST system's 10 best estimate of the tow vehicle's position. The SRC 42 warps the CAT(t) position estimate 62 forcing it to match the measured slant range 66 between the tow vehicle 12 and a known reference point 64. If the slant range 66 measurement is not available the LOST system's 10 final position estimate is CAT(t) 62. The correction is done by drawing a vector between the known reference point and the CAT(t) 62 position and forcing it to have a length that is equal to the measured slant range 66. This process alters both the along track and cross track components of the estimated position 44. This operation is shown in the following equation:

$$P_e(t) = P_{ref} + (CAT(t) - P_{ref}) R_m/R_a \quad (8)$$

where:

15 P_{ref} is the position of the known reference point

R_a is the range to the reference point using the tow vehicle's estimated position CAT(t)

R_m is the measured slant range between the tow vehicle and the reference point.

Bathymetry data, position and velocity over the sea bottom of the towing vehicle, ocean depth at the position of the towed vehicle, towed vehicle's velocity over the sea bottom and slant range from a known reference point to the towed vehicle may be stored in the memory or memory devices of a computer. The computer is also utilized to analytically determine the towed vehicle's position using the bathymetry data, position and velocity over the sea bottom of the towing vehicle, ocean depth at the position of the towed vehicle, the towed vehicle's velocity over the sea bottom, and slant range from a known reference point; as well as displaying and storing the computed towed vehicles position. The analytically determined information may be

Inventor: Beckman et al.
Serial No.

PATENT APPLICATION
Navy Case No. 80,239

5 displayed on either a video monitor or a printing device.

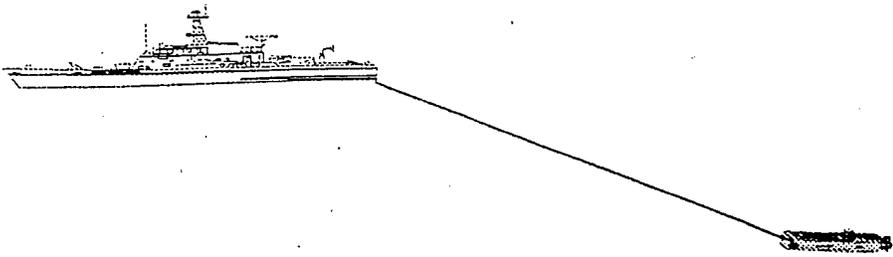
Although the invention has been described in relation to the exemplary embodiment thereof, it is well understood by those skilled in the art that other variations and modifications can be affected on the preferred embodiment without detracting from the scope and spirit of the invention as set forth in the claims.

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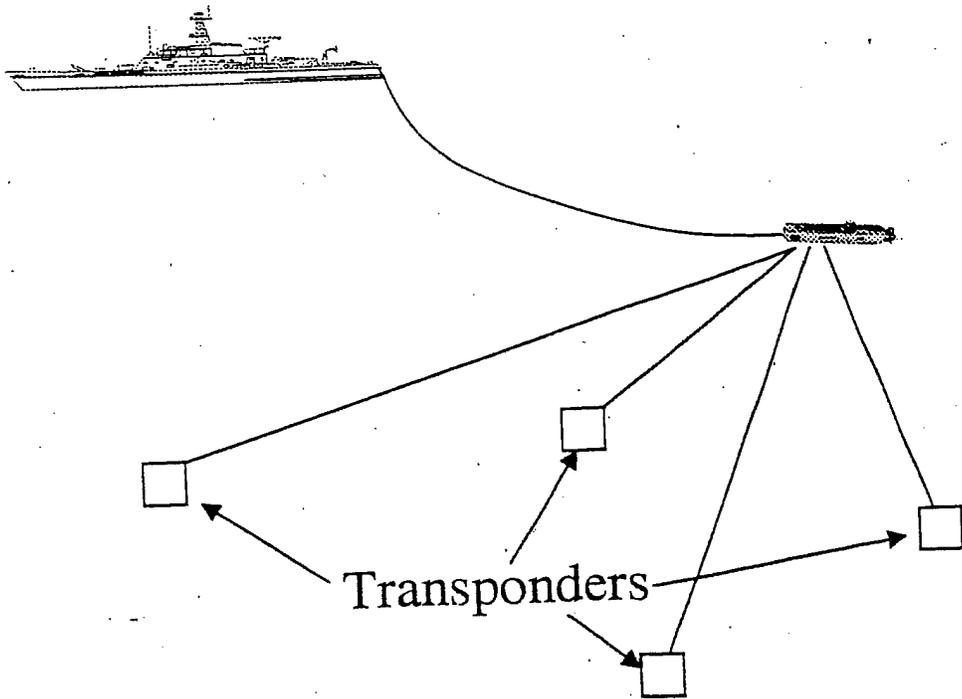
ABSTRACT OF THE INVENTION

The location of a submerged tow vehicle (LOST) system provides a device for accurately
10 determining a position of an underwater vehicle towed by a surface craft or aircraft, such as a
helicopter. The LOST system utilizes five sources of input data to compute a best estimate of the
towed vehicle's position. These are (1) high resolution bathymetry data in an area of the towed
vehicle's transit, (2) ocean depth at a position of the towed vehicle, (3) the towed vehicle's
velocity over sea bottom, (4) a slant range from the towed vehicle to a known reference point,
15 and (5) a position and course of the towing vehicle. The LOST system is comprised of a slant
range updater, a maximum likelihood estimator, a constrained adaptive tracker and a slant range
corrector.



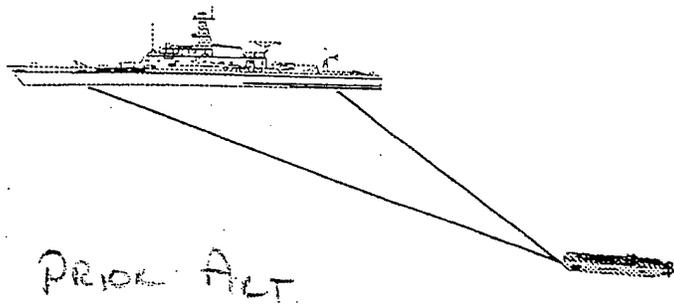
PRIOR ART

Figure 1



PRIOR ART

Figure 2



PRIOR ART

Figure 3

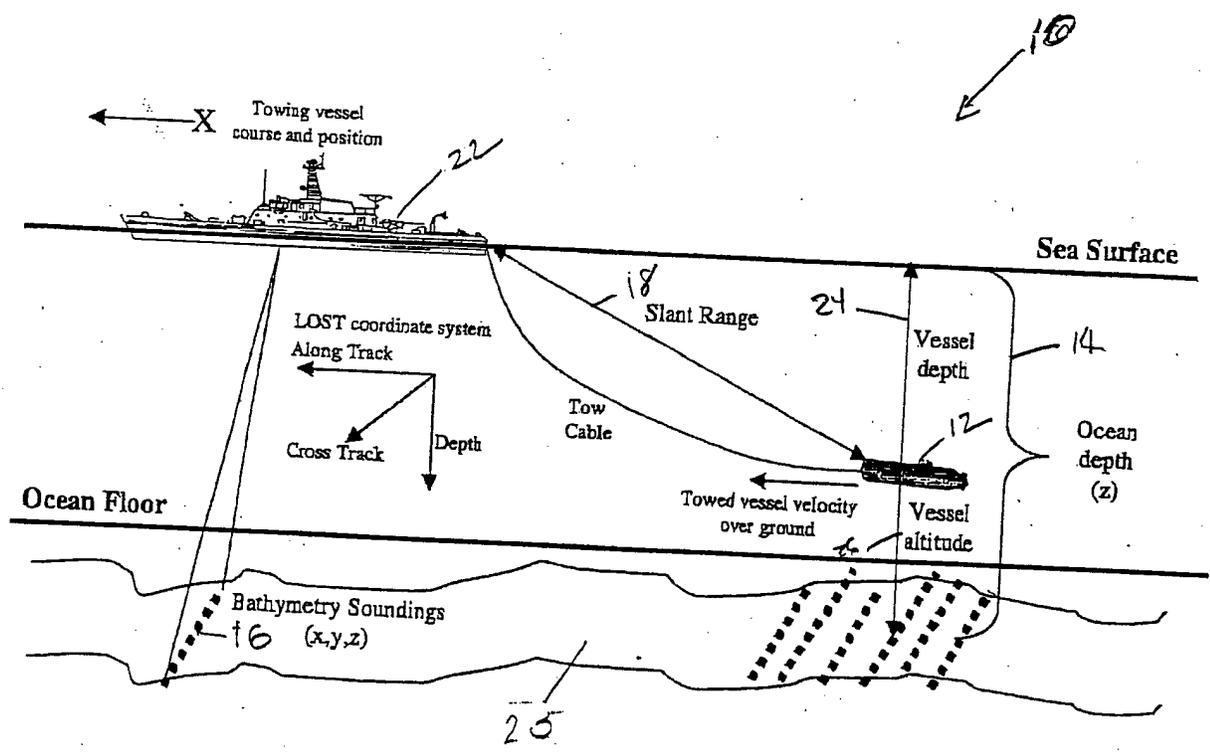


Figure 4

Side View

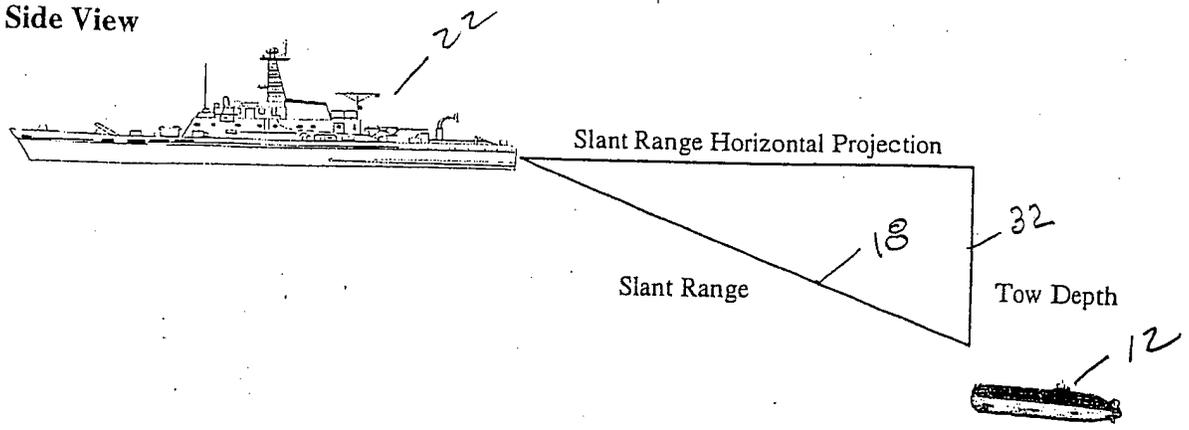


Figure 5a

Top View

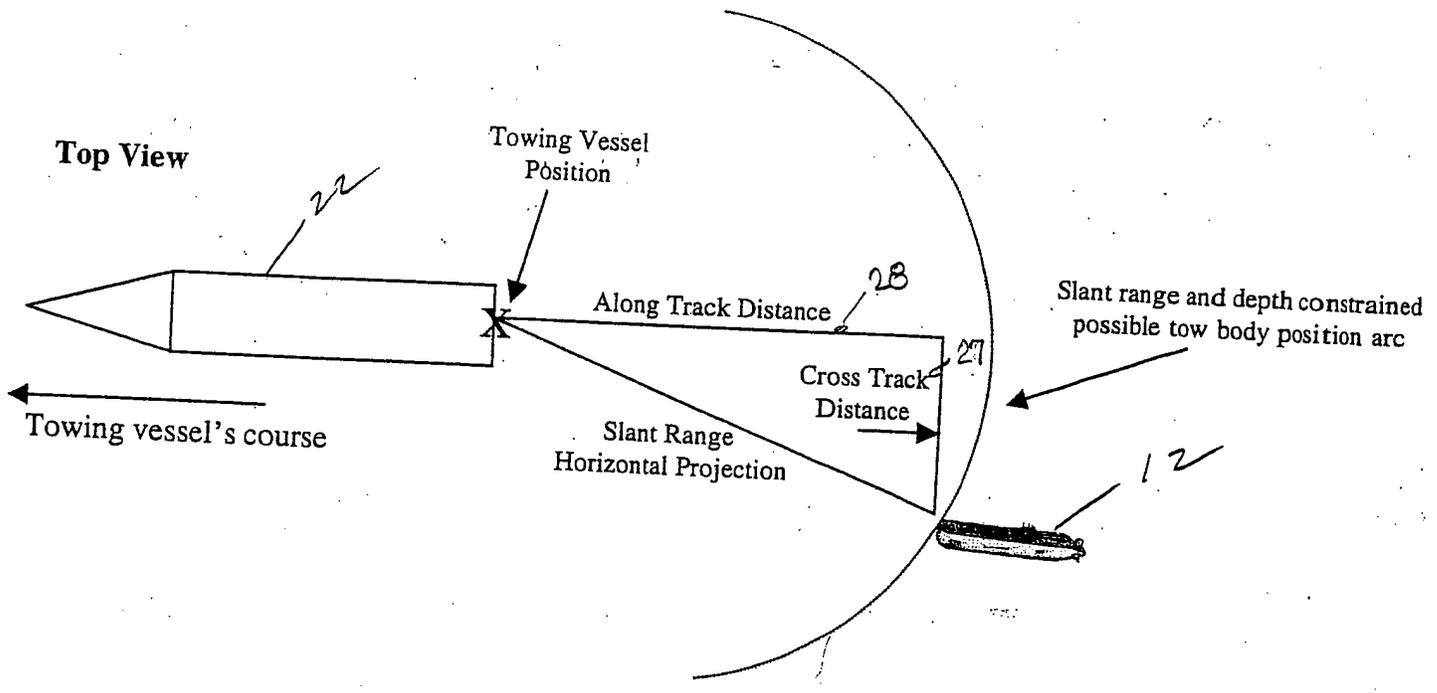


Figure 5b

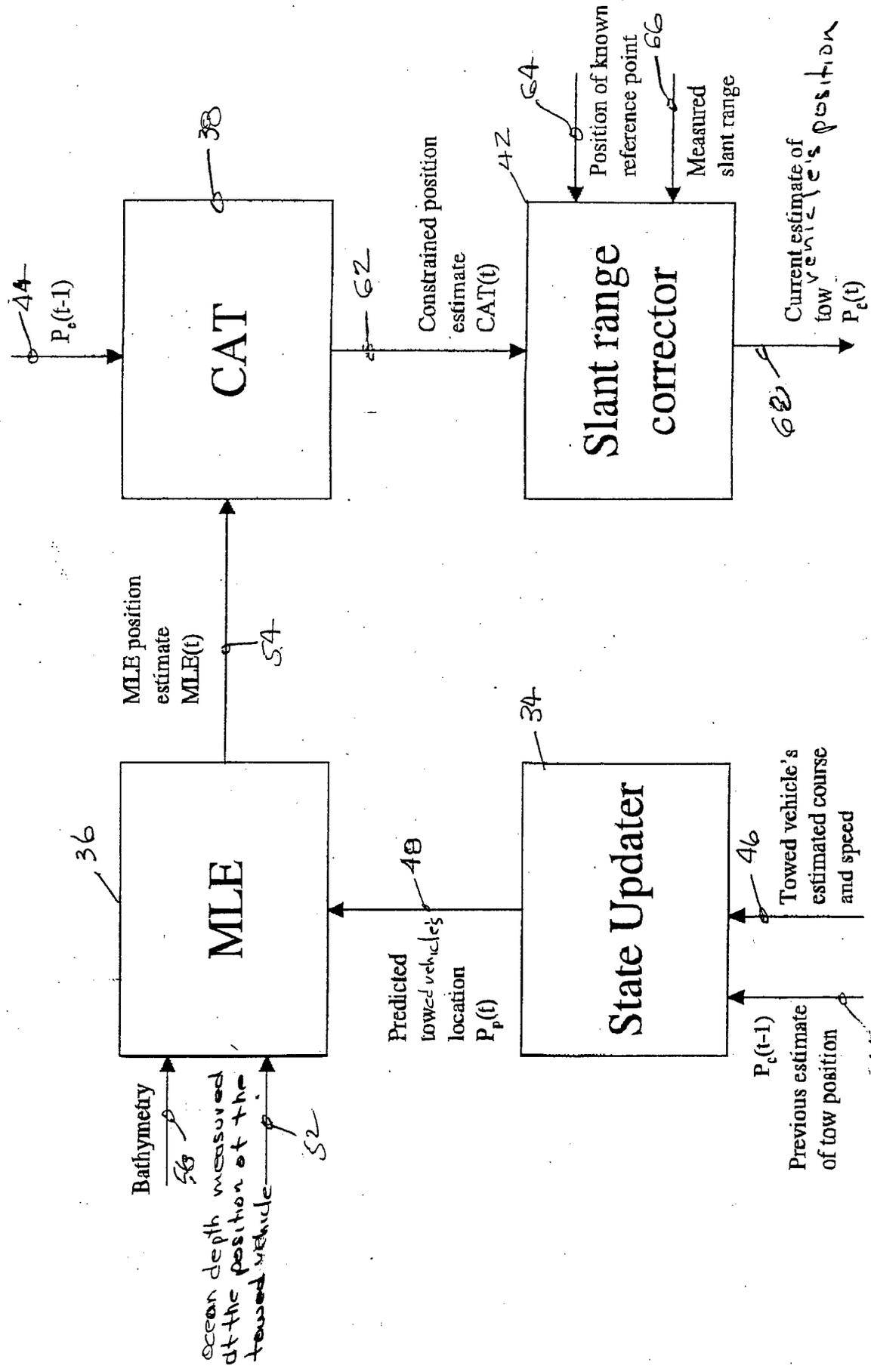


Figure 6