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Range-Only Underwater Target Localization: Error Characterization

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***Abstract* – Locating a target from range measurements using only one mobile transducer has been increased over the last years. This method allows us to reduce the high costs of deployment and maintenance of traditional fixed systems on the seafloor such as Long Baseline. The range-only single-beacon is one of the new architectures developed using the new capabilities of modern acoustic underwater modems, which can be time synchronization, time stamp, and range measurements.**

This document presents a method to estimate the sources of error in this type of architecture so as to obtain a mathematical model which allows us to develop simulations and study the best localization algorithms. Different simulations and real field tests have been carried out in order to verify a good performance of the model proposed.

***Keywords* – range-only, beacon localization, error characterization, underwater, underwater vehicles**

I. INTRODUCTION

The use of autonomous vehicles for oceanographic purposes has increased over the last years. One of the main drawbacks of these vehicles is the positioning, for the reason that the radiofrequency GPS signals suffer a rapid attenuation in an underwater environment, as it is well known. The main alternative for an absolute positioning system is the use of acoustic signals, which have the best performance in this environment.

The first acoustic underwater positioning system was called Long Baseline (LBL), created in the 1970s [1]. After this first system, others have appeared such as Ultra Short Baseline (USBL) or GPS Intelligent Buoys (GIBs). The main idea of these systems is the same: the distance between transponders can be obtained knowing the Time of Flight (TOF) and the sound speed in water using exchange messages.

Nowadays, new architectures have been developed using the new capabilities of acoustic modems. Different publications have appeared using multiple modems in acoustic Underwater Sensor Networks (UWSN) [2] which can also be used for synchronization and localization. On the other hand, in order to reduce the high costs of deploying and maintaining the beacons in an acoustic positioning system, other studies have been carried out using only one beacon. These studies refer to this technique as a Single Beacon (SB) positioning system [3]. Nevertheless, the main problem in all acoustic positioning systems is the sources of errors due to the complexity of the water channel.

This document presents a method to estimate the sources of error for a range-only beacon localization system. We use a Wave Glider to obtain multiple ranges at different positions in order to simulate an LBL system. Using this technique we can localize a specific target with an acoustic transponder. Identifying the sources of error in our system is necessary to perform multiple simulations to decide the best path shape and the best trilateration algorithm with which we can increase the precision of the system.

For this purpose, a mathematical model of error sources, a set of simulations and real field tests have been carried out.

II. RELATED RESULTS IN THE LITERATURE

The main problem in all acoustic positioning systems is the sources of errors due to the complexity of the water channel. McPhail and Pebody [4] describe similar techniques to estimate these errors and present results for the Autosub6000 AUV in a deep water test. Other works carried out on the AUV's positioning using range measurements include the work of Olson et al. [5]. In this work, the authors describe a Simultaneous Localization and Mapping (SLAM) system, where they use a voting scheme to find a beacon and then they use an Extended Kalman Filter (EKF) to refine both vehicle position and beacon locations. In their work, they only carried out simulations.

On the other hand, underwater communication interest has increased over the last years. There are a lot of factors which are involved in the underwater channel error, such as attenuation and noise, multipath propagation, and the Doppler Effect. The study of these errors and heir characterization have been conducted progressively over the last years, such as the work carried out by Stojanovic [6]. These studies are focused on the design of underwater communication systems, however they can also be used in range-only positioning to identify different sources of errors and study their performance.

III. DESCRIPTION OF THE METHOD

The general arrangement for the range-only beacon localization is shown in fig. 1. Where a Wave Glider performs a specific path in order to obtain the localization of a target on the seafloor. The target localization is computed using ranges between the Target (T) and the Wave Glider (WG), which are obtained using acoustic modems placed on both sides.

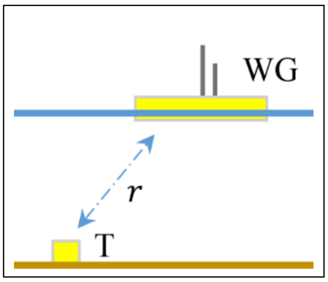

Fig. 1. Representation of the range-only target localization using range measurements between a WG and the target.

In time-based ranging the distance r between two beacons is measured using the Time of Flight (TOF) and the speed of sound in the water, using the following Eq. (1).

$$r = \frac{1}{2} T_{TOF}\, c \tag{1}$$

where T_{TOF} is the time that a message needs to travel from one point to another and c is the speed of sound in water ($c \simeq 1500\, m/s$). In two-way TOF the range is ½ because the message takes twice the time to travel from one point to another, and to return. In this system, the source error can be produced by the Wave Glider and the target, and by the underwater communication channel.

A. Range error model

The subject of measurement uncertainty is well known and multiple works exist related to it [7]. Errors during the measurement process can be divided into two groups, known as systematic errors and random errors. Therefore, the measured range can be modelled as Eq. (2).

$$\hat{r_i} = r + b(r) + \chi(r,i) \tag{2}$$

where $b(r)$ is the systematic error and $\chi(r,i)$ is the random error $\chi(r,i) \sim \mathcal{N}(\mu_{\varepsilon_R}, \sigma_{\varepsilon_R}^2)$ where μ_{ε_R} and $\sigma_{\varepsilon_R}^2$ are the mean and variance of the random error, respectively. In general μ_{ε_R} is assumed as equal to 0.

On the other hand, random errors in measurements are caused by unpredictable variations in the measurement system. In this case, we can consider two sources of error, the underwater channel and the electronic devices (where we have the Wave Glider and the seabed beacon). Both sources will affect the estimation of sound speed and TOF.

We will assume that systematic errors are well known and compensated or the algorithm can correct them, as in [4] algorithm. The assumption of Gaussianity in random noise is prevalent to many statistical theories and engineering applications. In the literature, authors have assumed a Gaussian distribution for representing the range estimation error [4]. Therefore, the range of our system is Eq. (3).

$$\hat{r_i} = \frac{1}{2} T_{TOF}\, c + \chi(r,i) \tag{3}$$

with a random error $\chi(r,i)$ and an uncertainty in the measurement of T_{TOF} and the knowledge of c. The uncertainty in a measurement is a parameter which characterizes the value dispersion that can be attributed reasonably to the measure. In this chapter, we present an estimation of this uncertainty using [8] guide, which is the most used guide and a reference in this field.

B. Channel dependency errors

These are one of the most relevant sources of errors for the characteristics of an underwater channel, and can be listed as follows:

Attenuation and noise

The attenuation is a peculiarity that effects all types of propagation waves. There are two mechanisms that decrease the intensity of a signal, the absorption and the distance. The first type depends on the signal frequency while the second type is for the spreading loss of the signal.

On the other hand, the noise in an underwater environment can be produced by many factors but in general, it is assumed that the power spectral density of underwater noise decays at a rate of approximately 18 dB/decade.

Therefore, a poor SNR will introduce a greater error in the range measurements, because the algorithms cannot compute the exact TOF of the signal. Which we compute as a random error type with variance $u^2(SNR)$, and can be estimated as in [9] with Eq. (4).

$$u^2(SNR) \geq \frac{1}{8\pi^2 B^2\, SNR} \tag{4}$$

where B is the bandwidth of the frequency.

Multipath

Multipath is a wave propagation phenomena that occurs in the ocean for two reasons: reflection and refraction. Reflection can take place over the sea surface or seafloor. This effect occurs specially in shallow waters, where we can have more echoes due to the proximity of the surface and seafloor.

Therefore, the geometry of the channel has an important role in multipath propagation. In a communication scheme, a sum of different paths can reach the receiver. Each one with its own attenuation (as a function of its length) and with different delays t_s. Therefore the variance can be Eq. (5).

$$u^2(M) = \frac{{t_s}^2}{4} \quad (5)$$

Doppler Effect

The relative motion between transmitter and receiver cause a shift into the signal frequency in an acoustic communication. In this case, relative velocity between the Wave Glider and the underwater target change the length of its range during transmission time.

A useful formula can be found in [10] to extract an error estimation model for Doppler Effect, where we can obtain its variance $u^2(D)$ considering a Gaussian distribution, obtaining Eq. (6).

$$u^2(D) = \frac{(T_i v_r/(c+v_r))^2}{4} \quad (6)$$

Variations of sound speed

In order to obtain sound speed we can use the relation between conductivity, temperature and depth, obtained from [10]. Therefore, for random estimation error, we will compute the variance of sound speed using the combined variance, and calculating all individual standard variance $u^2(T), u^2(S), u^2(z)$ for *T, S and z,* respectively. Eq. (7).

$$u^2(c) = 10.3a_T + 0.223a_S + 2.79 \cdot 10^{-4}a_z \quad (7)$$

where a_T, a_S and a_z are the ½ of square errors of temperature, salinity and depth, respectively.

C. *Electronic device dependency errors*

The source of errors produced by electronic devices used in both Wave Glider and underwater target are described below:

Acoustic Modems Resolution

In Benthos ATM-900 series the acoustic telemetry modem specifications, the manufacturer shows a resolution of 0.1 m for ranges from 0 to 999.9 m and 1 m of resolution for ranges from 1000 to 9999 m. Therefore, we can obtain its variance $u^2(MR)$ considering a Gaussian distribution as before, obtaining Eq. (8)

$$u^2(MR) = \frac{{\varepsilon_r}^2}{4} \quad (8)$$

where ε_r is the resolution of the modem.

GPS precision

Finally we can compute the error provided by the GPS. The Wave Glider uses a 12-channel GPS receiver as its primary navigation sensor, it also has on-board a tilt-compensated compass with three-axis accelerometers and a water speed sensor. This system provides navigation precision ε_{GPS} of better than 3 m (typically 1 m). Therefore, we can obtain its variance $u^2(GPS)$ considering a Gaussian distribution as before by Eq. (9).

$$u^2(GPS) = \frac{{\varepsilon_{GPS}}^2}{4} \quad (9)$$

D. *Calculation of overall random errors*

To conclude we can compute the combined standard variance u_c^2 with all individual variance of T_{TOF} and c uncertainty measurement previously explained and considering that all input quantities are independent. Therefore, the combined variance can be written as Eq. (10).

$$u_c^2(r) = \sum_{i=1}^{N} \left(\frac{\partial r}{\partial x_i}\right)^2 u^2(x_i) = \frac{1}{2}\sum_{i=1}^{N} c_i\, u^2(x_i) \quad (10)$$

where c_i is the coefficient to apply in each case. If range is $\widehat{r_i} = \frac{1}{2} T_{TOF}\, c + \chi(r,i)$ the total variance will be the sum of variances uncertainty of T_{TOF} and c with the variances of random noise $\chi(r,i)$.

IV. SIMULATIONS

The equations described in the previous section have been simulated using Python. In which we can observe the contributions of each individual error to the final error. In fig. 2 the Gaussian noise distribution for each source of error and the total error can be seen, where the total standard deviation σ_T of the range is 0.9 m. The parameters used in this simulation are shown in table I.

V. SEA-FIELD TEST

Lastly, we carried out a real field test to verify the error obtained in the simulations. In total, two series of tests were conducted. One with a target at 4000 m depth (Deep Sea) and another with a target at 40 m depth (Shallow Water).

A. *Deep sea target*

Firstly, two different paths around a target at 4000 m were made. The target is a Benthic Rover [11] which was deployed in the zone to take measurements of its

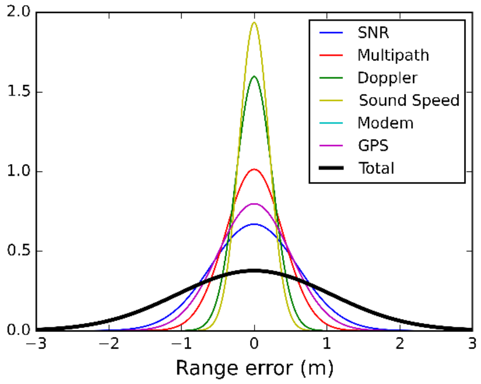

Fig. 2. Normal distribution of the range error for different sources (SNR, Multipath, Doppler Effect, Sound Speed variations, and Modem and GPS precision)

Table I. Error parameters for range error estimation model

Noise parameters	
Shipping activity (s)	0.5 (moderated)
Wind intensity (w)	3m/s (Smooth)
Attenuation parameters	
Temperature (t)	15 ºC
Salinity (s)	35 p.s.u.
Depth (z)	4 km
Ph (ph)	8
Latitude (o)	36.7
Transmission distance (l)	4 km
Frequency (f)	20 kHz
Spreading coefficient (k)	1.3 (cylin./sphere.)
Transmission parameters	
Power (s_tx)	20 W
Bandwidth (b)	1 kHz
Multipath parameters	
Spread time (t_s)	0.5 ms (low echoes)
Doppler parameters	
Time transmission (t_i)	1 s
Relative velocity (v_r)	0.25 m/s (0.5 m waves)
Sound speed parameters	
Temp. Variation (a_t)	0.1 ºC
Salinity variation (a_s)	0.1 p.s.u.
Depth variation (a_z)	0.1 m
Electronic devices	
Modem precision	1 m
GPS precision	1.1 m

environment, this type of vehicle moves at <1 m per day and for this reason scientists need to measure its new position periodically. We used the data obtained during two of these missions, where 63 ranges were taken for each path. After computing the target position using a trilateration algorithm, we were able to observe the error for each range, and consequently its standard deviation.

Fig. 3 shows the standard deviation of the error for the two paths. We can also see the simulation result obtained using the mathematical formulas explained above, with the parameters that are shown in table I. We can observe that with these parameters the result obtained in the simulations and in both tests are very similar (below 1 m). The standard deviation for the real field tests is 0.5 and 0.6 and the standard deviation for the simulation is 0.98 m.

B. *Shallow water target*

Finally, two paths around a target at 40 m depth were made to observe the range error behaviour in shallow water, fig. 4. To perform these tests an acoustic modem was deployed at a depth of 40 m in a zone of 80 m depth. 70 measurements of the range were taken during these tests. In this situation, we assumed a high possibility of echoes and noise, which can be generated because of the presence of multipath.

In the literature, [6] [10], we can find different works related to multipath studies, which in general observed a

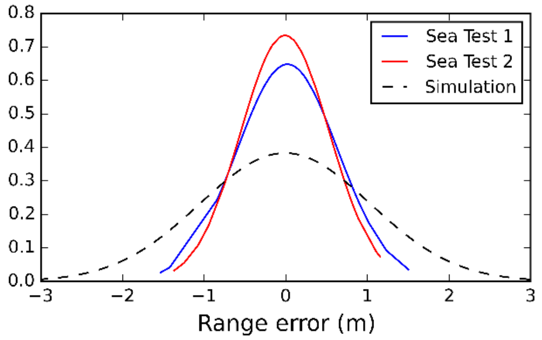

Fig. 3. Standard distribution of range error for two different paths around a target at a 4000 m depth. Which are also compared for the standard distribution obtained using the simulations, with parameters shown in table I.

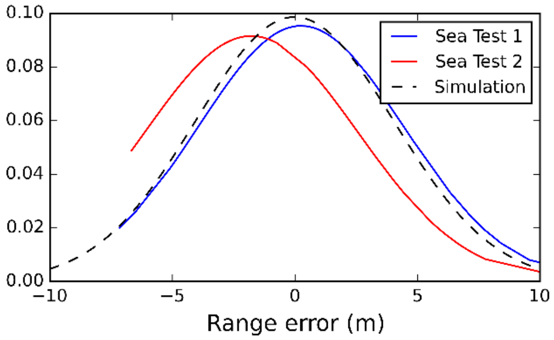

Fig. 4. Standard distribution of range error for two different paths around a target at 40 m depth (shallow water). Which are also compared by the standard distribution obtained using the simulations, with parameters shown in table I, and t_s equal of 5 ms.

total multipath spread t_s of tens of milliseconds.

This scenario is shown in fig. 4, where the standard error deviation is a factor greater than the previous scenario. In this case, the standard deviation is around 4 m. The simulation result is also plotted, which has the same values used in the previous simulations but with the difference of the spread time factor. In this case, we use a t_s equal of 5 ms because not all the echoes can have a consequence in time reception stamping.

On the other hand, one of the paths (red line in fig. 4) shows a nonzero mean. This is caused by some outliers measured because of the multipath and noise measurements, therefore it should handle again as a systematic error.

VI. NOVELTIES IN THE PAPER

The main novelty of this document is that we propose an error characterisation method for range only target localization using a Wave Glider, which is based on different publications related on acoustic communication and localization. Therefore, the main work was to define the source error and their parameters involved in the system. We also propose a mathematical equation to simulate the behaviour of this error with different configuration parameters. This characterisation and its mathematical formula have been tested and validated performing simulations and real field tests in different scenarios.

VII. CONCLUSIONS

In total, around 200 ranges between the target and the Wave Glider have been taken at different scenarios. With these tests we can observe the Gaussianity of the error. With a standard deviations between 0.5 m and 4 m. These values are similar to those obtained in the simulation.

Nevertheless, more tests are needed in order to compare exactly the performance of the error at different distances and multipath scenarios, and different sea conditions.

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