A bottom-following problem approach using an altimeter

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***Abstract*—Information on the profile of the bottom of the sea or river is of unquestionable relevance and importance. The applications for this are traditionally related with bathymetry, where the objective of mapping the bottom of the river or sea is achieved by using advanced ultrasound equipment. However, more recently, this information has found use in bottom-following applications, where the purpose is obtaining images or footage from the river or sea floor.**

This paper addresses the problem of bottom following by an Autonomous Underwater Vehicle in an environment which is not previously known. To accomplish this, the MARES AUV vehicle was equipped with an down-facing altimeter to continuously measure ranges to the bottom of the seabed.

The essential of this work consisted on fully integrating the altimeter with the navigation and control layers of the on-board software of the vehicle. First the altimeter settings were fine-tuned to minimize the number of spurious range measurements. After that, a Kalman Filter was implemented to smooth the noisy data and prevent possible wrong range measures to be propagated to the control loop. Finally, the whole experimental setup was validated, and the MARES AUV was able to execute several bottom-following missions in an open-water environment.

I. Introduction

With the development of Autonomous Underwater Vehicles (AUV), inspecting the bottom of seas, rivers, lakes, but also underwater infrastructures is becoming increasingly more interesting, easy and affordable. AUVs are now smaller, cheaper and incorporate large sets of sensors, making it extremely convenient to gather different kinds of information, in a very easy way. Underwater missions involving visual inspection of the seabed are now more and more common. These applications are for example bathymetry, monitoring of industrial structures, sonar or video imaging, and so on [1]. However, The bottom of rivers or seas, usually offers adverse and unpredictable conditions. The scarce light available and the turbidity of the water next to the seabed dramatically affect tasks related with the visual inspection. The ability to follow the bottom as closely as possible is of obvious relevance.

In perfectly known environments, navigating close to the bottom becomes a trivial navigation problem without much complexity. Nonetheless, in most cases it is impossible to know in advance the profile of the bottom. Having the capability to safely navigate close to the bottom without neglecting the safety of the vehicles and equipments involved can be extremely valuable. In this paper we address the problem of bottom following, using an altimeter, in shallow-water environments which are not previously known, by u

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The remaining of the article is organized in the following way: the experimental setup is described in section II, and after that, and in section III we introduce the Kalman Filter algorithm to be used. Section IV describes the between of the range measures with the navigation layer of the software some results, both simulated and and experimentally taken during operations in the Douro river are presented in section V. Finally, in the last session, some conclusions are presented as well as orientations for future work.

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II. Experimental Setup

Bottom-following was initially described as "maintaining a fixed altitude above an arbitrary surface whose characteristics may or may not be known" [5]. In this paper, we address the problem of bottom following with the MARES (Modular Autonomous Robot for Environment Sampling) AUV.

The MARES AUV, in Figure 1, is a highly modular torpedo-shaped 1.5 meters long AUV, designed to be able to carry a wide variety of payload sensors, in different vehicle configurations. Weighting 32kg, and propelled by 4 motors, the vehicle achieves a very high degree of manoeuvrability with an almost decoupled control of the horizontal and vertical motion of the vehicle [6]. However, the major defining characteristics of MARES is the ability to hover in the water column, and perform trajectories with arbitrary small horizontal and vertical speeds, making it a most adequate vehicle for the intended bottom-following operations. The MARES is equipped with a set of sensors for navigating in dead-reckoning mode, like a pressure sensor and an inertial measurement unit (IMU), that consists on three accelerometers, three gyroscopes and three magnetometers, all aligned with the x, y and z axis of the vehicle. Additionally, operations are also supported with an acoustic Long Baseline network. This network, that consists on a set of two acoustic beacons or buoys, makes it possible to overcome the drifting inherent to dead-reckoning techniques.

Fig. 1. AUV MARES

Nowadays it is widely known that the most reliable way of assessing the distance to the bottom in underwater environments is by using sonar techniques, mostly due to the unique characteristics of sound propagation in the water. To be able to assess the distance of the MARES to the bottom of the seabed, the vehicle was equipped with an altimeter in a downward-faced configuration, to continuously measure the vehicle distance to the bottom. The Imagenex Model 862, in Figure 2 was the sensor used. This is a completely self-contained altimeter that operates at frequencies of 330Khz and ranges of up to 50 meters, adequate enough to shallow-water environments, like rivers or near-shore sea. This altimeter has a 10^{o} conical beam, and the footprint on the bottom will in general be an ellipsoid. For slant terrains, the altimeter will always provide the range corresponding to the first reflection.

The altimeters rely on sonar techniques and, as such, on the propagation of acoustic waves, to measure ranges. In a rather simplistic way, what the altimeter does is to emit a sound wave at a given frequency, and during a given time period, and then wait to detect the reflection of that same wave. As the sound waves travel, they are attenuated by the medium where they travel, in this case the water. The same happens when a sound wave hits an object, with the reflected wave being attenuated when comparing to the original wave. By considering the velocity of the sound in water fairly constant, then the distance covered by the sound is proportional to the time of travel, and computing these distances is straightforward by timing both emission and reception instants.

Fig. 2. The Imagenex 864 altimeter

Sound waves propagate extraordinarily well in the water, even faster than in the air, with speeds of approximately 1500m/s. Although the speed of sound in water can be considered fairly constant, there are some environmental factors that make it vary from site to site. Environmental parameters like temperature, salinity or even depth are known factors that can directly affect the propagation and attenuation of sound; also, the attenuation that a sound wave is subject to when hitting an object and being reflected will vary significantly with the properties of the object. In the case of the bottom of the sea or river, if the seabed is sandy, the attenuation with the reflection will be much higher than if the seabed would be rocky.

Given that the altimeter in use can be configured with different parameters for range, gain and pulse length, it must be calibrated accordingly. These parameters are in fact of crucial importance, and failing to do so can negatively influence a mission, as exemplified in Figure 3. In a first approach, the altimeter was thoroughly tested in a small tank, in the lab. The tests allowed to understand the influence of the different parameters to be calibrated in the observed ranges. Despite that, and as expected, the optimal parameters that were empirically found in the tank, were rather different from the ones used in missions performed in the river. In the same way, it is likely that these parameters would need some tuning for missions performed under different environmental conditions, e.g. in the sea.

On both of the graphs displayed in Figure 3, an example of the profile of the bottom of the river can be seen, taken during a calibration mission in Douro river, close to Porto, in June 2011. The altimeter was attached to an autonomous surface vehicle - the ZARCO ASV - and set to continuously ping the bottom. The figure presents the range measurements from the altimeter throughout the time, while the ASV was performing random trajectories at the surface. On the left side of Figure 3, though it is possible to perceive the profile of the river, the set of data is extremely noisy, with a lot of false points detected in the band of 2m to 4m; moreover, due to the apparent randomness of the noisy points, this data sets

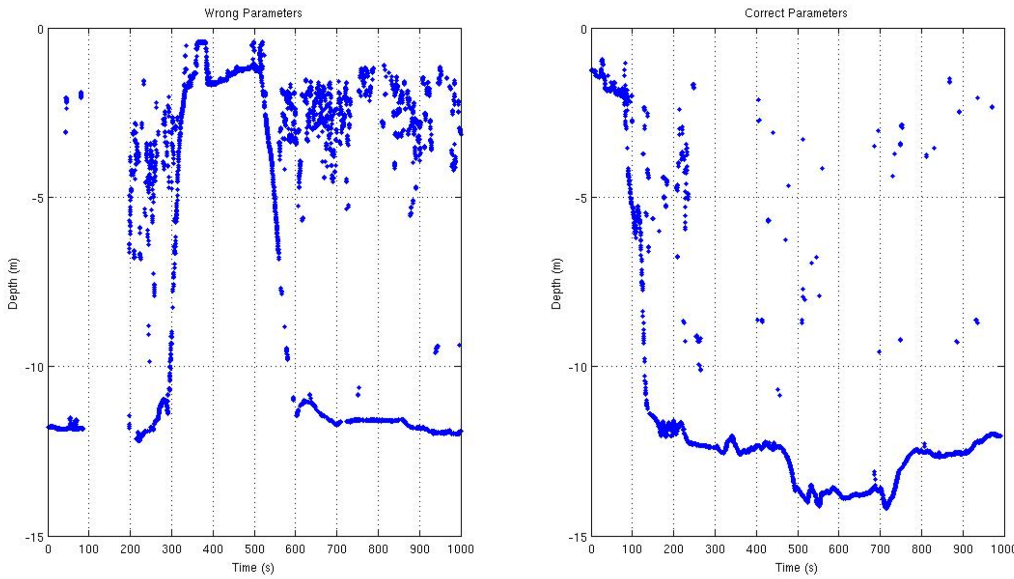

Fig. 3. Output of the altimeter: on the left, a situation when excessive gain and pulse length is depicted, with a lot of noisy measurements; on the right, a situation where the parameters have been correctly set

configures a situation where an efficient filtering of the noisy data would be extremely hard to achieve. This is a typical situation where the parameters of the altimeters were badly tuned: the gain was too high and the noise in the band of 2m to 4m is probably a cause of multiple reflections of the sound, both on the bottom of the seabed and at the surface. The image on the right side, on the other hand, shows the profile of the bottom of the river, taken at the same spot, but with the parameters correctly set. Even though it is possible to clearly see some outliers and some low-amplitude noise, there is an undoubtedly improvement to the previous situation.

III. Filtering

The output of the altimeter, when its configuration parameters are properly set, presents measures that are consistent throughout time. Despite that, and as expected, these measures still present some noise, most of the times in the same order of magnitude of the quantum of the sensor, which is 2cm. Moreover, this effect is more noticeable when the sensor is sending acoustic waves while moving horizontally, for example, when mounted on a vehicle which is moving with appreciable speeds.

The ranges measured by altimeter are supposed to generate proper depth references to be fed to the control of the vehicle and that necessarily need to present a relatively smooth behaviour. The need for filtering the raw altimeter measure naturally arises: on one hand outliers and spurious measurements need to be eliminated, and on the other hand, this stream of measures needs to be smoothed out. On top of that, it must be ensured that the delay introduced by the filtering process does not influence the control of the vehicle. Even though the vehicle dynamics are slow, delays higher the 0.5 seconds are already considered significant. An example of the raw output of the altimeter can be seen in Figure 4, where the presence of outliers is clear.

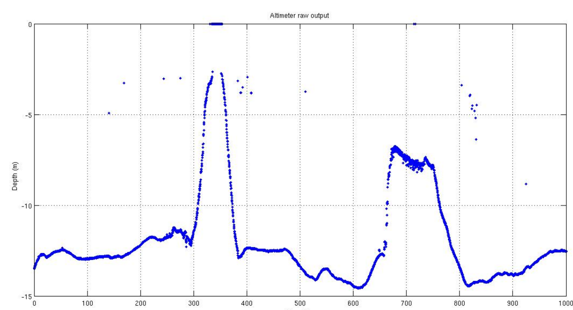

Fig. 4. Raw output of the altimeter; outliers are clearly identified

Given the filtering requirements, a choice for a one-dimension Kalman Filter came naturally, as it provides not only efficient smoothing, but also has the possibility to discard outliers by simply evaluating the covariance of the innovation. The state model for our systems is therefore uni-dimensional with its state being the depth, as given by the altimeter. The state model of the system was chosen to be a first order moving average:

$$z_{k+1} = z_k + u_k \tag{1}$$

Equation 1 tries to express the fact that the depth, z, should vary only by influence of the motion of the vehicle on the vertical plane. In that sense, $u_k = u \sin\psi + v \sin\psi$, ψ is the pitch angle of the vehicle and u and k are, respectively, the surge and heave movements of the vehicle.

The Kalman Filter algorithm is divided in to 2 different phases: the "time update", where the current state is projected ahead in time, according to the system model, and the "measurement update", where the projected estimate of the state is adjusted by an actual measurement. In our filter, new depth measures are available every 250 milliseconds, and the filter algorithm evolves according to the equations on (2);

$$\begin{aligned} S_{k+1} &= HP_kH^T + r \\ K_{k+1} &= P_kH^TS_k^{-1} \\ X_{k+1} &= X_k + K_k(z_k - HX_k) \\ P_{k+1} &= (I - K_kH)P_k \end{aligned} \tag{2}$$

On the other hand, in between every two consecutive measurements, the filter will then evolve according to equations (3). For the filter in question, $[A] = 1$ and $[B] = 1$; also, as we can obtain our state, the depth, directly by our measures, z_k, then also $[H] = 1$. Due to the lack of information regarding the stochastic characterization of the altimeter, the measurement noise r was assumed to be constant and equal to 0.1, which corresponds to half the sensor quantum; the process noise q, on its hand, was adjusted to improve the performance of the filter in terms of rejection of the outliers and delay.

$$\begin{aligned} X_{k+1} &= AX_k + Bu_k \\ P_{k+1} &= AP_kA^T + q \end{aligned} \tag{3}$$

A very important step of the Kalman Filter is the validation of the new measures, which can be performed by evaluating the covariance of the innovation, S_k. In fact, it is possible to define a parameter, γ, that will define whether a new measure, z_k, is valid and should be incorporated or if, on the other hand, should be discarded. Experimentally, it was found that setting γ to 0.5 offered the best results in terms of filtering noisy/spurious measurements. The obtained results are depicted in Figure 5.

$$\|z_k - Hx_k\| \, S_k^{-1} \leq \gamma \tag{4}$$

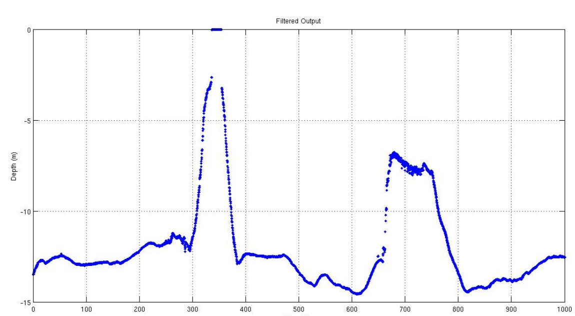

Fig. 5. Filtered output of the altimeter; outliers were removed

IV. Bottom Following and Control Strategy

As the ultimate goal of the present paper, we pretend to make the vehicle navigate at a given distance from the bottom. Typical applications, such as video acquisition for bottom inspection, requires the vehicle to be very close to the bottom in order to guarantee satisfactory results. Such problem is not trivial and becomes risky as the distance from the bottom decreases. The bottom-following missions foreseen and covered with this article are relatively simple. The MARES AUV controllers allow for a decoupled horizontal and vertical motions and our implemented bottom following technique takes advantage of that, by following a simple but effective approach. The Kalman filter outputs smoothed ranges to the bottom and consistent with the altimeter. The necessary references to the control of the vehicle will be generated by adding to these distances the depth of the vehicle Z_{PRS}, as given by the pressure sensor

$$Z_{REF} = Z_{PRS} + Z_{ALT} - D_f \tag{5}$$

In (5), D_f is the parameter that sets the distance to the bottom that the vehicle should maintain, and in this particular case it was set to 1.5. Besides collision with the bottom, we also wait to prevent situations of possible trap or loss of the vehicle. Therefore, Z_{REF} is bounded so that the vehicle is not allowed to submerge more that what is considered a safe depth. This value will obviously vary according to the environment where the missions are being executed. In a similar fashion, it is also important that the references don't vary in a very rough way. In that sense, $\dot{Z}_{REF}$ is also bounded.

V. Results

The results here presented are the outcome of a set of field trials with the MARES AUV, conducted during August 2011 in a dam in Douro river, located at the eastside Porto, in the north of Portugal. Due to some previous missions performed in the same place, the morphology of the bottom of the river is known with some detail thus making it an appropriate setting for the tests. The MARES AUV was equipped with the aforementioned altimeter, and the appropriate C++ routines were developed and integrated with the onboard navigation and control software of the AUV.

One of the challenges inherent to this work is to assess the accuracy of the ranges measured by the altimeter, since a wrong configuration of its parameters might lead to incorrect measurements. Even though this was tested in a small tank in the lab facilities, the parameters under use in the river were radically different from those ones. Reasons for this are the difference in the water parameters, like salinity and temperature, and also the characteristics of the bottom. A pressure sensor integrates the standard equipment carried, being straightforward to extrapolate the actual depth of the AUV relative to the surface. By comparing the measurements of depth given by this sensor with the expected motion of the vehicle and the ranges given by the altimeter, it is possible to check if both measures are consistent, thus allowing to verify if the altimeters is properly configured.

A couple of standard bottom-following missions were initiated at different times and different locations of the river, trying to depict different case-scenarios of operation. In all of them the purpose was to follow the bottom at a distance of 1,5 meters, the distance thought to be the appropriate for the envisioned applications. In Figures 7 to 9 the ranges to the bottom, measured by the altimeter, and the depth of the AUV, measured by the pressure sensor, were plotted along the time, allowing to verify the behaviour of the AUV for several bottom-following manoeuvres. Figure 7 depicts a situation when the AUV was initially at the surface level, and the waters were 8m deep. It is clear from the plot that at around 840s a bottom-following manoeuvre was initiated, and the AUV started to descend steadily, keeping at the same time a constant horizontal speed. At around second 890, the depth is of approximately 9 meters, and the range to the bottom of about 1.5 meters, consistent with what was expected. A similar situation is depicted in Figure 8, but at greater depths. The trajectory performed by the AUV on the vertical plane presents a small a subtle, but noticeable, overshoot and subsequent oscillation when trying to follow a given reference in depth. Similar oscillations can be seen on both figures 7 and 8. This effect can be observed on both range measurements to the bottom and depth measurements, and they are a good indicator on the AUV ability to follow smooth variations of the bottom profile.

More interesting, perhaps, are the results shown on Figure 9: it can be seen that initially the range to the bottom was of approximately 2 meters, while the AUV was in the surface. As the bottom-following manoeuvre was initiated the depth of the AUV keeps increasing steadily, while the range to the bottom slightly decreases to about 1.5 meters, with small variations throughout the duration of the mission. This is actually a very impressive result, as it clearly demonstrates the ability to follow arbitrarily changing bottoms. This, of course, as long as variations of the slope of the terrain are not too rough, and remain compatible with the maximum actuations that the vehicle can withstand. As opposed to the previous figures, where the profile of the bottom was more or less stable, here the AUV follows a descending profile correctly. Also in this figure, it is clear that smooth changes in the bottom profile are correctly followed by correspondent changes in the AUV trajectory, for example around second 3100.

VI. Conclusion

This paper describes an effective bottom-following method for AUVs using an altimeter. Moreover, and by equipping the MARES AUV with such sensor, it was possible to experimentally verify that this solution achieves good results as the vehicle performs trajectories that closely resemble the profile of the bottom of Douro river. The first challenge was to configure the altimeter in a proper way and tuning its parameters to adequate levels. The next step was the use of an adequate filter to smooth the ranges measured by the altimeter, removing at the same time obvious outliers. In that sense, the ability of the Kalman Filters to reject measures by evaluating the covariance of the innovation, revealed itself to be fundamental. Finally, the whole algorithm was integrated with the onboard control software of the MARES AUV, and tests were conducted, that allowed to tune all the parameters for optimal results.

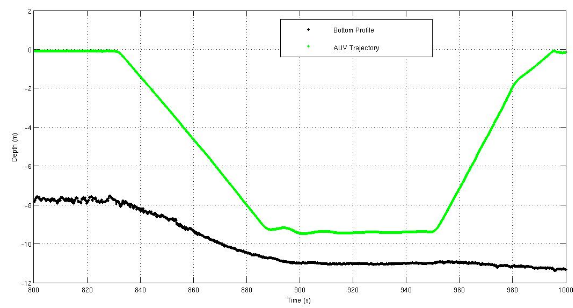

Fig. 6. Bottom of the river and the correspondent trajectory performed by the vehicle

All the applications that require to closely follow the bottom of the sea or rivers are likely to find use in the work here presented, for example the inspection of underwater structures. In addition, traditional bathymetry tasks could also be performed in this way, as exemplified in figure 6. There, the trajectory of the vehicle can be seen together with the profile of bottom of the river, obtained by combining depth data of the pressure sensors and ranges to the bottom. Possibilities for future work are quite encouraging. On one hand, a more complex Kalman Filter, containing a model for the sea bottom could be used. Using this information would allow to infer about the upper bounds on maximum depth, velocity and pitch that the vehicle should pose, to properly map the seabed. Moreover, depending on the confidence on the bottom depth measure and on the rugosity, the vehicle's pitch could be adjusted to anticipate possible unexpected obstacles or sudden slope variations. However, practical limitations on actuation would naturally bound the pitch angle.

Acknowledgment

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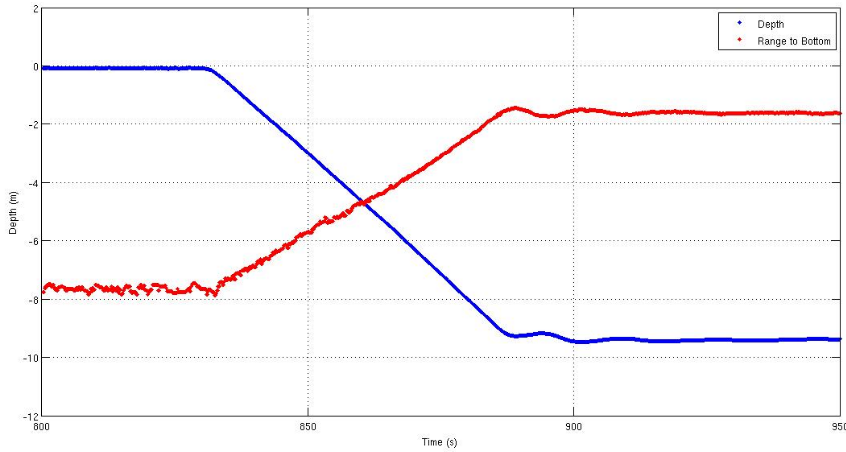

Fig. 7. Example 1 for depth and ranges to the bottom acquired over time

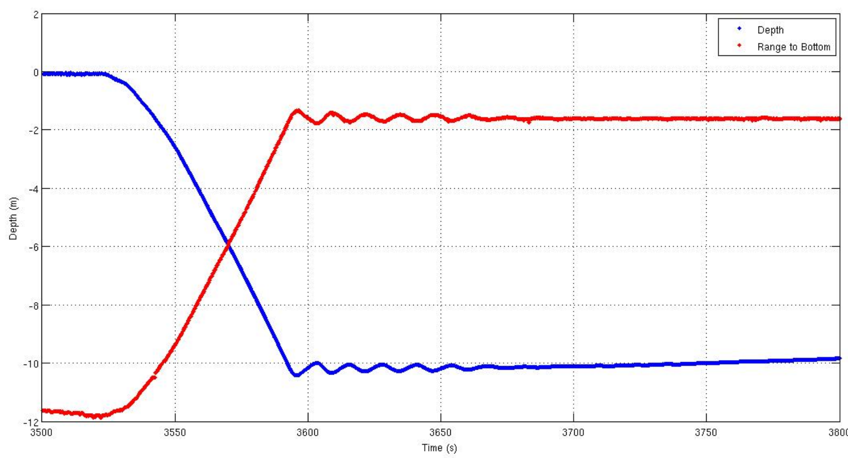

Fig. 8. Example 2 for depth and ranges to the bottom acquired over time

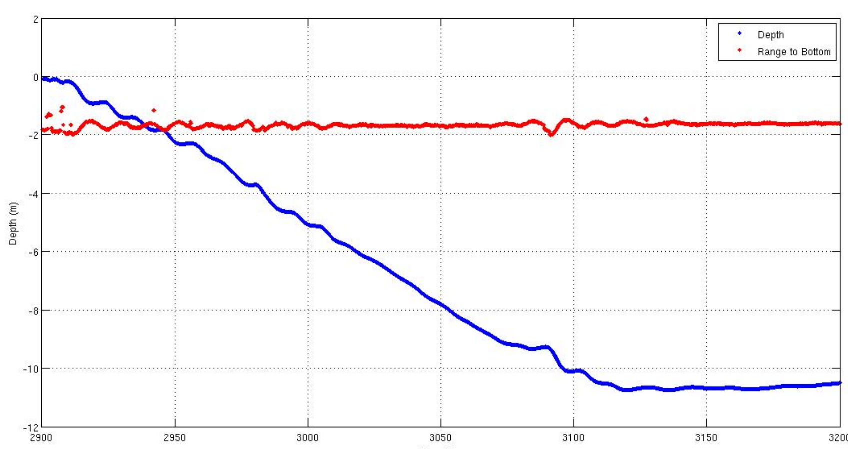

Fig. 9. Example 3 for depth and ranges to the bottom acquired over time