# Deepwater Applications for Brazilian Pre-Salt Exploration Using Underwater Sensor Networks

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## ABSTRACT

This paper proposes an underwater positioning system built with sensors distributed over the submarine infrastructure responsible for the oil production, which will be located by trilateration of acoustic signals emitted by units (vessels and platforms) with known coordinates. However, the acoustic signals needed to the calculation of the position depend on the vessels within sensors range. Thus, this work investigates the system behavior, analyzing the acoustic signals available for sensors using the ONE (Opportunistic Network Environment) simulator and scenarios based on the Brazilian offshore oil exploration area.

KEY WORDS: Underwater communications; acoustic; sensor networks; positioning; deepwater monitoring.

## INTRODUCTION

The new frontier of oil exploration in Brazil is located in a region 200 km off the coast called pre-salt which comprises an area of approximately 800 km in length and 200 km in width, encompassing three basins (Santos, Campos and Espírito Santo) (Carminatti *et al*., 2008). The operation in water depths up to 3000 m is the challenge to be overcome, requiring technologies to support the operational control in this extreme environment. Therefore, new communication techniques should be used to obtain information of subsea infrastructure.

Operation and maintenance of the infrastructure responsible for the uptake and distribution of oil in the underwater environment are extremely complex due to the harsh conditions. In addition to the adverse chemical conditions of the salty water, the seabed in Brazil is irregular in some places presenting an extreme slope, which exposes the structures of exploitation to great instability.

Underwater monitoring networks can provide a continuous verification on the operating conditions of underwater infrastructure of oil exploration. The accurate measurement of underwater position can allow the detection of seabed instability. Therefore, the use of sensor networks on seabed for underwater positioning monitoring enables verification of submarine displacements that can cause damage to structures, helping to prevent oil spills in the marine environment. However, underwater communication is subject to several limitations that cause interference in the propagation of the acoustic signal, resulting in small binary transmission rates. Thus, the development of an architecture based on underwater communication with Delay/Disruption Tolerant Networks presented in Cerf et al. (2007) becomes a necessity due to the limitations imposed by that subsea environment.

The development of underwater positioning system provides for the availability of the subsea mapping with references issued by units on the surface, which allows the location with geographic coordinates and depth. Therefore, the positioning will be useful in monitoring the activities of installation and operation of subsea structures such as the deployment of equipment at the head of oil wells, which should be installed in compliance with the perfect alignment for docking. In addition to allow monitoring the movement of remotely operated vehicles (ROV - Remotely Operated Vehicle) and autonomous underwater vehicles (AUV - Autonomous Underwater Vehicle), widely used in oil exploration activities.

This paper proposes a deepwater positioning system based on a DTN (Delay / Disruption Tolerant Network) monitoring network, built with acoustic sensors installed over the subsea infrastructure, which will be located by trilateration of acoustic signals emitted by logistic-support vessels and oil production units. The sensors must receive at least three signals of points with known coordinates (vessels and platforms) in order to perform the trilateration of acoustic signals received. The objective is to analyze the feasibility and behavior of the system reproducing the movement of vessels in the ONE (Opportunistic Network Environment) simulator (Keränen, Ott and Kärkkäinen, 2009), demonstrating that in scenarios compatible with the offshore environment, the sensors will be able to calculate their position.

The remainder of this paper is organized as follows: Section 2 presents related works and Section 3, the location methods used in positioning systems. Section 4 introduces the proposed underwater positioning system. In Section 5 we show the analysis of the monitoring system. Section 6 presents the results, while Section 7 concludes the paper and present topics for future work.

## RELATED WORK

Urick (1983) presents the basic principles of underwater acoustic transmission, emphasizing the characteristics that influence the speed of sound in water such as the pressure (depth), density, temperature and salinity. The results presented by Sozer, Stojanovic and Proakis (2000) on underwater communication open the way for using networks of wireless communications in the underwater environment. The study of underwater communication performed by Stojanovic (2006) presents the underwater features that influence the transmission of data.

The underwater communication challenges are described in Heidemann *et al*. (2006), where the difficulties imposed by the media and the constraints of the acoustic channel, such as interference, bandwidth, reflections, error rate and range are highlighted. An architecture for underwater networks and its requirements was proposed in Akyildiz, Pompili and Melodia (2007). The study identifies different approaches for medium access control, network and transport layers, showing an evaluation of different protocols. Another analysis of the problems of underwater sensor networks is also found in Liu, Zhou and Cui (2008). A routing protocol based on the hydraulic pressure for underwater sensor networks proposed by Lee *et al*. (2010) explores the levels of measured pressure to forward the data to buoys on the surface.

A sensor network for coral reefs monitoring is presented in Vasilescu *et al*. (2005). This acoustic network utilizes AUVs to collect data, mixing short-range optical communication with acoustic communication. Penteado, Costa and Pedroza (2010) proposed a sensor network that obtains oceanographic data to monitor ocean currents. This network is composed of fixed acoustic sensors that communicate with a sink responsible for external communication. Recently, Ribeiro, Pedroza and Costa (2011) proposed an underwater monitoring system in a DTN network composed of sensors distributed over the subsea pipelines. Data collection is undertaken by vessels used for logistic support of the oil exploration.

Some proposals based on the location determination use the characteristics of the signals propagation based on the position calculation. The GPS (Global Positioning System) is the best known example. This system is based on satellite radio navigation, consisting of 24 satellites, equally spaced in six orbital planes, located 20,200 km above the Earth, that transmit two coded signals, one for civilian use and one for military use (Kaplan, 1996). The satellites of the system transmit navigation messages to the GPS receiver, which calculates its position in 3D - latitude, longitude and altitude.

Other proposals may not use satellites for location. The proposal of Song (1994) that performs the location using signals from the cellular system was the precursor for the study of location through GSM cellular system proposed by Varshavsky *et al*. (2006). Gunnarsson and Gustafsson (2005) discuss the basic possibilities associated with mobile positioning in wireless networks with a sensor fusion approach and model-based filtering. A tracking system for vehicular ad hoc networks is proposed in Boukerche *et al*. (2008), showing how to combine the techniques of vehicle location by data fusion to provide a more robust tracking system.

Unlike the works presented, we propose an underwater positioning system composed of sensors that are located by trilateration of underwater acoustic signals emitted by vessels and platforms. Thus, we study the system ability to determine sensor location. No reference was found in the available literature that addresses the provision of a positioning system specific for deepwater environment considering mobility and the constraints of offshore oil exploration area.

## METHODS OF LOCATION

The position identification of a mobile or fixed element in a coordinate system can be accomplished in several ways. Whatever the coordinate system adopted, these methods require knowledge of location of at least three reference points in the system and metrics to estimate the distance of the unknown node from the reference points and their coordinates. Thus, the location methods generally have two basic components: an estimation of the distance and computational calculation of the position.

### Estimating the Distance

The estimated distance is obtained from the characteristics of the transmitted signal between two nodes. This estimate can be implemented based on the Received Signal Strength Indicator (RSSI), Angle of Arrival (AOA), Time of Arrival (TOA), or a combination of these methods.

The method to estimate the distance by measuring the received signal strength (RSSI) is based on verification of the fading of the transmitted signal (Savvides *et al*., 2001). However, this indicator is highly influenced by noises, obstacles, and the type of antenna, which makes it hard to model mathematically. The main source of error is the effect of shadowing and fading caused by signal multipath. In systems where the power of underwater acoustic signal is controlled to save the battery of the sensors, the measurement can suffer changes (Stojanovic, 2006).

The angle of arrival (AOA) of received signal can also be used by location systems (Niculescu and Nath, 2003). This angle is used to estimate the distance between the transmitter and receiver. The AOA estimation is done using directive antennas or a set of receivers arranged uniformly. The dispersion of the signal around the receiver and transmitter can change the measurement of the angle of arrival, limiting the range of the measuring devices. The need for extra hardware and interferences, restrict the use of this method. In underwater acoustic communication, transmissions are surrounded by sources of interference that affect the reception, making the approach AOA possibly impractical in this environment.

The last technique of distance estimation uses the measurement of the signal propagation time (Savvides *et al*., 2001). This method can work with the difference in propagation time of multiple signals (Differentiate Time of Arrival - TDOA), or measuring the propagation time of a single signal (Time of Arrival - TOA).

In TDOA approach, the differences in the arrival times for the transmitted two signals are used. These signals must have different propagation speeds, such as radio/ultrasound or radio/acoustic. This option can not be used in the underwater environment due to the lack of alternatives to the transmission of the second signal.

The measurement by the TOA method estimates the distance between the transmitter and receiver finding the unidirectional propagation time. Geometrically, this gives a circle centered on the point of reference, where the receiver should be. In this case, the distance between two nodes is directly proportional to the time the signal takes to propagate from one point to another. Thus, if a signal was sent at time $t_1$ and reached the receiving node at the time $t_2$, the distance between the transmitter and receiver is $d = c\ (t_2 - t_1)$, where c is the speed of signal propagation and $t_1$ and $t_2$ are the times when the signal was sent and received. The accuracy of this estimate type depends on the synchronization between the nodes.

### Calculation of Position

The location methods use the measures of distances performed by the node up to three or more reference points, running a series of calculations to define the position. The process of defining the position depends on the used method, which may be based on trilateration, multilateration or triangulation.

The trilateration method is the most basic and intuitive one, which is calculated considering the geographical location of a node through the intersection of three circles. To estimate a position, at least three reference points associated with the respective distances to the node ($d_1$, $d_2$, $d_3$) (Savvides *et al.*, 2001) are required. The circles formed by the position and distance of each point of reference, can be represented by the formula $(x - x_r)^2 + (y - y_r)^2 = d_r^2$, where (x, y) is the position that want to be computed, ($x_r$, $y_r$) is the position of the reference node r, and $d_r$ is the distance from the node to the reference point r. Thus, the location of the node is the point of intersection of three circles, considering the hypothetical case with no errors in the estimates of distances (Fig. 1 (a)) or in an area of intersection if considered the real case with measurement errors (Fig. 1 (b)).

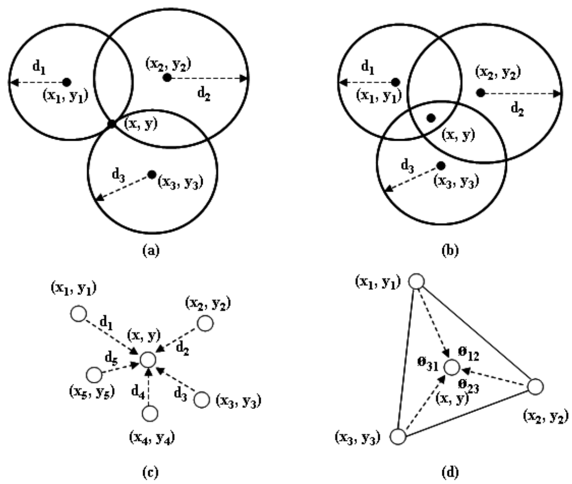


Fig. 1. (a) Hypothetical model of trilateration; (b) realistic model of trilateration; (c) multilateration; (d) triangulation.

The multilateration is a generalization of trilateration (Patwari *et al.*, 2005), which can be used when there are more than three reference points (Fig. 1 (c)). In this case, the calculation uses a system of equations for determining the location. The number of operations is much higher, increasing the processing load on the node, which usually makes it difficult to use.

The triangulation is applied when using the technique based on measuring the angle of arrival rather than distances (Savvides *et al.*, 2001). The node estimates its angle to each of the three reference points, and based on these angles and the reference positions (which form a triangle), calculates its position using simple trigonometric relationships (Fig. 1 (d)).

### Application Requirements

Generally, to estimate a position, a node uses at least three estimates of distances, each with an associated error. Although desirable, the accuracy is not the only important feature in choosing the most appropriate method for the application. Other factors should be considered, such as cost, hardware, processing and energy. Thus, the method to set the position depends on the application requirements.

Underwater positioning applications that work together with monitoring systems may use lower precision techniques. For these applications, the precise location of the sensor in some cases is unnecessary, being important only the neighborhood information. However, in underwater activities requiring precision, a specific positioning system fitted with close and dedicated reference points can be used, increasing the measurement accuracy.

## UNDERWATER POSITIONING SYSTEM

The use of acoustic sensor networks for monitoring the position in underwater environments is possible since the sensor receives the coordinates of three reference points and is able to estimate distances. The mapping of the underwater position is particularly important in monitoring the release of new lines of submarine pipelines (Solano *et al.*, 2007), in monitoring of installation maneuvers and movement of subsea structures (Chung, 2010).

The Campos Basin area is approximately 115,000 $km^2$ and can be divided into two regions, called transition and exploration regions (Fig. 2). Transition region is a transition area that has logistic-support vessels moving between the coast and oil fields. Exploration region is the producing oil area that concentrates most of the submarine infrastructure, responsible for the operation of the oil production fields. In this region, the logistic-support vessels perform a specific routine of units supply and anchoring.

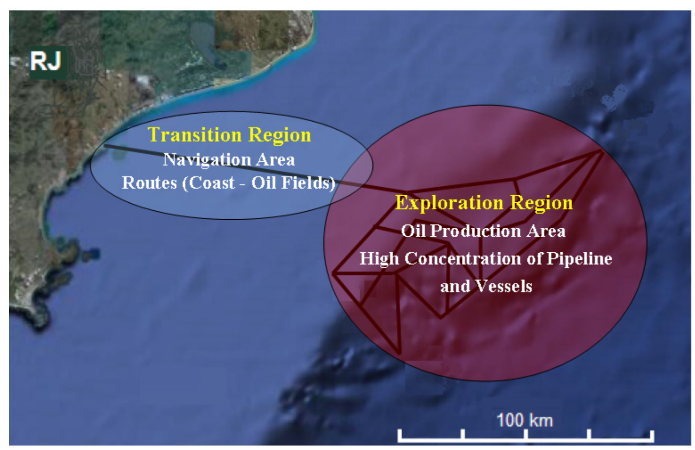


Fig. 2. Navigation area of logistic-support vessels.

Logistic-support vessels have GPS system, radio communication, and in many cases, satellite link and their routes are coincident with the subsea infrastructure, becoming together with the production units (platforms) the most appropriate option to be reference points needed for determining the positioning of sensors.

The long distances and dispersion of offshore installations affect the vessels density within sensors range. Thus, these vessels may not be reachable to sensors at all times, making the movement of vessels very important to the availability of reference points for the positioning and capture of information from the sensors. In this case, the use of logistic-support vessels and the units of production can increase the chances of having at least three reference units for sensors.

## Underwater Communications

The sound speed in water is about 1500 m/s, which is four times faster than the sound speed in air, but still five orders of magnitude smaller than electromagnetic waves speed in the air (Urick, 1983). This feature implies a latency of approximately 0.67 s/km. Thus, the speed of sound in the ocean is an important oceanographic variable that determines the acoustic wave propagation. Many empirical equations for calculating the sound speed in this environment have been developed using the values of salinity, temperature and pressure/depth of the water. A simplified expression for the sound speed in water is shown in Equation 1 (Su, Venkstesan and Li, 2010), where c is the sound speed in water, T is the temperature (in Celsius), S is salinity (in parts per thousand) and z is the depth (m). For most cases, this equation is sufficiently accurate.

$$c = 1449.2+4.6T–0.055T^2+0.00029T^3+(1.34–0.01T)(S–35)+0.016z \quad (1)$$

The acoustic waves are mainly interfered by noise caused by reflections, obstacles and turbulence, but the loss caused by absorption is the factor that most influences the propagation time. Still, it is possible to transmit information via acoustic modems which reaches up to 5 km range with transmission rates of 5 kbps [Stojanovic 2006].

## Underwater Sensor Network

Underwater sensor network is based on nodes equipped with sensors and acoustic modems also used in Vasilescu *et al*. (2005). The nodes can communicate with mobile nodes (vessels) or fixed nodes (platforms) to receive information from the coordinates of reference points. This network type, allows nodes to maintain an autonomous operation, where sensors are responsible for the position calculation and sending messages to the control center. Thus, sensors can be used to monitor positioning even in real time, but this operation must be planned to ensure longer life of the sensors.

The positioning sensor network is part of the monitoring system proposed by (Ribeiro, Pedroza and Costa, 2011), where all mobile nodes can collect the position information in DTN (Delay/Disruption Tolerant Network) underwater domain. The sensors are installed in the subsea infrastructure and programmed to calculate the position whenever three reference points become available. Each of these samples is encoded into a data packet, usually around 1 kbyte.

The positioning system uses a DTN sensor network, but the localization process is performed through a single communication hop between the reference points (vessels and platforms) and underwater sensors. This feature is related to the need to conserve battery life of the sensors. Thus, on the positioning process, the sensor only receives the signals and calculates the reference position not needing to transmit data, saving energy.

## Location Algorithm

The representation of the localization process performed by underwater positioning system is shown in Fig. 3, where the references to positioning were given by a logistic-support vessel, a FPSO (Floating Production Storage and Offloading) and a platform. The point in the center of the triangle on the surface is the representation of underwater sensor position in geographic coordinates. This representation together with the depth information allows mapping underwater objects by following a well-known location model.

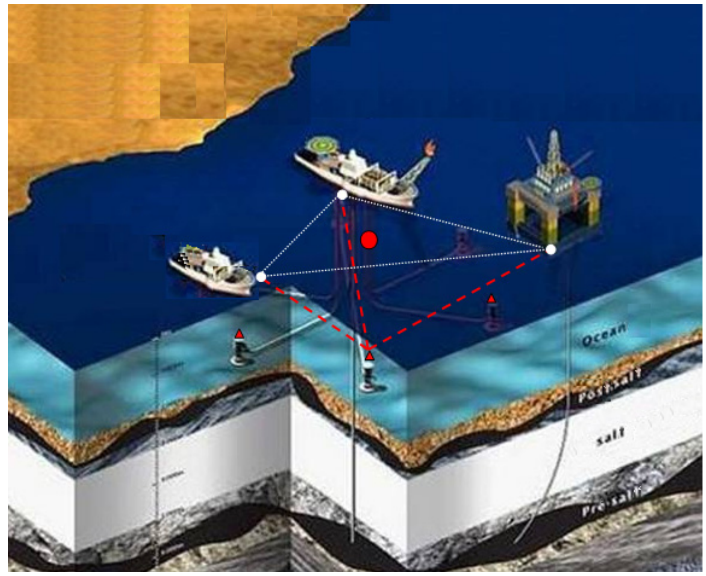


Fig. 3. Deepwater positioning system.

The sensor can be activated with a control message that initiates the process of calculating the position. Once the sensor is activated, it estimates the distance and calculates the position with the coordinates of the reference points.

Estimates of the distances will be performed by the method TOA (Time of Arrival). According to Fig. 4, the underwater sensor P has estimated distances $d_{pa}$, $d_{pb}$ and $d_{pc}$ of references A, B and C this point can be represented on the surface through the decomposition of triangles. This point on the surface will be in the same plane of the reference points, making it possible to determine their coordinates (x, y) by trilateration.

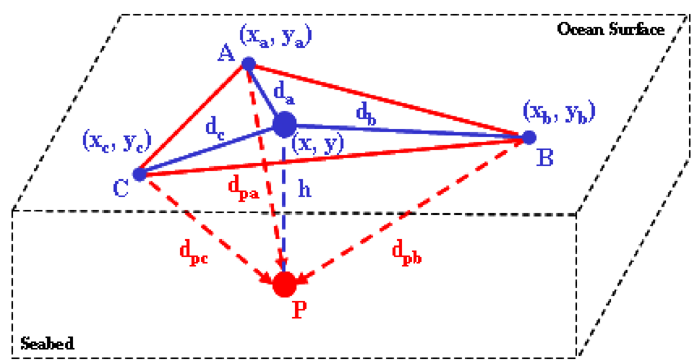


Fig. 4. Process definition of coordinates and depth.

The coordinates for points A, B, C and P are respectively (x, y), $(x_b, y_b)$, $(x_c, y_c)$ and $(x_p, y_p)$. The distances from the point on the surface for the three reference points A, B and C are $d_a$, $d_b$, $d_c$, and can be represented by Equations 2, 3 and 4.

$$(x_p-x_a)^2 + (y_p-y_a)^2 = d_a^2 \quad (2)$$
$$(x_p-x_b)^2 + (y_p-y_b)^2 = d_b^2 \quad (3)$$
$$(x_p-x_c)^2 + (y_p-y_c)^2 = d_c^2 \quad (4)$$

The distances $d_a$, $d_b$ and $d_c$ are obtained by the decomposition of the triangles. So we have three equations for two unknowns, making it feasible to obtain the position of point P on the surface. Thus, it is possible to position an object underwater with geographic coordinates and depth.

## PERFORMANCE ANALYSIS

The analysis of the proposed underwater monitoring system is done through a series of simulations designed to verify system performance during navigation of vessels in the transition and in the exploration regions. The goal is to show the network behavior in each scenario to verify the positioning system viability using the fleet of logistic-support vessels and the production units as points of reference. The underwater sensors must be able to get their position through these references, with a sampling period appropriate to the needs of the operation of the Campos Basin.

To evaluate and compare the monitoring system performance the ONE simulator proposed by Keränen, Ott and Kärkkäinen (2009) was used. ONE uses a specific movement model that can be customized to represent the actual displacement of the vessels responsible for the logistical support of the oil exploration. These displacements depend on each region:

- Transition Region: containing a total of 5 sensors, this equals 1 sensor every 20 km over the subsea pipelines. In this area, the vessels often travel great distances without stopping and at almost constant speeds;

- Exploration Region: containing a total of 20 sensors distributed in strategic points to take advantage of the production unit range, which in some cases already provide two reference points. In this area, the vessels travel shorter distances with constant stoppages in the production units (fixed platforms, semi-submersible platforms and FPSOs - Floating Production Storage and Offloading) and may remain anchored waiting for new operational plans.

The simulations consider a network with 25 sensors, 54 production units and up to 400 mobile nodes (vessels) and a control center outside the network. The mobile nodes are randomly distributed over the network and they move according to the mobility model. The sensors, production units and the routes for each region are shown in Fig. 5.

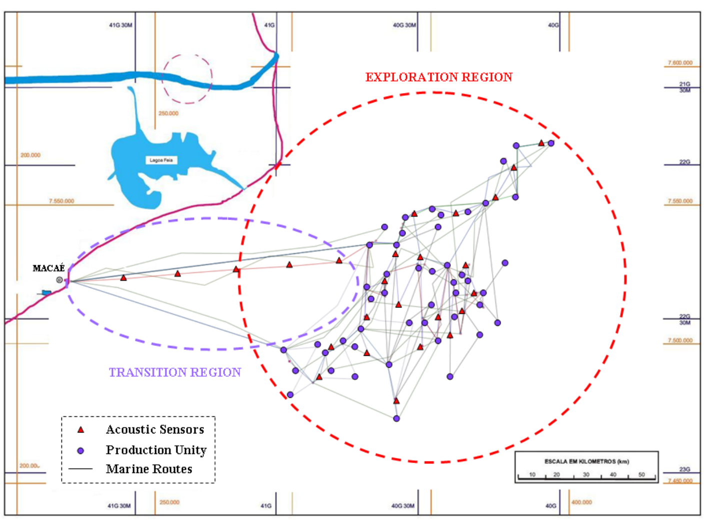


Fig. 5. Basic scenario of simulations.

Currently, there are 254 logistical-support vessels operating for Petrobras, but the expectation is that this number will increase to 465 by 2013, reaching a total of 504 vessels by 2020. This information is based on the presentation of the Petrobras business plan 2010 - 2014 made by Gabrielli and Barbassa (2010). As the Campos Basin is currently working with nearly 80% of Petrobras vessels fleet, we chose to use this number in the simulations.

The simulations aim to verify the following system information:

- Percentage of sensors reached by three references;
- Contacts made in the network;
- Average time to obtain a given position.

To simulate a realistic monitoring scenario, we considered the specific characteristics of the each region, which usually influences the type of movement and the vessels density. Only production units (platforms), sensors and mobile nodes (vessels) can move. The sensors have a very limited movement profile to represent displacements caused by movement of the seabed. The vessels in a typical operation, traverse the transition region staying for long times in the exploration region.

The parameters definition of the simulation was based on (Ribeiro, Pedroza and Costa, 2011), following the movement of vessels and the characteristics of acoustic transmission. The simulation period was 24 hours, covering an area of 250 km x 250 km (transition and exploration regions). The range of the underwater communication was defined as 5 km and the vessels moving at speeds that vary between 5 and 14 knots.

## SIMULATION RESULTS

The performance of the positioning system depends on the availability of network resources (vessels). Therefore, the displacement of vessels can affect the calculation of the sensor position. Thus, simulations were performed to verify the system behavior in relation to the movement and to the increase of the fleet of the logistic-support vessels.

As the vessels move according to the logistical support activities while providing a reference service to the positioning system, there is the unpredictability of contact which is an almost mandatory condition in this system. Therefore, checking the availability of three references by the network may indicate the probability of obtaining the sensors positioning.

Each simulation was performed to verify the ability of vessels together with the production units to provide three references for sensors. The evolution of this information with the increasing number of vessels can be seen in Fig. 6. In this case, it is noteworthy that the system allowed 100% of the sensors to obtain three references from 200 vessels, indicating that it is possible to verify the positioning of all the sensors in the network. However, for the network to be truly effective, this information must be provided with a frequency that allows the monitoring of real underwater conditions. Therefore, the number of contacts and the average time to obtain the positioning are important.

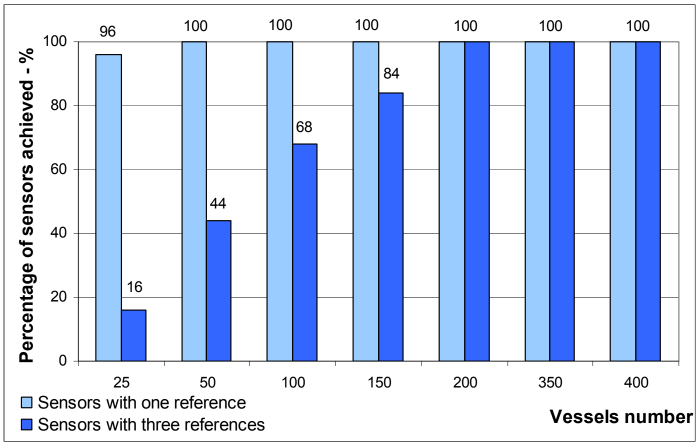


Fig. 6. Percentage of sensors achieved.

The increase of number of vessels in the network caused the increase of the number of network contacts (Fig. 7). This expected behavior indicates that the vessels number affects the system ability to provide three references for sensors, allowing more sensors to be able to calculate the position. However, this information is only relevant if it is associated to the average time that the sensor waits to obtain these references.

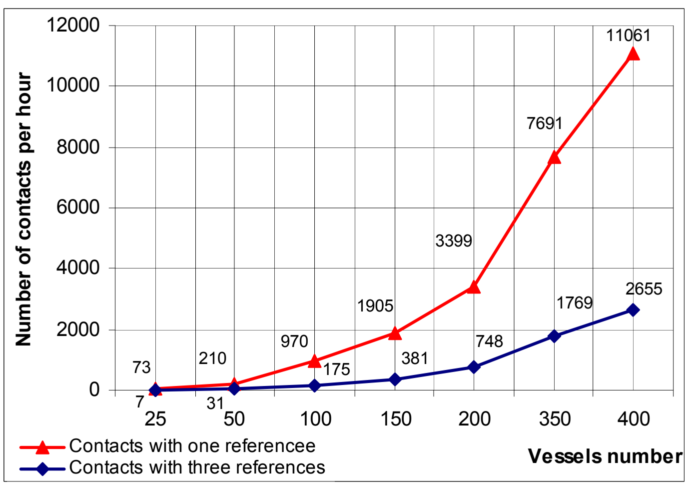


Fig. 7. Number of network contacts.

The frequency with which the sensors update their positioning is essential to define what kind of application will be supported by the system. Fig. 8 shows that from the scenario currently found in the Campos Basin (200 vessels), the sensors wait about 48 min to obtain three references, allowing to monitor the position of underwater infrastructure. This condition may be improved reaching 20 min in 2013 (350 vessels) and 14 min in 2020 (400 vessels). The values are high compared with conventional systems, but represent the minimum response time to detect any seabed slide. In this case, it would be possible to activate the emergency maintenance service in a short time if there was any oil spill, reducing the environmental damage.

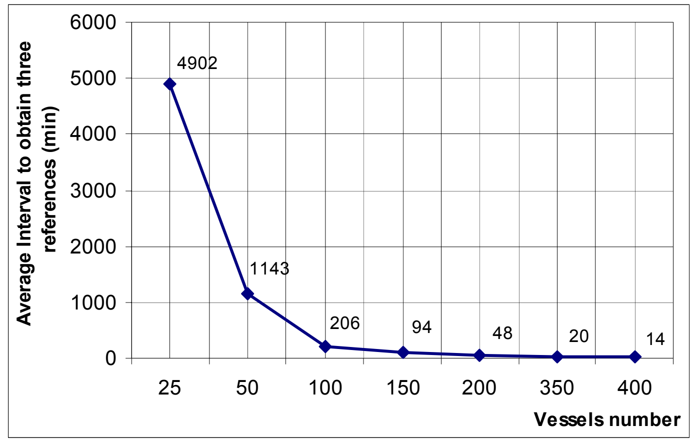


Fig. 8. Average interval to obtain three references.

The performance of the positioning system is affected by the availability of reference units within sensors range. However, the use of fixed reference units (platforms) in certain areas allows sensors to be less dependent on vessels and in some cases require only a mobile reference point. It was verified that this behavior is exclusive to the exploration region, being the transition region dependent on vessels due to lack of fixed reference units.

## CONCLUSIONS AND FUTURE WORK

This work proposed an underwater positioning system for the specific environment of the offshore Campos Basin. The objective was to verify the system behavior and to analyze the feasibility of using the logistic-support vessels and platforms in the task of providing the necessary references to obtain the positioning of underwater sensors.

Although vessels are not working specifically for the positioning system, it was noted that in conjunction with the production units (platforms) they can provide the necessary references so that the sensors are able to calculate their positions.

Despite the unpredictable communication of system, it was possible the location of all sensors in the network with a sampling that allows the monitoring of displacements caused by the instability of the seabed in order to detect situations that may cause oil spill and consequently damage to the submarine environment. Thus, the general behavior of the system was satisfactory, with consistent results that demonstrate the feasibility of monitoring the positioning in current and future scenario found in the oil exploration area of Campos Basin.

As future work, we intend to investigate the degree of precision provided by the underwater positioning system proposed. This precision will take into account the characteristics of underwater acoustic communication.

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## REFERENCES

Akyildiz, IF, Pompili, D, and Melodia, T (2007). "State of the art in protocol research for underwater acoustic sensor networks," SIGMOBILE Mob. Comput. Commun, vol 11, no 4, pp 11–22.

Boukerche, A, Oliveira, HABF, Nakamura, EF, and Loureiro, AAF (2008). "Vehicular Ad Hoc Networks: A New Challenge for Localization-Based Systems," Computer Communications vol 31 (12), pp 2838–2849.

Carminatti, M, Wolff, B, and Gamboa, L (2008). "New exploratory frontiers in Brazil," 19th World Petroleum Congress, pp 1-11.

Cerf, V, Burleigh, S, Hooke, A, Torgerson, L, Durst, R, Scott, K, Fall, K, and Weiss, H (2007). "Delay-Tolerant Networking Architecture," RFC 4838, DTN Research Group.

Chung, JS (2010). "Full-Scale, Coupled Ship and Pipe Motions Measured in North Pacific Ocean: The Hughes Glomar Explorer with a 5,000-m-Long Heavy-Lift Pipe Deployed," International Journal of Offshore and Polar Engineering, vol 20, no 1, pp 1–6.

Gabrielli, JS, and Barbassa, A (2010). "Business Plan 2010 – 2014," http://www.petrobras.com.br/ri/Download.aspx?id=10932.

Gustafsson, F, and Gunnarsson, F (2005). "Mobile positioning using wireless networks: possibilities and fundamental limitations based on available wireless network measurements," IEEE Signal Processing Magazine 22 (4), pp 41–53.

Heidemann, J, Ye, W, Wills, J, Syed, A, and Li, Y (2006). "Research challenges and applications for underwater sensor networking," IEEE Wireless Communications and Networking Conference, pp 228-235.

Kaplan, E (1996). "Understanding GPS Principles and Applications," Artech House.

Keränen, A, Ott, J, and Kärkkäinen, T (2009). "The ONE Simulator for DTN Protocol Evaluation," Proceeding of the 2nd International Conference on Simulation Tools and Techniques - SIMUTools '09, pp 1-10.

Lee, U, Wang, P, Noh, Y, Vieira, L, Gerla, M, and Cui, J (2010). "Pressure Routing for Underwater Sensor Networks," Proceedings of the 29th conference on Information communications INFOCOM'10, pp 1676-1684.

Liu, L, Zhou, S, and Cui, J (2008). "Prospects and Problems of Wireless Communciation for Underwater Sensor Networks, Wiley Wireless Communications and Mobile Computing," Special Issue on Underwater Sensor Networks, vol 8, no 8, pp 977-994.

Niculescu, D, and Nath, B (2003). "Ad Hoc Positioning System (APS) Using AOA," Proceedings of Twenty-Second Annual Joint Conference of the IEEE Computer and Communications - INFOCOM 2003, vol 3, pp 1734-1743.

Patwari, N, Joshua, N, Kyperountas, S, Hero, AO, Moses, RL, and Correal, NS (2005). "Locating the nodes - cooperative localization in wireless sensor networks," IEEE Signal Processing Magazine, 22 (4), pp54–69.

Penteado, D, Costa, LHMK, and Pedroza, ACP (2010). "Deep-ocean Data Acquisition Using Underwater Sensor Networks," 20th International Offshore (Ocean) and Polar Engineering Conference - ISOPE-2010, vol 1, pp 383-389.

Ribeiro, FJL, Pedroza, ACP, and Costa, LHMK (2011). "Deepwater Monitoring System Using Logistic-Support Vessels in Underwater Sensor Networks," 21st International Offshore (Ocean) and Polar Engineering Conference - ISOPE-2011, vol 2, pp 327-333.

Savvides, A, Han, CC, and Srivastava, MB (2001). "Dynamic fine grained localization in ad-hoc sensor networks," Proceedings of 5th International Conference on Mobile Computing and Networking – MobiCom 2001, pp 166-179.

Solano, RF, Genaio, MC, Ayres, A, and Cezar, GS (2007). "Design and Installation Challenges of Jubarte Gas Pipeline in the Shore Approach Area," 17th International Offshore (Ocean) and Polar Engineering Conference - ISOPE-2007, vol 1, pp 995-1001.

Song HL (1994). "Automatic vehicle location in cellular communications systems," IEEE Transactions on Vehicular Technology 43 (4), pp 902–908.

Sozer, E, Stojanovic, M, and Proakis, J (2000). "Underwater acoustic networks," Journal of Oceanic Engineering, vol 25, no 1, pp 72–83.

Stojanovic, M (2006). "On the relationship between capacity and distance in an underwater acoustic channel," 1st ACM International Workshop on Underwater Networks (WUWNet), pp 41-47.

Su, R, Venkstesan, R, and Li, C (2010). "A Review of Channel Modeling Techniques for Underwater Acoustic Communications," Proceedings of 19th IEEE Newfoundland Electrical and Computer Engineering Conference, pp 1-5.

Urick, R (1983). "Principles of Underwater Sound," McGraw-Hill.

Varshavsky, A, Chen, MY, Lara, E, Froehlich, J, Haehnel, D, Hightower, J, LaMarca, A, Potter, F, Sohn, T, Tang, K, and Smith, I (2006). "Are GSM phones the solution for localization?," Proceedings of 7th IEEE Workshop on Mobile Computing Systems and Applications - WMCSA'06, pp 20–28.

Vasilescu, I, Kotay, K, Rus, D, Dunbabin, M, and Corke, P (2005). "Data collection, storage, and retrieval with an Underwater Sensor Network," Proceedings of the 3rd International Conference on Embedded Networked Sensor Systems, pp 154-165.