

Improved Correction Localization Algorithm Based on Wave Direction Spectrum for Underwater Wireless Sensor Networks

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Abstract: Localization is an important topic in the underwater wireless sensor networks (UWSN) because sensor nodes are randomly scattered over a region and can get connected into a network on their own. In this paper, we proposed an improved correction localization algorithm based on wave direction spectrum for underwater wireless sensor networks. First, we use the length of anchor nodes and depth of nodes to compute the radius and achieve the initial positioning. Second, we estimate the moving distance of nodes through analyzing the wave direction spectrum, the correction coefficient was computed for X-axis, Y-axis, Z-axis respectively to correct the coordinate. Simulation shows that the localization accuracy of the proposed algorithm is better under the same time and speed environment than USP algorithm and SLMP algorithm. Copyright © 2014 IFSA Publishing, S. L.

Keywords: Underwater wireless sensor networks (UWSN), Underwater location, Dynamic correction, Wave direction spectrum.

1. Introduction

In recent years, underwater wireless sensor networks (UWSNs) have been a topic issue. Improving ocean exploration and satisfying the needs of many underwater applications is one important reason, such as: oceanographic information collection, warning systems for natural disasters, military underwater surveillance and location, auxiliary investigation, industry and ecological applications, and so on [1].

Underwater wireless sensor networks consist of a various number of relatively low-cost, self-organization, and mobile sensor nodes to monitor nearby oceanic environment [2]. The location of underwater wireless sensor networks is an important measure for these applications. Because of the unique characteristics of underwater environment, many

proposed location algorithms for terrestrial wireless sensor networks could not be directly applied to underwater wireless sensor networks. The anchor node whose location could be known in advance through GPS (Global Positioning System) [3] or other direct localization method is the commonly method to assist location, but existing direct localization technologies can't be directly used in underwater environment, namely, the underwater nodes which have no self-localization ability can't be used as beacon nodes. Usually use Autonomous Underwater Vehicle (AUV) [4] or indirect positioned super node [5] as the beacon node. Obviously, these methods may bring about high cost, low accuracy and poor flexibility.

Many researchers have carried out researches on the location algorithm of underwater sensor networks, but an important characteristic has been ignored,

namely active-restricted. For the application of terrestrial wireless sensor networks, after the nodes have been deployed, their locations were relatively stable. But for ocean environment, nodes usually move with ocean current, tide, wind and other factors. In order to avoid nodes deviate from the monitoring fields, usually connect the sensor nodes to some fixed anchor nodes through cables [6]. In this paper, we design an improved localization algorithm based on dynamic correction (LADC) for underwater sensor networks.

The major contribution in this paper has three aspects:

- 1) Design an adaptive localization algorithms, it uses RSSI method to measure the distance of nodes.
- 2) Using the relationship of adjacent nodes to estimate the distance of neighbor nodes in underwater environment to correct the errors.
- 3) Show the performance of ALCA by simulation results.

2. Related Work

In the past several years, a number of localization protocols have been proposed. Most localization methods in sensor networks require a few nodes called anchors which already know their absolute locations via GPS or other direct methods. There are two type nodes, one is anchors, there are typically equipped with high-power transmitters to broadcast their location to nearby anchors and other nodes. The remainders are unknown nodes, which estimate their own locations through the anchor location information and the communication links [7]. Based on the type of information used in localization, localization schemes are divided into two classes: one is range-based scheme which include range measurement and location estimation, another is range-free scheme which does not depends on range measurement for localization.

Range-based protocols usually use two nodes distance or angle information to estimate the location. Common techniques for distance/angle estimation include Time of Arrival (TOA), Time Difference of Arrival (TDOA) [8], Angle of Arrival (AOA) [9], or Received Signal Strength Indicator (RSSI) [10] to compute the distance and then convert these distance information to location. A silent positioning in underwater acoustic sensor networks was proposed in document [4]. It depends on the locally measured information at a sensor node by TDoA scheme to detect the range differences from the node to four anchor nodes, then using Trilateration method to estimate the three-dimensional sensor node location. Underwater localization in sparse 3D acoustic sensor networks(USP) was proposed in [11], the algorithm simplifies the three-dimensional positioning problem to two-dimensional via projection techniques, the distributed localization model includes offline forecast period and distributed positioning stages. In

document [5], AUV-aid localization for underwater sensor networks was proposed, it does not need a priori infrastructure or synchronization between sensor nodes, it mainly elaborates node localization methods using AUV and talk over the trade offs involved. Scalable localization with mobility prediction for underwater sensor networks (SLMP) [12] takes into account the different nature of the anchor node and the general nodes in the sensor networks, and node movement principle affected by the flow, it uses hierarchical way to localize different nodes position. For anchor nodes which have larger energy and computing ability, it uses the complex calculations to ensure positioning accuracy. For ordinary node s which have limited energy and computing power, it utilizes the ordinary operation for localization. The disadvantage of range-based methods is that the localization error closely related to the accuracy of distance estimation. An efficient localization for large-scale underwater sensor networks was proposed in [13], it uses a hierarchical method to divide the whole localization process into two sub-processes: anchor node localization and ordinary node localization. For ordinary nodes, it uses a distributed 3-dimensional Euclidean distance estimation method to estimate localization.

Because of the hardware limitations of sensor devices and node dynamic mobility in the underwater environment, the range-based location accuracy may be not ensure, so the range-free algorithms which do not rely on range measurement may be an efficient schemes. DV-hop [14], SDP [15] and APIT [16] and so on usually give coarser localization information. In UWSN, a 2D area localization scheme (ALS) [17] is a centralized scheme which provides a node's estimation in a given area rather than its exact coordinates, it uses the minimum transmit power from a central sink to estimate its position. Zhou *et al.* proposed a 3D multi-stage area localization scheme (3D-MALS) [18], it combines the concepts of ALS and LSL-DET. It uses detachable elevator transceivers (DET) and extends ALS to 3D. It has better localization accuracy than ALS. A 2D underwater localization scheme (UDB) [19] makes use of underwater acoustic transducer angle to estimate nodes position which through the first and last beacon information and the vertical channel used in UDB is characterized by little or no time dispersion. Another 3D underwater localization scheme (LDB) [20] uses a single AUV which traverses a preprogrammed route and performs vertical beaconing periodically, it assumes that the underwater position of AUV is known and it moves with average and known speed. Zhou H. *et al.* proposed an area localization scheme for large scale underwater wireless sensor networks in [18], it extends two-dimensional location scheme to three-dimensional underwater location scheme. A different range-free localization schemes based on fingerprinting (PM, PCA, PF) have been proposed in [21]. It involves two stages, in offline stage: the receiver position is known and places at reference location to

collect samples of other acoustic communication signals; in online stage: the receiver is employed in unknown location to responsible for collecting signals from different frequencies to build signal vector, and the offline stage is prior to the online stage.

All of these algorithms mentioned above can't directly used in underwater sensor networks, because common underwater node can't be used as anchor node. In this paper, we proposed an improved localization algorithm based on dynamic correction (DCLA) for underwater sensor networks. First, we use the length of anchor nodes and depth of nodes to compute the radius and achieve the initial positioning. Second, we estimate the moving distance of nodes through analyzing the wave direction spectrum, the correction coefficient was computed for X-axis, Y-axis, Z-axis respectively to correct the coordinate.

3. Network Model

In underwater sensor networks, nodes mobility is affected by ocean currents, tides and other factors. It is important to avoid the underwater flow sensor nodes going away or flowing away the deployment area. In most marine monitoring sensor networks, underwater nodes are connected to the anchor via underwater cable. Anchor are heavy, when sank to the seabed, they maintain their position and no longer moving, the underwater sensor nodes connected to anchor floating in the sea and moving with ocean currents, anchor node is the movement center and the moving radius is the cable length, namely, the moving range of underwater sensor nodes are restricted to a limited area [3]. This type of sensor nodes was named as activities-constrained underwater sensor nodes. When it was anchored in the sea bed, it floats in the sea and moves within the hemisphere area at its anchor. We named this underwater sensor networks as the active limit underwater sensor networks.

In the three-dimensional underwater network, sensor nodes float at different depths in order to observe a given phenomenon. One possible solution is to attach the underwater sensor nodes to a surface buoy through the wire which the length can be adjusted so as to adjust the depth of each sensor node [22]. However, despite this solution allows for easy and rapid deployment of sensor networks, multiple floating buoys may impede the ship sailing on the surface, or they can be easily detected and deactivated by enemies in the military setting. In addition, the floating buoys are vulnerable to weather and tampering or pilfering.

For these reasons, different methods can be used to anchor the sensor device to the seabed. In this structure, depicted in Fig. 1, each sensor is anchored to the seabed and equipped with a floating buoy that can be inflated by a pneumatic pump. The buoy pushes the underwater sensor towards the ocean

surface. The depth of the sensor can be regulated by adjusting the length of the anchor line that connected the underwater sensor to the anchor by the electronic engine control which dwells on the sensor. One challenge of this architecture facing is the impact of ocean currents on the regulation of the sensor depth.

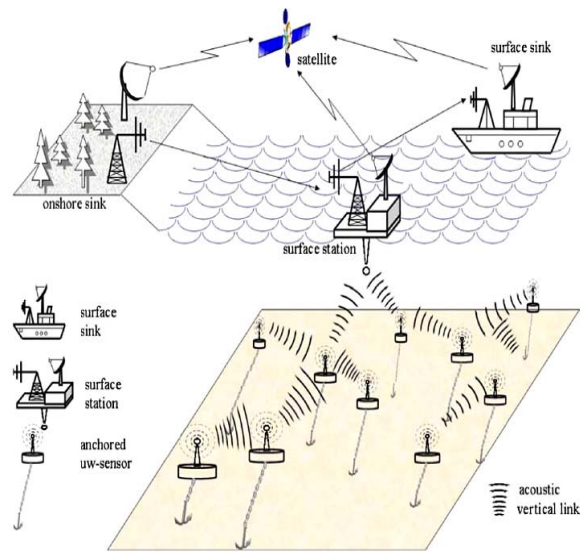


Fig. 1. Architecture for 3D underwater sensor network.

Suppose that a set of anchored sensors is deployed in the underwater convex space $D \in \mathbb{R}^3$ with a volume of $L \times W \times H$, where \mathbb{R} is the set of all real numbers. The sensors are highly probable to offset their static position because of water flow or underwater creatures touch. The topology of UWSN can be represented as graph $G(V, E)$, where the finite set of nodes $V = \{V_1, V_2, \dots, V_n\}$ and the set of links $E \subseteq V \times V$. Static positions of nodes are known, whereas the positions after movement are unknown.

The assumption was described as follows:

$\forall v_k \in V$, $RC(k)$, $RS(k)$, $e(k)$ is respectively denotes the communication radius, sensing radius and residual energy. Any sensor node v_k may either in asleep or awake state, then there are $RC(k)=RS(k)=0$. The set of awaking nodes $W = \{v_k \mid v_k \in V, RS(k) > 0, RC(k) > 0\}$, $\forall v_k, v_{k'} \in V$ or $\forall p, q \in D$, where p and q are geometric points, the distance refers as $d(k, k')$ and $d(p, q)$.

The coordinate of v_k at time T is expressed as a triple $p_k = (x_k, y_k, z_k)$, where x_k , y_k and z_k are respectively denote the X-axis, Y-axis, Z-axis coordinate. The anchored sensors are prone to drift off their static positions. Most of underwater nodes could measure the pressure on it by pressure sensors, and compute out the depth H . As the cable length L is determined before deployment, the nodes active radius R in the horizontal plane could be calculated by Right-Angled Triangle Theorem [3].

$$R = \sqrt{L^2 - H^2} \quad (1)$$

Specific description was shown in Fig. 2.

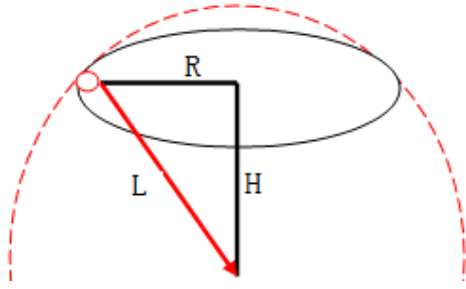


Fig. 2. Model of an active-restricted underwater sensor node.

4. Improved Correction Localization Based on Wave Direction Spectrum for UWSN

For the first time of localization, the node to be localized broadcasts its spherical coordinate, depth and cable length, at the same time receives other node's position information. The node carries out location computation process when it has received two messages came from two different nodes.

4.1. Node Coordination Positioning

As in Fig. 3, node A, B and C are the nodes to be localized. Their current positions are (X_A, Y_A, Z_A) , (X_B, Y_B, Z_B) , (X_C, Y_C, Z_C) , spherical center coordinate are (X_{AO}, Y_{AO}, Z_{AO}) , (X_{BO}, Y_{BO}, Z_{BO}) , (X_{CO}, Y_{CO}, Z_{CO}) , and cable lengths are L_A, L_B, L_C . In the horizontal plane, it can be obtained.

$$\begin{cases} (X_A - X_{AO})^2 + (Y_A - Y_{AO})^2 = R_A^2 \\ (X_B - X_{BO})^2 + (Y_B - Y_{BO})^2 = R_B^2 \\ (X_C - X_{CO})^2 + (Y_C - Y_{CO})^2 = R_C^2 \end{cases} \quad (2)$$

In the communication process, node A broadcasts its spherical center coordinate, depth and cable length to sensor node B and C. sensor node B and C respectively computes d_{AB} and d_{AC} from them to sensor node A based on signal arrival time [3]. The distance between two nodes could be calculated by fellow formula:

$$d = c \times T_{OA}, \quad (3)$$

where c is the underwater sound velocity which widely used empirical formula is Wilson equation [3], and TOA is the time of arrival.

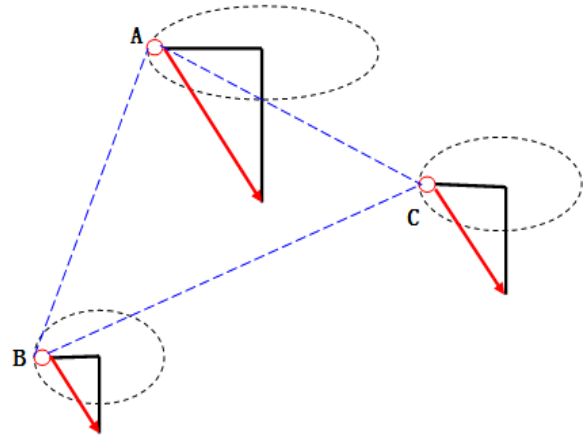


Fig. 3. Communication process.

The distance between node A and node B can be calculated by Formula (4) [3].

The distance d_{BC} and d_{AC} can be computed at the same method. So node C can use these results to get following equations [3]:

$$\begin{cases} (X_A - X_B)^2 + (Y_A - Y_B)^2 + (Z_A - Z_B)^2 = d_{AB}^2 \\ (X_B - X_C)^2 + (Y_B - Y_C)^2 + (Z_B - Z_C)^2 = d_{BC}^2 \\ (X_A - X_C)^2 + (Y_A - Y_C)^2 + (Z_A - Z_C)^2 = d_{AC}^2 \end{cases} \quad (5)$$

In which, the node's coordinates of Z axes could be transformed from depth H. So the three nodes position could be obtained.

4.2. Node Position Correction Based on Wave Direction Spectrum

Wave spectrum $S(\omega)$ plays an important role in the study of wave theory, it is the numerical description for the internal structure of the wave, but also it reflects some outside characteristics of the waves [23]. This article uses Pierson-Moscowitz spectrum (PM spectrum) based on wind [24]. Formula (6) is the mathematical expressions.

$$S_{PM}(\omega) = \frac{8.1 \times 10^{-3} g^2}{\omega^5} \exp\left[-0.74 \times \left(\frac{g}{u\omega}\right)^4\right] \quad (6)$$

In which, $g=9.8$, u is the velocity at 19.5 meters above the water surface; ω is the angular frequency. ω is $8.656 / u$ through differentiating for Formula (6). PM describes the distributed relationship between energy and frequency, but in actual, energy is related to the direction, $D(\theta)$ is the spectral function which must satisfy the Formula (7)

$$\int_{-\pi}^{\pi} D(\theta) d\theta = 0 \quad (7)$$

In this paper, we use the following direction function [25]

$$D(\theta) = \frac{2}{\pi} \cos^2\left(\frac{\theta}{2}\right) \quad (8)$$

Since the energy distribution in the frequency and in the direction is irrelevant, so the wave energy distribution function can be expressed as a multiplying of wave spectrum function and direction function which as show in Formula (9).

$$S(\omega, \theta) = S_{mv}(\omega)D(\theta) = \frac{8.1 \times 10^{-3} g^2}{\omega^5} \exp[-0.74 \times (\frac{g}{u\omega})^4] \frac{2}{\pi} \cos^2\left(\frac{\theta}{2}\right) \quad (9)$$

Let the wave-front equation as the following formula:

$$z = \xi(x, y, t) \quad (10)$$

So the three-dimensional random wave-front equation can be described as Formula (11) by Longuet-Higgins [3]

$$\xi(x, y, t) = \sum_{i=1}^m \sum_{j=1}^n a_{ij} \cos(k_i x \cos \theta_i + k_j y \cos \theta_j - \omega t + \varepsilon_{ij}) \quad (11)$$

In which, i is the wave frequency, j is the range of wave propagation; k_i is the wave number; ε is a random phase between $0 \sim 2\pi$; n is the number of divided frequency; m is the number of division direction.

The relationship of volatility and spectrum is

$$a_{ij} = \sqrt{2S(\omega, \theta) \Delta\omega \Delta\theta} \quad (12)$$

In which, $S()$ is the energy distribution function of wave, $\Delta\omega$ is the increment of ω , $\Delta\theta$ is the increment of θ .

The speed of node p at t_k+1 could be obtained through the coordination of node p at t_0, t_1, \dots and t_k as shown in Formula (13) [26]

$$v_k = f'(t) |_{t=k} \quad (13)$$

In which x is shown as follow:

$$x = f(t) = N_k(t) + R_k(t) \quad (14)$$

$$N_k(t) = f(t_0) + f[t_0, t_1](t-t_0) + f[t_0, t_1, t_2](t-t_0)(t-t_1) + \dots + f[t_0, t_1, \dots, t_k](t-t_0)(t-t_1) \dots (t-t_{k-1}) \quad (15)$$

$$R_k(t) = f[t_0, t_1, \dots, t_k](t-t_0)(t-t_1) \dots (t-t_k) \quad (16)$$

Similarly, the speed of node p along y, z direction could be calculated respectively, namely v_y, v_z .

So the speed of node p could be calculated by Formula (17)

$$v = \sqrt{v_x^2 + v_y^2 + v_z^2} \quad (17)$$

So the distance of moving between the interval of time for node

$$d' = v \times \Delta t \quad (18)$$

In which Δt is the interval time.

The distance of node A, B, C could be calculated respectively through Formula (18), they were put into Formula (2), it can be form the following equation:

$$\begin{cases} (X'_A - X_A)^2 + (Y'_A - Y_A)^2 = d'^2_A \\ (X'_B - X_B)^2 + (Y'_B - Y_B)^2 = d'^2_B \\ (X'_C - X_C)^2 + (Y'_C - Y_C)^2 = d'^2_C \end{cases} \quad (19)$$

Then use Formula (4-5) can get the offset position of node A, B, C, namely, (X'_A, X'_A, X'_A) , (X'_B, X'_B, X'_B) , (X'_z, X'_z, X'_z) .

The offset coordinate of node A is dynamic, so we define the $\lambda_{AX}, \lambda_{AY}, \lambda_{AZ}$ as the offset coefficient respectively in X-axis, Y-axis, Z-axis.

$$\lambda_{AX} = \frac{1}{(X_A - X'_A)}, \lambda_{AY} = \frac{1}{(Y_A - Y'_A)}, \lambda_{AZ} = \frac{1}{(Z_A - Z'_A)} \quad (20)$$

So the correction coordination of node A could be described in Formula (21)

$$\begin{cases} \bar{X}_A = \lambda_{AX} X_A + (1 - |\lambda_{AX}|) X'_A \\ \bar{Y}_A = \lambda_{AY} Y_A + (1 - |\lambda_{AY}|) Y'_A \\ \bar{Z}_A = \lambda_{AZ} Z_A + (1 - |\lambda_{AZ}|) Z'_A \end{cases} \quad (21)$$

5. Simulation Results

This section provides a detailed quantitative analysis comparing the performance of our scheme with USP algorithm and SLMP algorithm.

We have implemented our proposed protocol in NS-2 (ver. 2.31) [27], the deployment area is a cube area of $500 \text{ m} \times 500 \text{ m} \times 500 \text{ m}$, the communication radius R of nodes is 15 meters, all nodes random moved according to literature [28].

Fig. 4 shows the relationship between the localization error and time for USP algorithm, SLMP algorithm and our algorithm. Simulation results show that the localization accuracy of USP algorithm is gradually increased in the initial phase because of the number of unknown nodes increasing, but due to the cumulative errors too large, the position error

becomes large. SLMP positioning algorithm can't use the front information, so the localization accuracy is not affected by time. Our algorithm uses the wave spectrum predicted the moving speed and distances, it has further improved the positioning accuracy. We can see from the Fig. 4, our improved algorithm has the more obvious advantages which compared with other two algorithms.

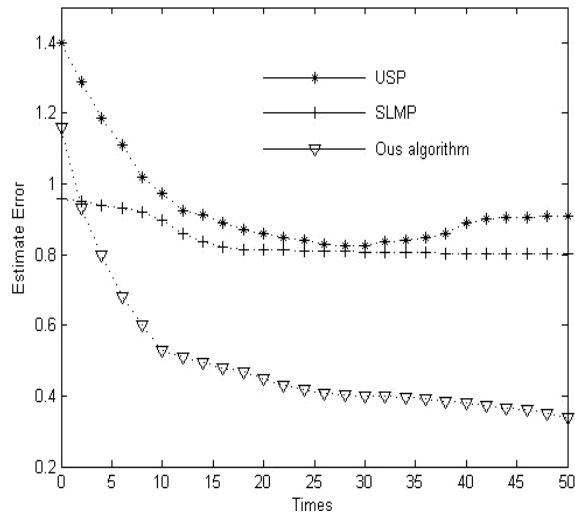


Fig. 4. The relationship between position error and times.

Fig. 5 shows the relationship between the localization error and speed for USP algorithm, SLMP algorithm and our algorithm.

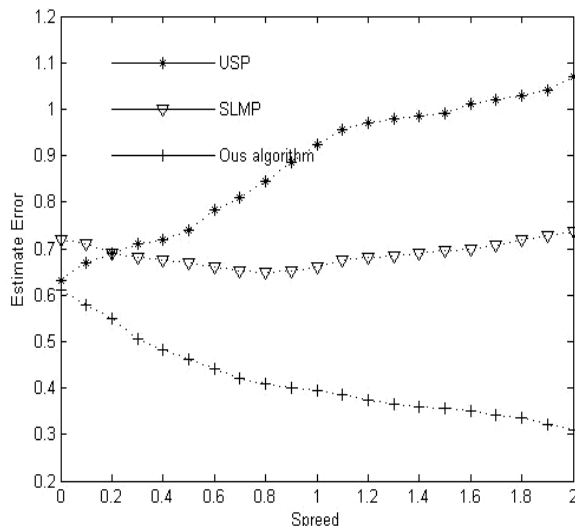


Fig. 5. The relationship between position error and speed.

Simulation results show that the localization error of USP algorithm is continues increases, this is because with the increasing of nodes speed, it lead to the topology of unknown nodes in around is

frequently changed. SLPM algorithm use specific mathematical model to estimate ordinary nodes, so the positioning ordinary nodes has a little impacted by nodes moving, the localization error curve is overall relatively flat along the speed. In our improved algorithm, with increasing speed, nodes received more messages from anchor nodes, node can flit the impossible coordinates to reduce the positioning error, meanwhile, it use nodes moving speed to correct nodes coordinates, so when the speed is increased, the localization accuracy of our algorithm is not reduce. We can see from Fig. 5, the localization error of our improved algorithm is continuous reduce when the speed further increases, and the total positioning error is less than the other two algorithms.

6. Conclusions

For underwater wireless sensor networks (UWSN), identifying the location of each sensor node is an important issue, which is also a challenging task. In this paper, we proposed an improved correction localization algorithm based on wave direction spectrum for underwater wireless sensor networks. First, we use the length of anchor nodes and depth of nodes to compute the radius and achieve the initial positioning. Second, we estimate the moving distance of nodes through analyzing the wave direction spectrum, the correction coefficient was computed for X-axis, Y-axis, Z-axis respectively to correct the coordinate. Simulation shows that the localization accuracy of the proposed algorithm is better under the same time and speed environment than USP algorithm and SLMP algorithm.

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