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Computer Vision Techniques Applied for Reconstruction of Seafloor 3D Images from Side Scan and Synthetic Aperture Sonars Data

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The Side Scan Sonar and Synthetic Aperture Sonar are well known echo signal processing technologies that produce 2D images of seafloor. Both systems combines a number of acoustic pings to form a high resolution images of seafloor. It was shown in numerous papers that 2D images generated by such systems can be transformed into 3D models of seafloor surface by algorithmic approach using intensity information contained in a grayscaled images.
The paper presents the concept of processing the Side Scan Sonar and Synthetic Aperture Sonar records for detailed reconstruction of 3D seafloor using Shape from Shading (SFS) techniques. This approach is one of the basic techniques used in computer vision for the objects reconstruction. The algorithms proposed in the paper assume Lambert model of backscattering strength dependence on incident angle and utilize additionally the information from shadow areas for solving obtained set of equations. The proposed concept was verified by simulation study. The obtained results of 3D shape reconstruction are presented and the performance of the algorithms are discussed.

1 Introduction

3D acoustic imaging of the seafloor has become increasingly important for different underwater engineering activities such as pipeline tracking, wreck inspection, mine hunting and seafloor monitoring and characterisation. At present, acoustic sensors offer the most reliable sight inside underwater environments for these purposes. They offer a longer range and wider angle coverage compared to video cameras or other sensors and map well the environment in turbid waters.

Side scan and synthetic aperture sonars are one of the most widely used imaging systems in underwater environment. Although some limitations, such as these inability to directly recover seafloor depth information, in comparison with more powerful sensors like multibeam systems. Most of very attractive images of seafloor and wrecks represents acoustic data obtained by modern multibeam sonars, which allow for their direct 3D visualization [1]. However, many 2D images acquired by side scan sonars exist, that could be transformed into 3D representation in an algorithmic way using echo intensity information, contained in grayscale images.

The fundamental principle of imaging sonar systems is based on the signature of the reflection or backscattering of acoustic energy by a target on the seafloor. It is suggested by Jackson [2] that Lambert's Law provides a good fit to seabed backscattering since roughness and volume scattering mechanisms tend to mimic Lambert's Law. Consequently, he has compared Lambert's Law to his composite roughness backscattering model, therefore Lambert's Law may be considered to provide a good approximation of the bottom backscattering.

Several techniques of 3D geometry reconstruction for seabed surface or submerged objects using side-scan sonar images has been reported [3, 4]. Mainly, they use the techniques based on the problem inverse to image formation, namely Shape From Shading (SFS), which is one of classical problems in computer vision [5]. In the construction of a seabed elevation map from side-scan images, the SFS technique relays on calculating the local slope of bottom relief, given the image pixel intensity, the assumed dependence of bottom surface backscattering coefficient on incident angle (what corresponds to reflectance map in classical SFS), and the estimated local incident angle value. The Lambert's Law is often used as a model of the angular dependence of the bottom scattering coefficient.

In this paper, two methods for 3D seafloor and submerged objects shape reconstruction from side scan and synthetic aperture sonar are presented. The first method of data processing is used for 3D wreck and other submerged object shape reconstruction and its imaging. The direct application of classical SFS technique seems not to be best suited to wreck visualisation because it leads to obtaining very smooth shapes which differ significantly from actual forms of artificial objects. The proposed method utilises two combined techniques. Firstly, the local altitude gradient estimation by SFS algorithm using the Lambert's Law as backscattering coefficient angular dependence function. Secondly, the estimation of the elevation change using the dimension of acoustic shadow areas. The second method for reconstruction of 3D seafloor relief, also based on the SFS approach, is presented. It was developed as the modification and extension of the wreck reconstruction method. For estimation of a bottom depth at a given pixel of sonar image, it uses the information from both currently processed and previous ping and, allows the local surface element orientation to have two degrees of freedom.

2 3D wreck shape reconstruction and visualization

2.1 Algorithm description

The developed algorithm used few assumptions [6], like straight line propagation path of acoustic wave in water column, reflectivity model is known, altitude H of the sonar transducer is known. The normal to an insonified surface is perpendicular to y axis, e.g. to the track direction (it was applied as the simplest way of removing the problem of ambiguity in the relation between reflectance and a surface element orientation, where the latter has two degrees of freedom in general). The dimensions along vertical (z) axis of an object to be reconstructed are small in comparison with the sonar transducer altitude. Finally, the intensity (grey level) of a pixel on sonar image is proportional to the acoustical intensity of backscattered echo.
The geometry used in derivation of the algorithm is presented in Fig. 1. In an image obtained from side-scan sonar survey, each pixel belonging to a given line across survey track represents a sample from an echo envelope at time instant t_i and corresponds to a point P_i on seabed surface or submerged object. Its across-track co-ordinate x_i can be expressed as follows:

$$x_i = \sqrt{\left(\frac{ct_i}{2}\right)^2 - H^2} \qquad (1)$$

where $t_i \geq \frac{2H}{c}$, c – sound speed in water.

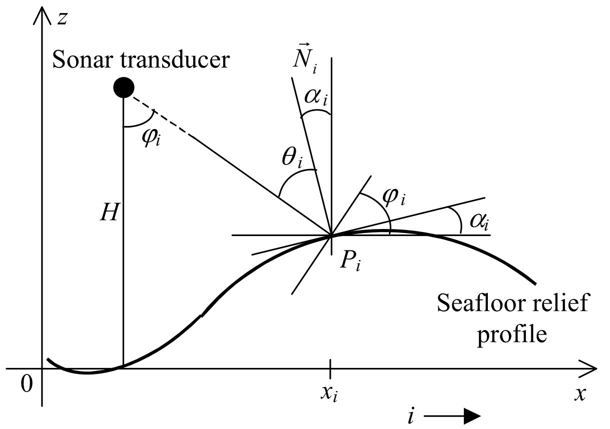


Fig. 1. The geometry used in the algorithm: H_i – the sonar tow fish altitude, $\vec{N}_i$ - surface normal vector, α_i - bottom slope angle, θ_i - incidence angle, φ_i - transmission angle

The algorithm of the altitude (z co-ordinate value) estimation was applied separately to each line across the track in a processed side-scan sonar image, and may be summarized as follows. Firstly, the initial z value z_0 was assumed. Secondly, if the currently processed i-th pixel was not recognized as the beginning of a shadow area (e.g. its intensity was above a chosen threshold value I_{th}), the processing scheme based on SFS was applied, namely the local incidence angle θ_i was estimated from pixel intensity by inverting the backscattering coefficient angular dependence function. The Lambert's Law-like function of seafloor backscattering coefficient s_s versus incident angle θ was used here

$$s_s(\theta) = \frac{I_s}{I_{0s}} = \cos^2\theta \qquad (2)$$

where I_s – backscattered acoustical wave intensity at a unit distance from seabed, originated from a unit seabed surface area, I_{0s} – incident wave intensity. The altitude z_{i+1} of the consecutive point P_{i+1} was estimated assuming the local gradient of the surface altitude along x axis as:

$$\text{Grad}_x z(x_j, y_i) = \frac{\partial z(x,y)}{\partial x}(x_j, y_i) = \tan\alpha_i \qquad (3)$$

approximated using the finite difference as:

$$\frac{\Delta z_i}{\Delta x_i} = \frac{z_{i+1} - z_i}{x_{i+1} - x_i} \qquad (4)$$

From the above equations, z_{i+1} was calculated as:

$$z_{i+1} = z_i + (x_{i+1} - x_i)\tan\alpha_i \qquad (5)$$

where the surface slope angle α_i was calculated as

$$\alpha_i = \varphi_i - \theta_i \qquad (6)$$

where φ_i was local transmission angle calculated as

$$\arctan(x_i / H) \qquad (8)$$

Otherwise, i.e. in a case of a shadow zone detection, the length of shadow area along x axis was calculated as

$$\Delta x_{sh} = x_{i+j} - x_i \qquad (9)$$

where j – the number of pixels belonging to a currently detected shadow area. Then the altitude values from z_{i+1} to z_{i+j} were set to unknown, and the z_{i+j+1} value was calculated as

$$z_{i+j+1} = z_i - \frac{\Delta x_{sh}}{\tan\varphi_i} \qquad (10)$$

i.e. the height of the local relief element producing the shadow zone of size Δx_{sh} was assumed to be

$$\frac{\Delta x_{sh}}{\tan\varphi_i} \qquad (11)$$

Fig. 2 presents in a schematic way the influence of the I_{th} on the algorithm results for two cases of I_{th} values. Fig. 4a shows the sample dependence of the intensity value on x co-ordinate for a given fragment of one line in side scan sonar image, along with two I_{th} values indicated. Fig. 4b presents the reconstructed seabed altitude for these two cases. For I_{th2} case, the larger shadow zone occurs and no reconstruction is obtained inside $[x_a, x_b]$ range.

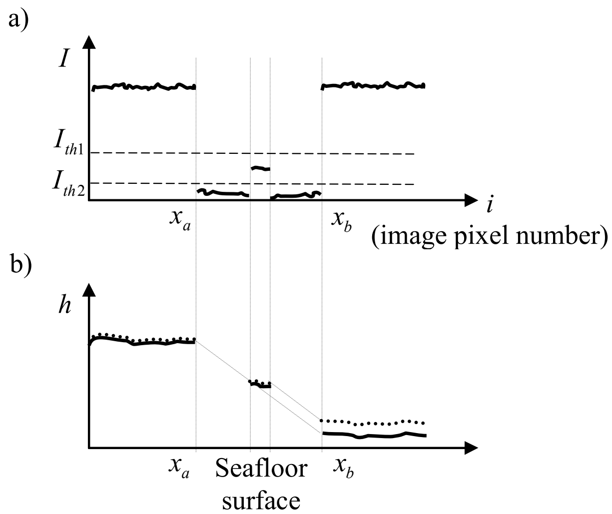


Fig. 2. The influence of the shadow threshold value I_{th} on the altitude reconstruction algorithm results

2.2 Results

The developed procedure of wreck 3^D shape reconstruction was tested on side-scan sonar data downloadable from Marine Sonic Technology, Ltd. site. The sample wreck image acquired by side-scan sonar is presented in Fig. 3.

For visualization of the reconstructed 3D model of submerged wreck the Virtual Reality Modelling Language (VRML) was used [7]. VRML is a popular language used in modeling of virtual reality in various fields, like computer graphics, medicine astronomy geography and navigation.

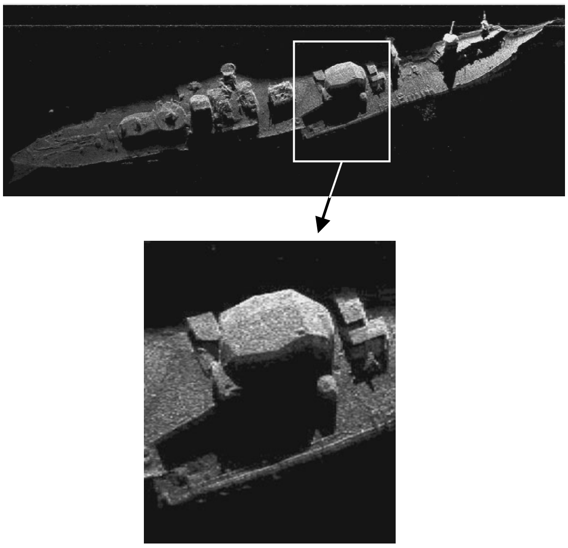
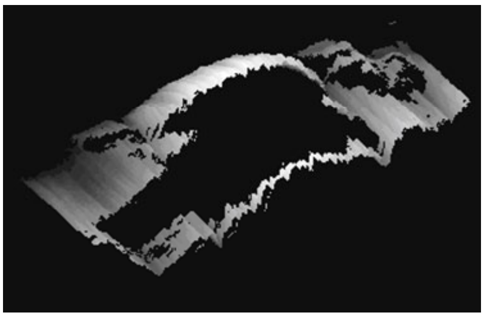


Fig. 3. Image of the USS Utah, resting in Pearl Harbor near Ford Island, acquired by the U.S. Army 7th Engineer Detachment using Sea Scan Centurion system operated at 600 kHz

The comparison of the results obtained when applying two different shadow threshold values $I_{th1} = 0.05I_{max}$ and $I_{th2} = 0.1I_{max}$ is presented in Fig. 4, It may be seen that for lower I_{th} value case (Fig. 4a), more details of the reconstructed shape may be visible than for higher I_{th} value (Fig. 4b). But on the other hand, if the I_{th} is too low, the artefacts may occur due to using the information from very dark, and possibly noised pixels, for the object local altitude slope estimation.

a)



b)

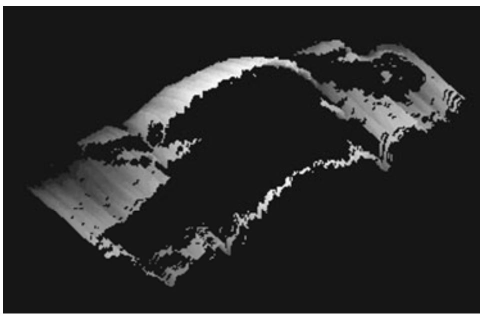


Fig. 4. 3D wreck shape reconstruction results using two different values of I_{th} a) $I_{th1} = 0.05I_{max}$ b) $I_{th2} = 0.1I_{max}$

3 3D seafloor relief reconstruction

3.1 Algorithm description

The second part of the paper concerns the seafloor relief reconstruction method from side scan and synthetic aperture sonar data. the method development, the same set of assumptions as in case of 3D wreck shape reconstruction was applied, with two exceptions [8]. Firstly, local surface element orientation to have two degrees of freedom. Secondly, no shadow zone occurrence was assumed. The geometry used in derivation of the reconstruction algorithm is presented in Fig. 5. The beam of a side scan sonar covers an angular sector from $\varphi_{\min}$ to $\varphi_{\max}$.

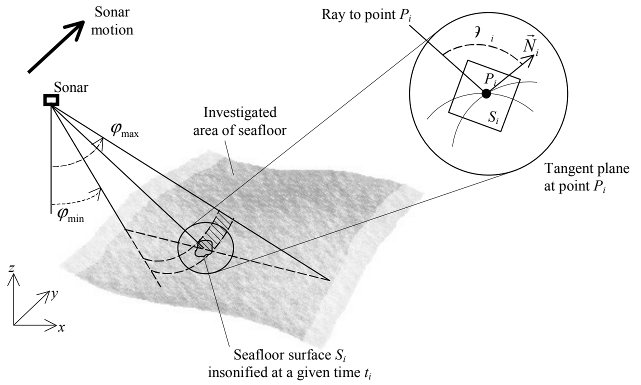


Fig. 5. Geometry used in derivation of the seafloor relief reconstruction algorithm

Similarly as in wreck shape reconstruction case, the relation between the time instant t_i in an echo envelope and the across-track co-ordinate x_i of a corresponding point P_i on seabed surface, may be expressed by eq. (1). At the time instant t_i, the seafloor surface S_i is insonified, the area of which may be for a flat bottom case expressed by the classical equation:

$$S_i = \varphi_V R_i \frac{c\tau}{2\sin\varphi_i} \tag{12}$$

where φ_V – the along tract transducer beamwidth, R_i – the range from the transducer to the point P_i, τ - the transmitted pulse length.

Also, the backscattering model was assumed as Lambert-like form (eq. (2)), but unlike previously, the θ_i angle between ray to point P_i on seafloor surface and normal $\vec{N}_i$ to a plane tangent to surface at P_i does not need to be defined in vertical plane XOZ.

The 3^D bottom relief was reconstructed by estimation of an altitude $z(x, y)$ sequentially for consecutive discrete points (x, y) on a plane, using the scheme depicted in Fig. 6. For the (i, j) iteration (where i – number of processed line in the sonar image corresponding to one sonar ping, j – number of pixel belonging to this line), i.e. the point $P_{ij} = (x_j, y_i, z(x_j, y_i))$ altitude estimation, the local triangle facet was being taken into account, with vertices at two previously estimated points $P_{i-1\,j} = (x_j, y_{i-1}, z(x_j, y_{i-1}))$ and $P_{i\,j-1} = (x_{j-1}, y_i, z(x_{j-1}, y_i))$, and currently estimated point P_{ij}. Using the applied model, the value chosen for z_{ij} allows for calculation of normal $\vec{N}_i$ to the surface facet, the angle θ_i and the local intensity I_i value, which then many be compared with that from the original sonar image. The analytical form of the expression for optimal z_{ij}, i.e. that giving I equal to a measured value, is impossible to obtain in a general case. On the other hand, it may be shown that in the applied model, $I_i(z)$ is a monotonic function of z variable within the range $[z_{ij\min}, z_{ij\max}]$, where $z_{ij\min}$ corresponds to $\theta_{ij\min} = 0°$ and $z_{ij\max}$ to $\theta_{ij\max} = 90°$. Therefore, the simple binary algorithm, starting from initial $[z_{ij\min}, z_{ij\max}]$ searched interval, was used for z_{ij} estimation. It was the iterated algorithm which in k-th iteration proposed the new $z_{ijk\mathrm{mid}}$ as the midpoint of the current $[z_{ijk\min}, z_{ijk\max}]$ interval, and then appropriately reduced the interval to its left or right half. Namely, if an echo intensity I calculated for $z_{ijk\mathrm{mid}}$ was less than intensity taken from the currently processed pixel of sonar image, the left half was chosen for the consecutive iteration, otherwise the right half was chosen.

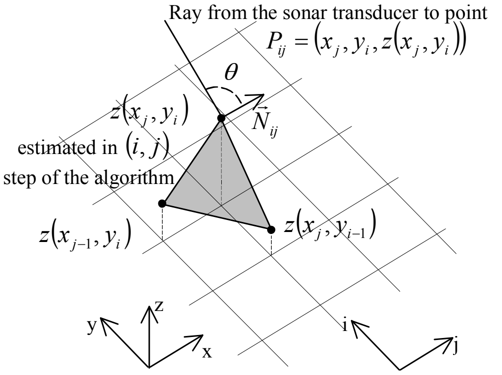


Fig. 6. Illustration of the bottom altitude $z(x_j, y_i)$ estimation in (i, j) iteration of the algorithm

3.2 Results

The developed procedure of 3D seafloor relief reconstruction was tested on side scan and synthetic aperture sonar data. Sample seafloor image obtained from side scan sonar survey is presented in Fig. 7.

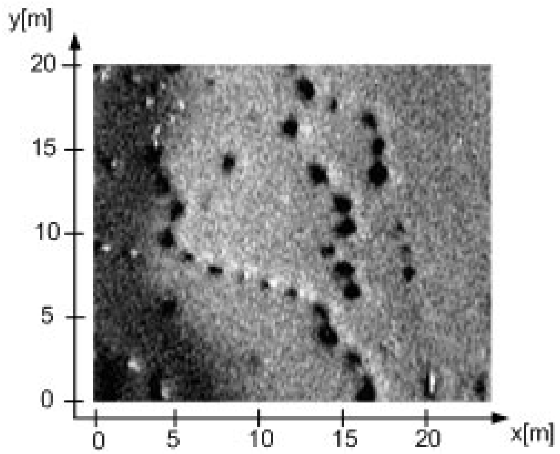


Fig. 7. Sample seafloor image obtained from side scan sonar data

The reconstruction results obtained using the developed algorithm are presented in. Fig. 8a. The magnified images of the selected part of reconstructed bottom surface is presented in Fig. 8b, and with texture from sonar image in Fig. 8c.

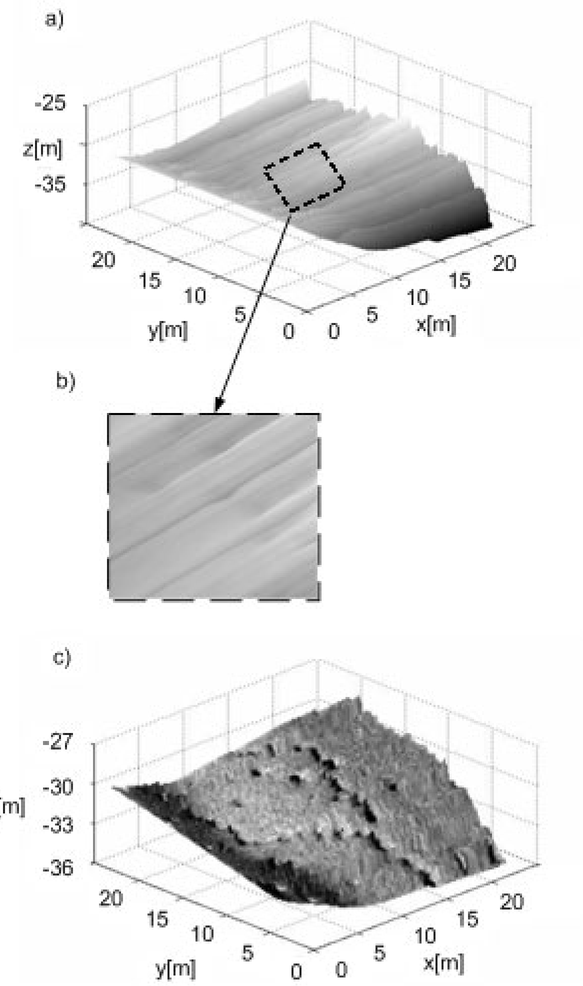


Fig. 8. Bottom relief reconstruction results a) for whole side scan sonar image b) magnified image of selected area c) with texture from sonar image

Sample seafloor image from original synthetic aperture sonar survey is presented in Fig. 9.

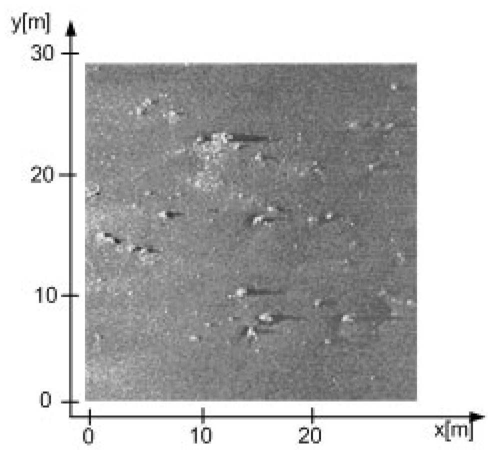


Fig. 9. Sample seafloor image obtained from synthetic aperture sonar data

The reconstruction results obtained using the developed algorithm are presented in. Fig. 10.

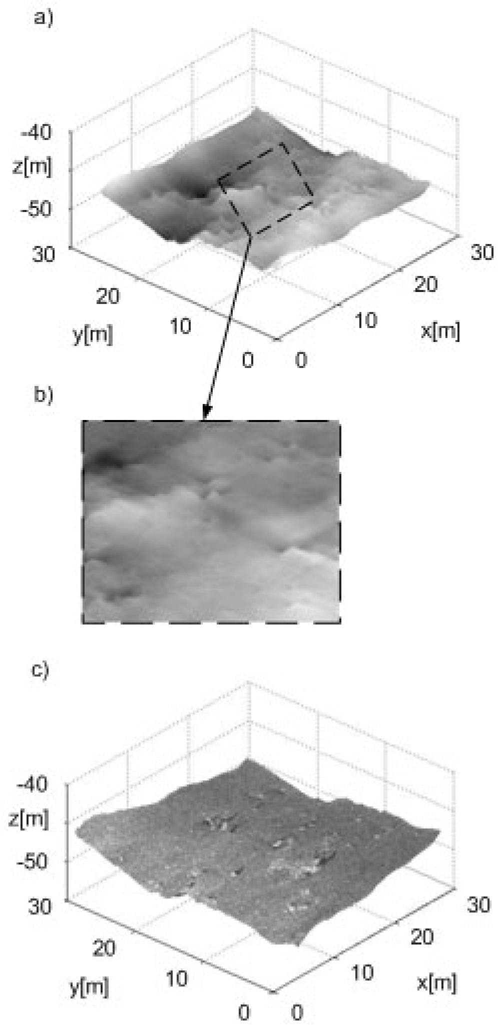


Fig. 10. Bottom relief reconstruction results a) for whole synthetic aperture sonar image b) magnified image of selected area c) with texture from sonar image

4 Conclusions

Two methods based on Shape from Shading (SFS) approach for 3^D reconstruction of seafloor and submerged objects shape from side scan and synthetic aperture sonar records were presented. The advantage of the presented methods is their simplicity and the ability to produce the results within sequential, i.e. "one run" processing of side scan sonar data. The presented preliminary results are promising both in seafloor relief reconstruction and wrecks shape imaging. The future work should concentrate on implementation of more advanced both SFS and shadow processing algorithms. In particular, the authors predict that in the presented seafloor reconstruction algorithm, during sonar image processing, the performance improvement could be achieved by taking into account the information obtained not only from a current ping and one previous ping, but from a number of previously processed pings, combined for instance with the application of the weighted averaging technique.

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