# A Fast SAS Image Simulator Based on HPR Algorithm

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***Abstract*- Image Simulator is an important part in SAS development for automatic target recognition. The paper presents a fast SAS image simulator based on hidden points remove (HPR) algorithm. The proposed method models the target with three dimensional (3D) points and the target image is obtained by the combination of many ideal point responses of visible scatters projected on a predefined image plane. The 3D point visibility is judged by the HPR algorithm with approximate accuracy and less computational complexity. The simulation results show that the proposed method can obtain approximately the same image quality compared with ray tracing method but require less time, demonstrate the effectiveness of the HPR algorithm.**

***Keywords— Underwater Acoustics; Synthetic Aperture Sonar; Simulation; HPR***

## I. INTRODUCTION

Recently, synthetic aperture sonar (SAS) has been widely used for remote sensing in seafloor topographic survey and marine resources investigation. Simulation tool is a very important part of SAS studying. Because at-sea experiments are complicated to implement, we often meet the problem of lacking sufficient real data. The SAS image simulator is developed to simulate the ocean scene realistically. A practical image simulator can create images precisely from a predefined scene with the system parameters such as depth, beamwidth and carrier frequency. By such means large amounts of simulated high resolution SAS images can be obtained and could be applied in automatic target recognition research as the input source data.

Many simulation methods have been developed for SAR (short for synthetic aperture radar)/SAS simulator. Those simulators can be categorized as two types. The first type bases on the Digital Elevation Model (DEM) of the target[1-3] and the second type bases on the 3D model [4, 5]. The method based on DEM model is simple and easy to implement. However, the DEM model cannot simulate the complex scenes, especially the scene contains closed surface. The 3D model base on the assumption that the targets and seafloor are composited by a cloud of point reflectors with three dimensional coordinates, and the simulation methods based on 3D model can simulate the complex scene by adjusting the density of points. As the simulation result is the raw echo data or the final image, these simulators also can be categorized as two types. The first type generates the original echo then makes the imaging process [1-3]. The second type neglects the imaging process [4, 5], and produces a final SAS/SAR image directly. In this paper, we focus on the second type simulator. As we known, one of the key steps by using 3D model is to evaluate each point visibility. The well known tactical to realize the point visibility is the ray tracing method. The ray tracing method can obtain the invisibility points in the shadow region accurately, but has the disadvantage of computation time consuming.

In this paper, the hidden point removal (HPR) algorithm[6] is proposed to realize the shadow points estimation based on the 3D model of the scene. The HPR algorithm is recently developed in optical image processing for computer vision and can be realized simply and quickly. Usually an SAS system works on high carrier frequency ( $f_c >= 20kHz$ ) and short distance ($10^2 \sim 10^3 m$ ). According to ray theory, rays can be regarded as rectilinear, so the optical method can be used to approximate. The new developed SAS simulator in this paper by using the HPR algorithm to create simulated scene include four steps. The first one is to create a point cloud model of the 3D scene and target. Then the visibility of each point is estimated by using the HPR algorithm. Furthermore, the beampattern of each point is calculated with the defined geometry of scene and sonar system. Finally, the simulated SAS image is produced by using the visible points and their beampattern. The effectiveness of the proposed SAS simulation method is verified based on a scene composited of 640k 3D points and the datasets of simulated SAS images with different elevation and azimuth angles are present. The results show that the proposed method can obtain approximately the same image quality compared with ray tracing method but require less time, demonstrate the effectiveness of the HPR algorithm.

## II. SAS IMAGE MODEL

An ideal SAS image model is given in this section and the SAS Geometry is shown in Figure 1. Here $H$ is the depth of water, $v$ is the velocity of SAS platform, $\alpha$ is the squint angle and $\beta$ is the depression angle. Target locates in the coordinates $o-xyz$, sonar move along $x$ axis with uniform velocity $v$ and $\mathbf{x}_e = (1,0,0)^{\mathrm{T}}$ is the unit vector of x axis. The sonar light of sight can be expressed as follow

$$\mathbf{i}_{los} = (\sin\beta\cos\alpha, \sin\beta\sin\alpha, \cos\beta)^{\mathrm{T}} \quad (1)$$

where $(\cdot)^{\mathrm{T}}$ is the transpose factor. Because the axis x and sonar light of sight are both in the image plane, the normal of the image plane can be expressed as follow

$$\mathbf{\Omega}_e = \mathbf{i}_{los} \times \mathbf{x}_e = \left(0, \cos\beta, -\sin\beta\sin\alpha\right)^{\mathrm{T}} \quad (2)$$

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Thus, the image plane can be represented by the following expression

$$\boldsymbol{\Pi} = \left(\mathbf{i}_{los}, \hat{\mathbf{x}}_e\right)^{\mathrm{T}} \tag{3}$$

where $\hat{\mathbf{x}}_e$ is the equivalent azimuth of the image plane, which can be expressed as follow

$$\hat{\mathbf{x}}_e = \boldsymbol{\Omega}_e \times \mathbf{i}_{los} \tag{4}$$

It is noted that $\mathbf{x}_e$, $\hat{\mathbf{x}}_e$ and $\mathbf{i}_{los}$ are in the image plane and $\hat{\mathbf{x}}_e$ is perpendicular with $\mathbf{i}_{los}$.

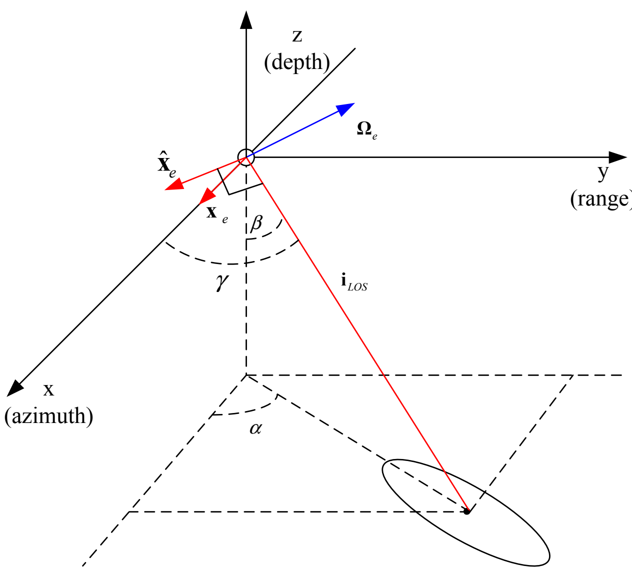



Figure 1. SAS system Geometry

As we know, SAS image is a 3D scene projected to a 2D image plane. It is given that an arbitrary point scatter position can be expressed as follow

$$\mathbf{x}_i = [x_i, y_i, z_i]^T \tag{5}$$

The position of the scatter in the image plane can be expressed as follow

$$\mathbf{u}_i = \boldsymbol{\Pi}\mathbf{x}_i = [\hat{x}_i, \hat{y}_i]^{\mathrm{T}} \tag{6}$$

where $\hat{x}_i$, $\hat{y}_i$ are the azimuth location and range location after projection in the image plane.

It is assumed that the bandwidth of the transmitter signal is $B_r$ with pulse time width $T_p$. $t_m$ is the slow time in the azimuth, $\hat{t}$ is the fast time in the range. We have $t_m = mT_r, t_m \in (-T/2, T/2)$, $T$ is the synthetic aperture time, $T_r$ is the pulse repetition interval. $\hat{t} \in (T_s, T_f)$, $T_s$ is the sampling start time, $T_f$ is the sampling end time in the range. Thus, the ideal point response can be express as follow[7]

$$\begin{aligned} s(\mathbf{u_i}) = s(\hat{x}_i, \hat{y}_i) = B(\mathbf{n_i}, \mathbf{i}_{los})\mathrm{sinc}[B_d(t_m - \frac{\hat{x}_i}{\hat{v}})] \\ \mathrm{sinc}[B_r(\hat{t} - \frac{2\hat{y}_i}{c})]\exp(\frac{-j4\pi\hat{y}_i}{\lambda}) \end{aligned} \tag{7}$$

Where $B(\mathbf{n_i}, \mathbf{i}_{los})$ is the scatter beampattern and will be treated in section III, $\mathbf{n}_i$ is the normal of the facet the scatter located on, $c$ is the sound speed in water, $\lambda$ is the wavelength, $B_d$ is the Doppler frequency bandwidth, which can be expressed as follow

$$B_d = \frac{2\hat{v}}{D} \tag{8}$$

where $D$ is the aperture diameter and $\hat{v}$ is the velocity projected to $\hat{\mathbf{x}}_e$, we have

$$\hat{v} = v \sin\gamma \tag{9}$$

Where $\gamma$ can be expressed as follow

$$\cos\gamma = \cos\alpha \sin\beta \tag{10}$$

As SAS system is a liner system, the final image can be regarded as a summation of all point response and can be written as follow

$$S = \sum_{i=1}^{N} s(\mathbf{u_i}) \tag{11}$$

where $N$ is the visible scatter number.

In order to obtain the final SAS image based on the model shown in (11), there are three problems needed to be resolved. The first one is how to model the 3D underwater scene. The second one is how to calculate the point scatter beampattern. The most important problem is how to estimate the visible points to form the final SAS image. Many effective methods have been proposed to work out the first two problems. In our paper, we focus on the 3D points visibility estimation and a fast calculation tactical named HPR method is proposed to be used.

## III. 3D Underwater Scene Modeling

### *A. Seafloor Modeling*

As for the seafloor, we can either import real bathymetric data or use simulation data. The simulation data assume the seafloor topography is a random rough seafloor. A random rough seafloor[8] in a predefined space can be described in statistical terms by using the depth probability distribution function and the autocovariance function. Depth probability distribution function describes the deviation of the seafloor depth from a certain reference depth (usually the average depth of the scene) and autocovariance function describes the undulate degree of the seafloor. The depth probability distribution function can be expressed as follow

$$p(\zeta) = \frac{1}{\sigma\sqrt{2\pi}} \exp(-\frac{\zeta^2}{2\sigma^2}) \tag{12}$$

where $\sigma$ is the root mean square (RMS) of the depth and the autocovariance function is defined as

$$\begin{aligned} C(\rho_x, \rho_y) &= <\zeta(x_1, y_1), \zeta(x_2, y_2)> \\ &= \sigma^2 \exp[-(\frac{|x_1 - x_2|^2}{\rho_x^2} + \frac{|y_1 - y_2|^2}{\rho_y^2})] \end{aligned} \tag{13}$$

Where $(x_1, y_1)$ and $(x_2, y_2)$ are two different points along the sea floor and $\rho_x$, $\rho_y$ are correlation length.

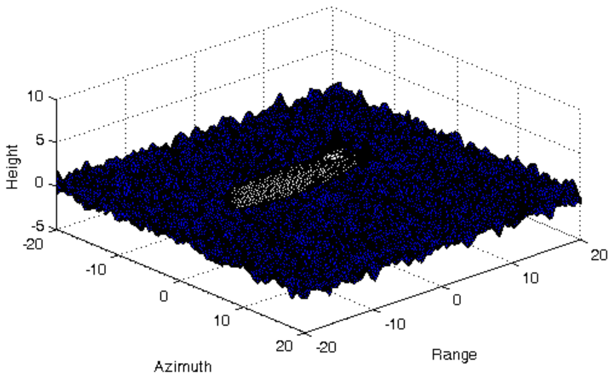



Figure 2. Simulation scene include target and seafloor background

*B. Target Modeling and Scatter Beampattern Calculation*

A submarine model with .X format shown in Figure 2 is used as an interested target in the simulated scene. The .X is a common format to model a 3D target and is freely available on the internet. This adopted submarine is constituted by 18,519 vertexes and 24,636 triangular facets. In order to apply point cloud scattering model and HPR algorithm, the number of vertexes is not enough, so a spline function curved surface interpolation method is used to generate final point cloud scatter model.

The beampattern has obviously influence in SAS image simulation. A beampattern estimation method based on Lambert's Law [9] is adopted in this paper. The Lambert's Law can be written as follows:

$$B(\mathbf{i}_{los}, \mathbf{n}_i) = 10\log(\frac{\eta_0}{\pi}) + 20\log\frac{\mathbf{i}_{los}\cdot\mathbf{n}_i}{|\mathbf{i}_{los}||\mathbf{n}_i|} \tag{14}$$

where $\mathbf{i}_{los}$ is the Sonar Line of Sight (SLOS), $\mathbf{n}_i$ is the normal of facet which point scatter locates on, $\eta_0$ indicates roughness of the facet, $\eta_0 \in (0,1)$. The $\mathbf{n}_i$ can be calculated by the three vertex of the facet.

## IV. VISIBILITY ESTIMATION USING HPR ALGORITHM

The appearance of shadow zone is an important feature of SAS image. According to the ray theory, when the acoustic wave propagation is blocked, shadow zone will be introduced. Scatters in the shadow zone will be no echo, or "invisible". Thus, point visibility estimation algorithm need to be realized.

The conventional tactical to realize the point visibility is the ray tracing method. However, for a scene constituted by $n$ points, and incident rays number is $m$ typical ray tracing method requires $(nm)/2$ times intersection operation.

To reduce the computational complexity, a point visibility algorithm based on "Hidden" Point Removal (HPR) is proposed[6]. The HPR algorithm is developed in optical image processing for computer vision. The visibility of a point in a point cloud model can be directly evaluated by using HPR algorithm. The basic theory is reviewed here and a more complete treatment can be found in [6].

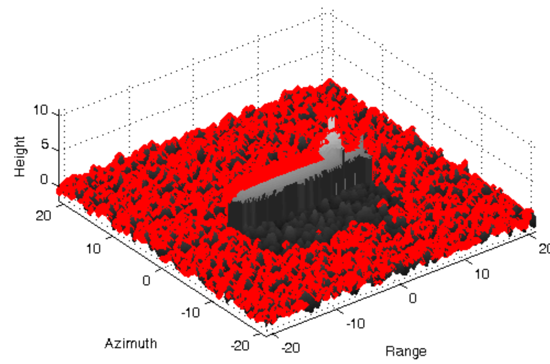
Given a set of points $P \in \{p_i \mid i \in N^*\}$ is sampled from a continuous surface $S$, and given a viewpoint V, the HPR is try to find if $\forall p_i \in P$, whether $p_i$ can be seen from V.

The HPR algorithm includes two main steps, spherical flipping and convex hull construction. Spherical flipping for each point $p_i \in P$ can be expressed as follow

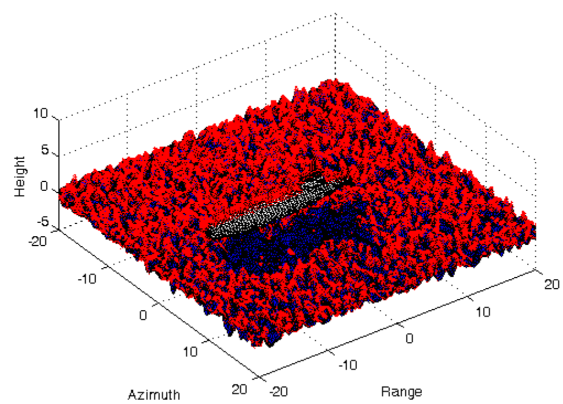
$$\hat{p}_i = f(p_i) = p_i + 2(R - |p_i - V|)\frac{p_i}{|p_i - V|} \tag{15}$$

where $R$ is the radius of spherical flipping reference circle. The set of transformed points is denoted as $\hat{P}$, $\hat{P} = \{\hat{p}_i \mid \hat{p}_i = f(p_i)\}$. Then, the point $p_i$ is marked visible if $\hat{p}_i$ lies on the convex hull of $\hat{P} \cup V$.

Given $n$ is the number of point in the point cloud model, the first step of HPR is spherical flipping and the computational complexity is $O(n)$. The second steps convex hull computation and the computational complexity is $O(n\log n)$. So, the approximate computational complexity of HPR algorithm is $O(n\log n)$ [6]. For ray tracing algorithm, it takes $(nm)/2$ intersection operations. It is assumed that the number of incident rays and point scatter is on the same order of magnitude and the computational complexity of ray tracing is $O(n^2)$ [10]. It is compared that the computational complexity of HPR is far less than ray tracing method.




(a)




(b)

Figure 3. Result of visibility estimation, (a) ray tracing method and (b) HPR, visible point scatters are marked red

## V. RESULT AND DISCUSSION

In order to demonstrate the validity of the algorithm introduced, a simulation experiment is conducted. Simulation parameters are given in Table 1.The target and scene are shown in Figure 2. Both ray tracing and HPR algorithm are used to estimate the visibility of point scatter in the scene. The results are showed in Figure 3 and the visible point scatters are marked as red color. From Figure 3, it is seen that HPR can obtain approximately the same result with ray tracing method. In this experiment, both HPR and ray tracing algorithm are implemented on a PC system with Intel Core i5 quad-core CPU and 8GB RAM. HPR algorithm takes 2.306s to finish the point visibility estimation. However, 743.6s is required for ray tracing algorithm. The final SAS image by using HPR algorithm is shown in Figure 4. It is seen that the shape of submarine is vivid and the features include shadow, edge, highlight, speckle noise and layover are obvious.

Table 1. Simulation Parameters

| Parameter | Value |
|---|---|
| Sound speed in water (m/s), $c$ | 1500 |
| Aperture diameter (m), $D$ | 0.2 |
| velocity projected to $\hat{\mathbf{x}}_e$ (m/s), $\hat{v}$ | 0.5 |
| Bandwidth of the transmitter signal (kHz), $B_r$ | 7.5 |
| Squint angle (degree), $\alpha$ | 90 |
| Depression angle (degree), $\beta$ | 60 |
| Wavelength (m), $\lambda$ | 0.075 |
| Range resolution (m), $\rho_{range}$ | 0.1 |
| Azimuth resolution (m), $\rho_{azimuth}$ | 0.1 |

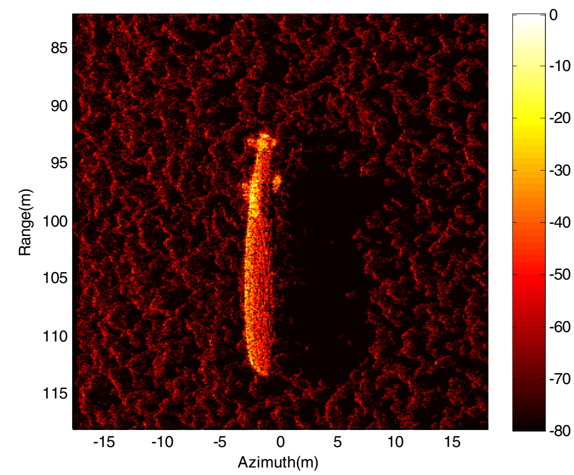



Figure 4. Result of the final simulation image

## VI. CONCLUSIONS

A fast SAS image simulator based on HPR algorithm is presented in this paper. It is shown that HPR algorithm to estimate the point visibility of the scene with 3D cloud points is effective and has the advantage of low computation complexity. The proposed SAS simulator can generate realistic SAS image on predefined image plane with different system parameters, different aspect angles. The final SAS image includes the important features obviously, such as vivid shape, shadow, edge highlight, speckle noise and layover. Thus, the output image can be applied in automatic target recognition research as the input source data.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