A Design of Space-borne AIS Scene Simulation Based on Density Distribution of Global Vessels

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Abstract. At present, the demand for application of space-borne Automatic Identification System (AIS) is increasing. Since more and more satellites are equipped with AIS payload, it is especially important to test the effectiveness of its performance. Owing to difficult test on AIS payload and high cost, this paper proposes a method of space-borne AIS scene simulation platform based on density distribution of global vessels, focusing on basic principle and design method of simulation scene. It contains detection range computing, the number of vessels within range and the detection probability of AIS receiver. Moreover, corresponding software and hardware have been designed. ‘Ocean-2B’ satellite-based AIS payload is used to test the performance of the scene simulation system, which indicates that the method can simulate real scene of receiving signals in orbit in a favourable manner.

1. Introduction

The AIS uses the very high frequency (VHF) band and Self-Organized Time Division Multiple Access (SOTDMA) to receive dynamic and static information of vessels, which can monitor and identify various vessels. SOTDMA is a core of this system, which is capable of navigation, positioning, collision avoiding and information exchange (the position, the route and the velocity) of vessels. However, the space-borne AIS is an information gathering system loaded with AIS payload which has high sensitivity in the satellite. It can easily receive a great deal of vessel information within satellite coverage to perform vessel-tracking and logistics controlling [1, 2].

The big difference between space-borne AIS and ground AIS is that the space-borne AIS has a wide coverage so that it can receive many signals from several SOTDMA networks. The LEO (Low Earth Orbit) whose orbit height is 600km can cover almost 12 million square kilometers of the area where contains a large number of vessels. For instance, if the covered area is located in the Mediterranean, it can include more than eight thousand vessels [3]. The coverage radius of SOTDMA network formed by various vessels at sea about 40~100 kilometers, because every SOTDMA sub-network is distributed independently. And there is no time synchronization among these sub networks. Thus, multi-network signal collision will inevitably occur for space-borne AIS, which causes drastic reduction of signal detection probability of space-borne AIS and even complete blockage of the channel [4, 5].

2. Coverage of the satellite

The location of satellite nadir point needs to be obtained before analyzing coverage of the satellite at certain time. The satellite nadir point is the intersection of the line which connects geocentric point,
the satellite and the earth’s surface. With the satellite moving, the track of satellite nadir point is gradually formed. Generally, the earth can be regarded as globular, assuming orbit height is $h$, eccentricity ratio $e$, orbit inclination $i$, right ascension of ascending node $\Omega$, argument of perigee $\omega$, true anomaly $f$. Considering the earth’s rotation, geocentric latitude $\varphi$ and geocentric longitude $\lambda$ of the satellite at certain moment $t$ can be computed as [6],

$$\varphi = \arcsin(\sin i \sin u) \quad (1)$$

$$\begin{align*}
\lambda &= \arctan(\cos i \tan u) + \Omega - \bar{S}(t) \quad \text{ascending} \\
\lambda &= 180^\circ + \arctan(\cos i \tan u) + \Omega - \bar{S}(t) \quad \text{declining}
\end{align*} \quad (2)$$

Where $u = \omega + f$ and $\bar{S}(t)$ is Greenwich mean sidereal time (GMST). Hypothetically, the AIS satellite is deployed omni-directional antenna to receive AIS signals. The width of the AIS satellite can be computed after antenna beam angle and orbit height are set[7]. It is shown in figure 1.

For instance, there is a target A. $S$ represents the satellite. $S'$ is the nadir point at the moment. $P$ points to the projective direction at local level where the line connects the target and the satellite. $\theta_1$ is the elevation angle of the target to the satellite. $\theta_3$ represents the covered angle. The relationship among these angles can be known as

$$\theta_3 = 90^\circ - \theta_1 - \theta_2 \quad (3)$$

In the triangle $\Delta AOS$, we can obtain

$$\frac{R_E}{\sin \theta_2} = \frac{R_E + h}{\sin(\theta_1 + 90^\circ)} \quad (4)$$

The width of the AIS antenna coverage on the ground is

$$l = R_E + \theta_3 \quad (5)$$

Thus, the upper and lower limits of the latitude and longitude can be calculated according to the width of the AIS antenna coverage to the ground and the latitude and longitude of satellite nadir point. In addition, the antenna coverage can cover the outer quadrilateral area of the circle for approximation when the width of the antenna is set on a small value. It is shown in figure 2.

**Figure 1.** coverage of one satellite
3. Computing the number of vessels within one AIS satellite coverage

This paper makes out a global vessel distribution chart at a certain time based on the data collected by ‘TT3’ of NUDT at certain time and that by certain business company within corresponding time [8, 9], shown in figure 3. In which, the red figure represents the number of vessels within certain latitude and longitude range.

The earth’s surface can be divided by some longitude interval $\Delta \lambda$ and latitude interval $\Delta \varphi$. Actually, longitude interval can be equal to latitude interval. The AIS receiving signals’ scene would be simulated more accurately on condition that the number of divided grids is large. But it also needs large computation resource. In principle, $\Delta \lambda \geq l$, $\Delta \varphi \geq l$, $l$ is the width of antenna coverage. For the convenience of grid division, let $\Delta \lambda = \Delta \varphi$. Thus, the number of grids $n_{cell}$ in the global wide area is

$$n_{cell} = \left( \frac{180}{\Delta \varphi} + 1 \right) \left( \frac{360}{\Delta \lambda} + 1 \right)$$

(6)

From Figure 4, we can see that there will be a certain number of vessels within part of sub-grids. And in every sub-grid, hypothetically, the distribution of the vessels is also even.

Generally, the satellite coverage area can be divided into nine parts which are shown in figure 5.

The yellow part represents approximation of satellite coverage area. $\varphi_i$ and $\lambda_j$ are the latitude and longitude respectively. At the moment, the relevant latitude and longitude form 9 blocks whose area is indicated by $S_{N}^{1} - S_{N}^{9}$. And $S_{n}^{1} - S_{n}^{9}$ is the area of divided satellite coverage. The number of vessels represented by $n_{1} - n_{9}$ in every block is equal or greater than zero and it is an integer. Assuming the global vessels are divided evenly in every block, the number of the vessels is

$$N_{1} = \frac{s_{n}^{1}}{S_{N}^{1}} \times n_{1}$$

$$N_{2} = \frac{s_{n}^{2}}{S_{N}^{2}} \times n_{2}$$

$$\vdots$$

$$N_{9} = \frac{s_{n}^{9}}{S_{N}^{9}} \times n_{9}$$

(7)
Thus, at the time $t_n$, the satellite covers $N(t_n)$ vessels.

$$N(t_n) = N_1 + N_2 + \ldots + N_9$$  

(8)

**Figure 3.** The global vessels distribution

**Figure 4.** Gridding of distribution of the global vessels
4. Simulation of transmitting signals

Besides the influence caused by the number of vessels within coverage range at a certain moment, factors like transmitting power, Doppler frequency shift, channel, transmitting cycle are also affecting the capability of receiving signals.

Transmitting power is established by AIS criterion [1]. And the velocity of the satellite to vessels is relatively high. Thus, considering vessels are relatively immobile, the Doppler frequency shift is

\[ f_d = \frac{v_{sat}}{c} \cdot f_c \cdot \cos \theta \]  

where \( v_{sat} \) is relative velocity, \( c \) is the light velocity, \( f_c \) is the carrier frequency, \( \theta \) is the angle between satellite motion and signal direction. In addition, the frequency of AIS channels has increased to four which are 161.975Mhz, 162.025Mhz, 156.775Mhz and 156.825Mhz [10]. And the transmitting cycle is set by AIS criterion [11].

For evaluating the performance of AIS receiver, detection probability of space-borne AIS is considered as an important indicator. In order to compute it, the MMSI code of every independent vessel must be gained from AIS message. The MMSI code is an identity of vessel. At the moment \( t_n \), vessels covered by satellite randomly send out AIS message. The number of vessels whose information can be obtained by the AIS payload is counted with distinctive MMSI code.

The discretization of satellite motion can be beneficial for counting vessels shown in Figure 6. During the motion of the satellite, when the upper and lower limits of the latitude and longitude reach the following condition, the simulator accumulates the MMSI code once

\[ \lambda(t_{n+1}) - \lambda(t_n) = 2\Delta\lambda \]  

\[ \Delta\lambda = \frac{l}{R_e} \cdot \frac{180}{\pi} \]  

\( \Delta\lambda \) transformed by the width of antenna is the difference of longitude. And the direction of satellite motion cannot affect the above-mentioned condition. Finally, gather message collected by AIS receiver within certain period of testing time based on MMSI code. More specifically, assuming that the space-borne AIS-receiver obtains \( N_m \) MMSI codes, and there are \( N_{trans}^m \) vessels-covered by satellite during the simulated time, the detection probability of the receiver is
Figure 6. The motion of satellite coverage

Figure 7. 'Ocean 2B' satellite motion

5. Simulation verification

Table 1. 'Ocean 2B' satellite parameters

| Parameter                                | Value       |
|------------------------------------------|-------------|
| Orbit semi-major axis                    | 7341.732km  |
| Inclination                              | 99.34015°   |
| Eccentricity                             | 0.00117     |
| Argument of perigee                       | 60°         |
| Right ascension of ascending node         | 20°         |

Table 2. Different sea area and the whole detection probabilities(%) 

|                     | Pacific | Atlantic | Indian Ocean | Arctic Ocean | Mediterranean | Global Average |
|---------------------|---------|----------|--------------|--------------|---------------|----------------|
| Single satellite    |         |          |              |              |               |                |
| loading              |         |          |              |              |               |                |
| single receiver      | 83.40   | 42.64    | 45.75        | 59.58        | 0.64          | 49.55          |
| Single satellite     |         |          |              |              |               |                |
| loading              |         |          |              |              |               |                |
| two receivers        | 97.24   | 67.09    | 70.57        | 83.23        | 1.27          | 67.53          |

The AIS signal generator and corresponding software have been designed according to part II and III. The AIS payload of 'Ocean 2B' Satellite whose major orbit parameters are shown in Table 1 has been considered as the testing object. And ten seconds is regarded as the interval to compute the position of the satellite nadir point. The satellite motion can also be displayed in STK shown in Figure 7.

Moreover, there is a table about global vessels distribution to count the number of vessels. At every moment, the AIS signal generator sends AIS message according to vessels kept in satellite’s coverage and preinstalled parameters which are carrier frequency, sending signal cycle and signal power, respectively. Especially, every vessel sends AIS message complying with SO-TDMA (Self-Organized Time Division Multiple Access). And when the simulation operates, the monitoring window is shown in Figure 8.

The window contains latitude and longitude, the upper and lower limits of the latitude and longitude within coverage range and the number of MMSI code of the vessels which have transmitted message. And the rest of the window displays the monitoring information of AIS signal simulator.
More specifically, the four channels represent four carrier frequency points of AIS signal. The signal power and sending cycle of the signal have been set in advance. The simulating time lasts 24 hours. The diameter of the FOV (field of view) is 2000km. The sensibility of AIS receiver is -111dBm. Finally, through the simulating test, the ‘Ocean 2B’ detection probability shown in Table 2 can be obtained through the number of vessels from several areas and the independent MMSI code.

From the table 2, we can know that serious signal collision happens in the Mediterranean since it has the highest density of vessels, which leads to the fact that the AIS receiver cannot obtain AIS message correctly.

![space-borne AIS scene simulator](image)

**Figure 8.** Monitoring window of simulation

6. Conclusions
This paper introduces the principle and method of designing simulating scene based on global vessel distribution. Meanwhile, corresponding software and hardware have been designed to test its performance combined with the ‘Ocean 2B’satellite-based AIS payload. The outcome indicates that this AIS scene simulating technology can guarantee the testing performance of AIS receiver on the ground.

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