# UNDERWATER ACOUSTIC MODEM WITH HIGH PRECISION RANGING CAPABILITY BASED ON SECOND-LEVEL CESIUM ATOMIC CLOCK

Jiaheng Li[1,2], Feng Tong[1,2,*], Weihua Jiang[1,2], Sumit Roy[3]

[1] Key Laboratory of Underwater Acoustic Communication and Marine Information Technology Ministry of Education, Xiamen University, Xiamen 361005, Fujian, China-(lijiaheng1009@163.com, ftong@xmu.edu.cn)
[2] College of Oceanic and earth, Xiamen University, Xiamen 361005, Fujian, China-(whjiang@stu.xmu.edu.cn)
[3] Department of Electrical and Computer Engineering, University of Washington, Seattle, WA, USA-(sroy@uw.edu)

**Commission IV, WG IV/5**

**KEY WORDS:** UAC, Ranging capability, Spread spectrum technology, Second-level cesium atomic clock.

**ABSTRACT:**

Equipped with a high-precision atomic clock can significantly improve the ranging accuracy of the underwater acoustic ranging system. However, the adverse characteristic of underwater acoustic channel (UAC) seriously deteriorates the ranging accuracy. In addition, as a timing device typically commercial cesium atomic clock is only designed to output second-level time reference, which cannot be applied to underwater ranging systems directly. To overcome this limitation, a new underwater acoustic modem with high precision ranging capability based on second-level cesium atomic clock is developed in this paper. The spread spectrum technology is chosen for highly reliable communication and the second-level commercial cesium atomic clock is used to ensure accurate clock synchronization. The proposed modem executes a predetermined ranging scheme based on spread spectrum technology. Specifically, at a certain specified second-level, the transmitter modem sends the ranging signal, and the receiver modem starts timing. Until the receiving modem detects the ranging signal, the propagation time is obtained and the single-item ranging capability is realized. The pool experiment shows the effectiveness of the modem, its ranging accuracy can reach cm level, and the average absolute error of ranging is 8 cm.

## 1. INTRODUCTION

To improve the capability of independent innovation in marine science and technology, marine technology that can effectively develop and utilize marine resources has increasingly become a new technology revolution, and the research on marine technology has also become a frontier field of current scientific research (Li et al. 2019) and (Melo et al. 2017).
Underwater communication and networking technology is one of the key technologies in marine technology (Gong et al. 2018) and (Yan et al. 2020). Accurate communication and precise ranging between those network nodes are of the utmost importance. Due to the long-distance transmission characteristics of sound waves underwater, underwater acoustic communication and ranging technologys are of great significance to underwater positioning, detection, communication, and networking technologies (Rodionov et al. 2020). Meanwhile, the technical system of underwater acoustic communication integration ranging plays a significant role in underwater acoustic navigation and communications integration (Jiang et al. 2016).
The underwater acoustic communication technology is mainly based on incoherent communication, and the common ones include frequency shift keying and spread spectrum communication (Wang et al. 2012) and (Zejak et al. 1994). However, the communication rates are often low. The application of coherent communication can greatly improve the communication rate, mainly including multiple phase shift keying, quadrature amplitude modulation and orthogonal frequency division multiplexing technology (Maheswaran et al. 2015) and (Liu et al. 2014). However, the performances are limited by channel conditions.

The basic of underwater acoustic ranging is to calculate the distance according to the propagation time and velocity of sound waves. Based upon different communication protocols, many different types of underwater acoustic modems are currently in existence. Using the orthogonal frequency division multiplexing (OFDM), the AquaSeNT AM-OFDM-12A model is rated to communicate as deep as 200 m and can range distances as far as 7 km (Domrese et al. 2014). Based on multiple frequency-shift keying (MFSK), the Teledyne Benthos ATM-885 LF Omni model modem is rated to communicate as deep as 2 km and can typically range distances of 2-6 km.
However, the random time-space-frequency parameter variation, strong multipath, fast fluctuation, and strict band limitation, the adverse characteristic of underwater acoustic channel (UAC) seriously impact the communication quality and further increase the measurement error of propagation time, thereby reducing the ranging accuracy. Therefore, the modems mentioned in (Domrese et al. 2014) exhibit poor performance to the poor environment.
The atomic clock is a high-precision and stable timing device, using the electrons inside the atom to control the movement of the clock (Zhao et al. 2015). More and more underwater platforms are equipped with atomic clocks for high precision timing. Therefore, based on the high-precision cesium atomic clock, the measurement error of propagation time for the above modems will drop significantly.
However, from the perspective of commercial atomic clocks products in (Xi'an Hongluyang Electromechanical Equipment Co., Ltd. 2021), typically commercial cesium atomic clock can only output second-level time reference, which is enough for timing purposes. Unfortunately, it cannot be applied to underwater ranging systems directly. Therefore, a new underwater

* Corresponding author

acoustic modem with high precision ranging capability based on second-level cesium atomic clock is developed in this paper. First, by using the spread spectrum technology, the adverse impact of UAC is overcome, thereby ensuring the reliability of communication. Second, a predetermined ranging scheme is executed in the proposed modem. Specifically, the second-level commercial cesium atomic clock is used to ensure accurate clock synchronization rather than get the time. That is, at a specified second-level, the transmitter modem sends the ranging signal, and the receiver modem starts timing. Until the receiving modem detects the ranging signal, the propagation time is obtained and the single-item ranging capability is realized. The pool experiment shows the effectiveness of the modem, its ranging accuracy can reach cm level, and the average absolute error of ranging is 8 cm.
The rest of the paper is organized as follows: Section II presents the strategy of underwater acoustic communication integration ranging. Section III introduces the system implementation. Section IV shows the experimental results and demonstrates the effectiveness of the proposed modem. Finally, Section V concludes the paper.

## 2. STRATEGY OF UNDERWATER ACOUSTIC COMMUNICATION INTEGRATION RANGING

To overcome the impact of poor UAC, direct sequence spread spectrum (DSSS) communication is used for highly reliable communication in this paper. And the strategy of underwater acoustic communication integration ranging is implemented on the STM32F4 microprocessor.

### 2.1 Basis of DSSS

DSSS communication improves the processing gain by spreading the spectrum of signals, and the bandwidth of the spread signal is much larger than the bandwidth of the original information signal. It has excellent anti-multipath and anti-interference capabilities and is widely used in the field of underwater acoustic communication.
Consider the classic direct sequence differentially coherent binary phase-shift keying (DS-DBPSK) strategy, the symbol width is $T_c$, and the m-th symbol after the difference of the bit information is $a_1(m)$. After spreading code modulation and carrier modulation, the output signal can be expressed as

$$s(t) = a_1(m)c(t)cos(w_c t), \tag{1}$$

where $c(t)$ is a PN sequence, and $w_c$ is the carrier frequency. Then the next symbol after the difference of the bit information can be written as $a_2(m-1)$, and the output signal can be expressed as

$$\begin{aligned} s(t-T_c) &= a_2(m-1)c(t-T_c)cos(w_c(t-T_c)) \\ &= a_2(m-1)c(t)cos(w_c t). \end{aligned} \tag{2}$$

After the UAC transmission, the correlation despreading process at the receiving end can be written as

$$\begin{aligned} r_i(t) \otimes c(t) &= a_i c(t) \otimes [c(t) \otimes h(t) + n(t)] \\ &= M^2\delta(t) \otimes h(t) + c(t) \otimes n(t) \\ &= M^2 h(t) + c(t) \otimes n(t), \end{aligned} \tag{3}$$

where $M$ is the length of PN sequence and $\otimes$ denotes convolution. $h(t)$ is the channel impulse response (CIR) with random delay spread and Doppler spread.
Generally, the channel is assumed to be consistent for one symbol duration, that is $h_m(t) = h_{m-1}(t) = h(t)$. Then, differentiating the despreading of the preceding symbol $corpre$ and following symbol $cornow$, which can be expressed as

$$\begin{aligned} corpre \times cornow =& a_1(m)a_2(m-1)[M^2h(t) + c(t)\otimes \\ & n_m(t)][M^2h(t) + c(t) \otimes n_{m-1}(t)], \end{aligned} \tag{4}$$

where $n_{m-1}(t)$ and $n_m(t)$ are the additive noises at the preceding symbol and following symbol.
The decision variable can be obtained by integrating the Eq. (4) within the symbol width, and the original information symbol shown in Eq. (5) can be recovered by symbol decision on the decision variable.

$$\begin{aligned} prod_{\mathrm{dssss}} =& a_1(m)a_2(m-1)\int_t^{t+T_c} [M^2h(t) + c(t) \otimes n_m(t)] \\ & [M^2h(t) + c(t) \otimes n_{m-1}(t)]\mathrm{d}t \\ =& a_1(m)a_2(m-1)\int_t^{t+T_c} [M^2h(t) + n'(t)]\mathrm{d}t, \end{aligned} \tag{5}$$

where $n'(t)$ is the additive noise. Fig. 1 shows the block chart of DSSS system.

### 2.2 Basis of ranging

There are two key factors in underwater acoustic ranging: maximum measuring distance and distance resolution. It is not difficult to find that the maximum measuring distance is proportional to the send (or transmission) power and the pulse width of DSSS system, and inversely proportional to the propagation loss of seawater.
Define the scattering loss of seawater as $\xi$, propagation distance as $d$, then the propagation loss $P(f,d)$ can be expressed as

$$P(f,d) = \xi d^\beta e^{\alpha(f)d}, \tag{6}$$

where $f$ is the sound frequency with the unit $Hz$, $\beta$ denotes the coefficient for different propagation conditions, and $\alpha(f)$ denotes the absorption coefficient which is shown as

$$\alpha(f) = \frac{A_1P_1f_1f^2}{f_1^2+f^2} + \frac{A_2P_2f_2f^2}{f_2^2+f^2} + A_3P_3f^2, \tag{7}$$

where $A_1, A_2, A_3$ are constants, $P_1, P_2, P_3$ denote pressure-dependent parameters, and $f_1, f_2$ are relaxation frequency parameter, which are the functions of the current seawater medium temperature, salinity and water depth.
For the different marine environments, the propagation losses are different. Meanwhile, the propagation loss in the same marine environment also changes with time. Therefore, a farther maximum measuring distance can only be obtained by increasing the transmission power or the pulse width.
On the other hand, the minimum distance resolution of DSSS system depends on the sound velocity $c$ and symbol width $T_c$, and can be expressed as

$$d_\Delta = \frac{1}{2}cT_c. \tag{8}$$

The distance between the transmitter and receiver is calculated according to the propagation time and velocity of sound waves. There are two main ranging methods: active ranging and passive ranging.

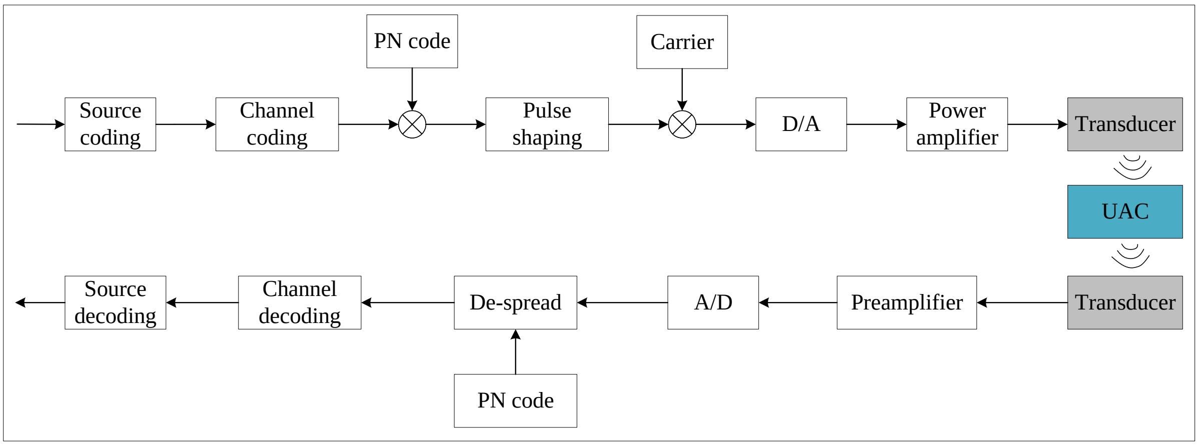


Figure 1. Block chart of DSSS.

For the active ranging method, the transmitter and receiver do not need time synchronization. The transmitter sends the ranging signal at $t_1$ and waits for the response signal. When the receiver detects the ranging signal, it immediately returns the response signal. Then, the transmitter records the reception time as $t_2$ when it detects the ranging signal, and calculates the distance between the transmitter and receiver according to the following formula

$$d = \frac{1}{2} c \left(t_2 - t_1 - \tau\right), \tag{9}$$

where $t_2 - t_1 - \tau$ is propagation time. $\tau$ is the fixed delay of the modem, which mainly includes the times of signal modulation and demodulation.

For the passive ranging method, the transmitter and receiver must maintain precise time synchronization and require a high enough time accuracy. The transmitter modulates the time $t_1$ of the current sending signal into the acoustic signal and sends it to the receiver. The receiver detects the sound signal and records the reception time as $t_2$. Further, the receiver demodulates the send time $t_1$ sent by the transmitter and calculates the distance between the transmitter and receiver according to the following formula

$$d = c \left(t_2 - t_1 - \tau\right). \tag{10}$$

It can be seen from the above formula that the ranging accuracy is mainly affected by the sound velocity measurement accuracy and the time measurement accuracy. $c$ is mainly affected by the temperature, salinity, and static pressure of the water, resulting in the change of underwater sound speed with the change of depth. The common empirical formula of sound speed is as follows:

$$c = 1449.22 + \Delta c_T + \Delta c_S + \Delta c_P + \Delta c_{STP}, \tag{11}$$

where $T$ is temperature with the unit °C, $S$ is salinity with the unit ‰, $P$ is static pressure with the unit $kg/cm^2$, and are defined as

$$\Delta c_P = 1.5848 \times 10^{-1} P + 1.572 \times 10^{-5} P^2 - 3.46 \times 10^{-12} P^4, \tag{12}$$

$$\Delta c_T = 4.587T - 5.356 \times 10^{-2} T^2 + 2.604 \times 10^{-4} T^3, \tag{13}$$

$$\Delta c_S = 1.19(S - 35) + 9.6 \times 10^{-2} (S - 35)^3, \tag{14}$$

$$\Delta c_{TPS} = 1.35 \times 10^{-5} T^2 P - 7.19 \times 10^{-7} T P^2 - 1.2 \times 10^{-2} (S - 35) T, \tag{15}$$

and the relationship between $P$ and water depth $z$ is as follows

$$P = 1.033 + 1.028126 \times 10^{-1} z + 2.38 \times 10^{-7} z^2 - 6.8 \times 10^{-17} z^4. \tag{16}$$

### 2.3 Scheme of predetermined ranging

Since the passive ranging system only needs one signal transmission, the system is simple and is widely used in underwater equipment. However, the passive ranging system requires precise time synchronization and a high enough time resolution, requiring a piece of additional timekeeping equipment for timekeeping. Due to the high timekeeping stability and clock accuracy, atomic clocks are usually used for time synchronization.

However, different atomic clock devices have inconsistent output time accuracy. For a second-level cesium atomic clock, only whole-second time information can be output. The time resolution is far from sufficient for ranging. Therefore, a predetermined ranging scheme with this kind of second-level cesium atomic clock is proposed in this paper.

The second-level commercial cesium atomic clock is used to ensure accurate clock synchronization. At a specified second-level, the transmitter modem sends the ranging signal. Meanwhile, the receiver modem starts timing and obtains the propagation time $t$ when it detects the ranging signal. Then, the receiving modem calculates the distance between the transmitter and receiver according to Eq. (17).

$$d = c \left(t - \tau\right). \tag{17}$$

## 3. SYSTEM IMPLEMENTATION

### 3.1 Hardware platform

The hardware platform of the proposed modem in this paper is shown in Fig. 2. As shown in Fig. 2, the hardware platform of the proposed modem mainly includes atomic clock module, core processing module, signal sending module, and receiving module.

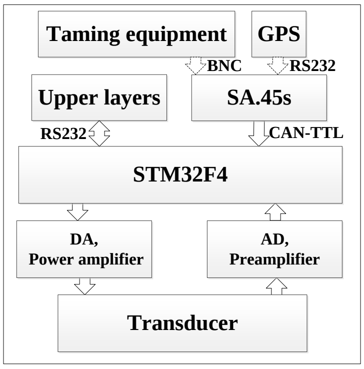


Figure 2. Hardware platform of the proposed modem.

The core processing module takes the STM32F4 series embedded processing chip as the core and is equipped with other peripherals. The strategy of DSSS and ranging are implemented on the STM32F4 microprocessor, Including DSSS signal modulation and demodulation, timing, ranging signal analysis.
The atomic clock module is embedded with Microsemi's SA.45s chip-level cesium atomic clock, with a frequency accuracy of $\pm 5 * 10^{-11}$ and power consumption of less than 120 mW. The module completes the self-locking process within 50 s after power-on and sets the time by parsing the global positioning system (GPS) protocol. After the module obtains time information from GPS, it performs high-precision punctuality and outputs accurate whole-second time information through the controller area network (CAN) bus every 10 s. The atomic clock module needs to be tamed first. Through RS232 and bayonet nut connector (BNC), the atomic clock module reads the current time from the GPS and is tamed by the taming device through BNC. After the taming is completed, the errors of the phase and frequency can be adjusted to within 1ns and $1.0 * 10^{-12}$ Hz, respectively. And then, the taming equipment and GPS information are no longer needed.
The signal sending and receiving modules mainly include D/A, power amplifier, preamplifier filter, A/D and underwater acoustic transducer, etc. When there is a communication request from the upper layer at the transmitter, the core processor module modulates the information to be sent into a DSSS communication signal, and sends it out through the signal sending module. When the DSSS communication signal is detected by the core processor module at the receiver via the signal receiving module, the information from the transmitter is immediately demodulated and sent to the upper layer.
When there is a ranging request, both the transmitter and receiver specifie a second-level for ranging through the atomic clock module. The core processor module directly generates the ranging signal and waits until the specified second-level to send it out through the signal sending module. Meanwhile, the receiver starts timing at the same second-level. When the ranging signal is detected by the core processor module at the receiver via the signal receiving module, the receiver stops timing and gets the propagation time. Then, according to Eq. (17), the distance between the transmitter and receiver is calculated and sent to the upper layer by the core processor module.

## 3.2 Software design

The flowchart of the proposed modem is shown in Fig. 3. It can be seen from Fig. 3 that the proposed modem contains both communication and ranging capability.
After the proposed modem starts to work, it is initialized first.

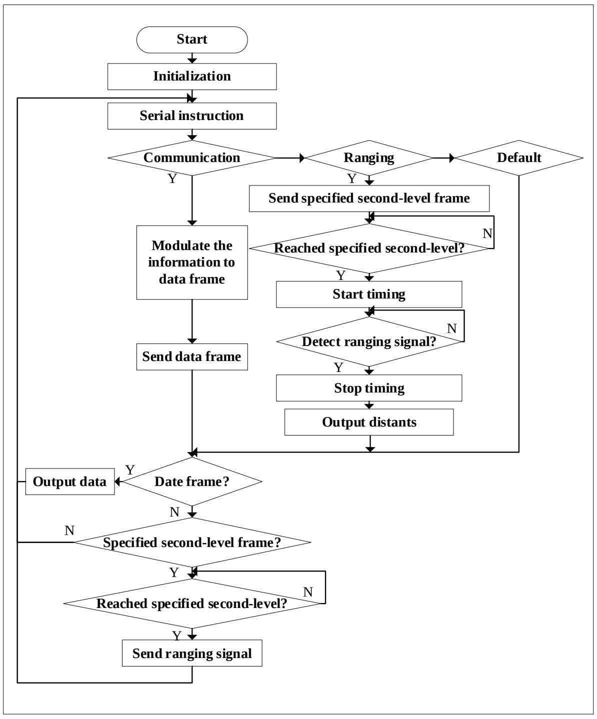


Figure 3. Flowchart of the proposed modem.

And then, the modem enters the inquiry mode. Through the RS232 serial port, the modem receives a data transmission and reception command or ranging command.
For the data transmission and reception command, the modem has two states: data transmission or data reception. For the state of data transmission, the core processor module at the transmitter modulates the information to data frame send the data frame. For the state of data reception, the core processor module at the receiver first determines whether it is a data frame. And then, the information is demodulated from the data frame and uploaded to the upper layer.
For the ranging command, the modem also has two states: ranging signal transmission or ranging signal reception. For the state of ranging signal transmission, the core processor module at the transmitter first specifies a specified second-level time and sends it to the receiver. When the specified second-level time is coming, the core processor module at the transmitter starts timing. Until detecting the ranging signal, the core processor module at the transmitter stops timing and calculates the distance. Finally, the distance between the transmitter and receiver is sent to the upper layer by the transmitter. For the state of ranging signal reception, the core processor module at the receiver demodulates the specified second-level time from the specified second-level frame. And then the receiver sends the ranging signal at the specified second-level time.
In addition, the ranging and communication capabilities can be mutually performed at the transmitter and receiver. This means that the transmitter and receiver can communicate with each other through spread spectrum and mutually verify the calculated distance information, thereby further improving the ranging accuracy.

| Spread gain | Carrier frequency | Chip rate | Bit rate | Bit per frame | PN code |
|---|---|---|---|---|---|
| 63 | 25 kHz | 2.34 k | 55.8 bps | 192 bps | M sequence |

Table 1. Parameters of DSSS modulation.

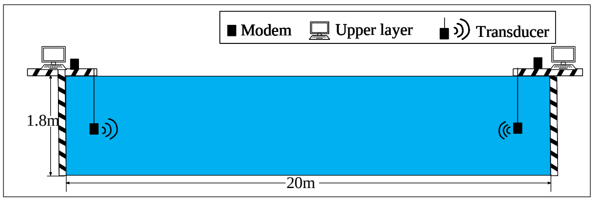


Figure 4. Experiment configuration.

## 4. EXPERIMENTAL RESULTS

To evaluate the effectiveness of the proposed modem, the communication and ranging performances are tested at different distances. The BER is used to verify the communication performance, where the absolute error is used to explain the ranging accuracy of the system. Experimental parameters are shown in Table 1. The transducer bandwidth is 21~29 kHz, with the sampling rate at 75 kHz. The spread gain is 63, the chip rate is 2.34 k, the bit rate is 55.8 bps, each frame contains 192 bit information, and the M sequence is selected as the PN code.

The pool experiment took place at the ocean physical acoustics experiment pool in Xiamen University, Xiamen, China. Fig. 4 shows the experiment configuration, the depth of the experiment field was about 1.8 m, and the length of the pool is about 20 m. The signals were transmitted between two transducers by the shore. Both the transducers were suspended at a depth of 1 m.

The experiment is carried out at different distances of 10 m and 15 m. Fig. 5 shows the time-frequency diagram of received DSSS signal. It can be seen that the delay extension of the pool is about 100 ms, and the SNR of the received DSSS signal is about 20 dB. The delay extension is mainly caused by the direct path, the reflection paths from the water surface and bottom, and scattering from the body of water. Due to the closed environment of the pool, the noise is small, so the SNR is relatively large. The above phenomenons reflect the harshness of underwater acoustic channel and difficulties for acoustic communication and ranging.

At different distances, multiple cyclic communication experiments are performed cyclically between the transceiver and receiver. The modem is able to communicate 100% of all the time, and the BERs are on the order of $10^{-4}$, which illustrates the reliability of the spread spectrum communication.

Table 1 shows the ranging results of the pool experiment. For different distances, five sets of tests were done. It can be seen from Table 1 that its ranging accuracy can reach cm level. At the true distance of 10 m, the minimum absolute error is 8 cm, and the average absolute error is 9 cm. At the true distance of 15 m, the minimum absolute error is 7 cm, and the average absolute error is 8 cm.

The above pool trial preliminary results show that the proposed modem realizes the integration of communication and ranging. Further, this modem is capable of achieving good communication performance at pool experiments with long delay extension. And, based on the second-level cesium atomic clock, the ranging precision could reach cm level. The above results verify the effectiveness of this new underwater acoustic modem.

| True distance/m | Estimated distance/m | Absolute error/cm |
|---|---|---|
| 10.00 | 10.09 | 9 |
| | 10.08 | 8 |
| | 10.09 | 9 |
| | 10.10 | 10 |
| | 10.09 | 9 |
| 15.00 | 15.08 | 8 |
| | 15.07 | 7 |
| | 15.08 | 8 |
| | 15.08 | 8 |
| | 15.09 | 9 |

Table 2. Pool experiment ranging results.

## 5. CONCLUSION

In this paper, a new underwater acoustic modem with high precision ranging capability based on second-level cesium atomic clock is developed. Combined with the high-reliability spread spectrum technology and second-level cesium atomic clock, the proposed modem can realize highly reliable communication and cm level ranging. The pool experiment verified the effectiveness of the proposed modem. The proposed modem can be applied to underwater acoustic navigation and communications integration and other ocean development fields.

## ACKNOWLEDGEMENTS

The authors are grateful for the funding of the National Key Research and Development Program of China (No.2018YFE01100 00) and the National Natural Science Foundation of China (No.1 1274259 and No.11574258) in support of the present research.

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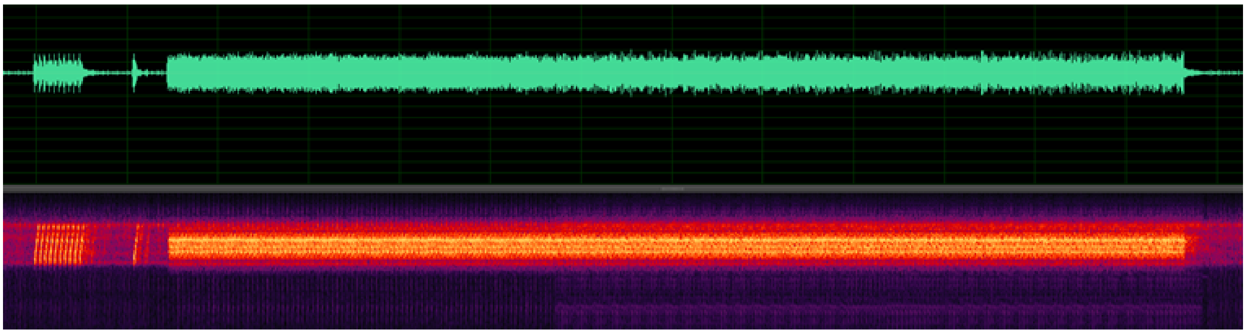

Figure 5. Time-frequency diagram of DSSS signal.

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