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Development of return signal simulator for chinese satellite altimeter prelaunch performance assessment

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Abstract: An ocean Return Signal Simulator (RSS) and the principles of the RSS with its means of testing and calibrating for a satellite altimeter were given. By using the chirp regeneration technique, full de-ramp technique, ocean return spectrum digitally synthesizing technique and high speed DSP technique, a full signal RSS was successfully developed for a Chinese satellite altimeter test and calibration, full range of time delay and full sea state simulation were achieved. Time delay precision is 0.2 ns, significant wave height (SWH) simulation precision 0.5 m and backscattered coefficient precision 1 dB. By using the RSS, the full system testing and calibrating experiment to the Chinese satellite altimeter were implemented. The results show the dynamic performance of the RSS and the altimeter are validated.

Key words: Radar; Altimeter; Altimeter; RSS; Microwave remote sensing

回波模拟器的研制及对卫星雷达高度计发射前的性能评估

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摘要：给出了回波模拟器的原理及其对卫星高度计的测试和定标方法。通过采用 chirp 重建技术、全去斜坡技术、海洋回波波谱数字合成技术和高速 DSP 技术，研制了一台用于卫星高度计测试和定标的全信号海洋回波模拟器，实现了海洋回波信号的全程路径延时模拟和全海况模拟。延时模拟精度为 0.2 ns、海洋有效波高模拟精度为 0.5 m、后向散射系数模拟精度为 1 dB；并将该模拟器用于了卫星高度计全系统的测试和定标。实验结果：有效验证了回波模拟器的原理及其对卫星高度计的测试和定标方法是可行的，也有效验证了一种卫星高度计的动态工作性能。

关　键　词：雷达；高度计；回波模拟器；微波遥感
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1 Introduction

The "Shenzhou IV" spacecraft altimeter is a nadir-looking, pulse-compression radar which operates in a pulse-limited mode, with the range measurement at Ku-band (13.9 GHz). The system generates a linear-FM (chirp) pulse waveform with a bandwidth of 332 MHz and a duration of 24 μs. The pulse repetition frequency (PRF) is approximately 4 800 Hz. The antenna is a 1.2 m diameter parabolic reflector. The beam width (2.6°) from a 334 km mean orbit altitude covers an area on the surface that has a diameter of over 15 km. The measurement area is restricted by the pulse-limited operation to an area of 1.1km for a flat sea surface or 3.7 km for a 5 m SWH surface. The received pulses are de-ramped to remove the linear-FM and processed by frequency filtering to form waveforms, each consisting of 64 samples of the power backscattered from a particular range. The 333 MHz pulse bandwidth results in these samples having a spacing of 0.45 m. This is also the resolution of the altimeter. The waveforms are processed by an adaptive tracker, which controls the altimeter through the various calibration, track, standby, and test modes, to format the height, AGC, wave height, status, and engineering data for output to the spacecraft telemetry system.

The altimeter performance mainly expected to be validated includes:

(1) Height tracking precision of 5 cm.

(2) SWH estimation accuracy of 0.5 m or 10% of SWH.

(3) Ocean backscatter coefficient (σ^0) resolved to an accuracy of ±1 dB.

(4) All function modes, surface acquisition and tracking performance test and validation.

The best way to ensure the altimeter in-orbit performance is as expected after launch, is to validate it over the range of in-orbit operating conditions before launch. This is a very important section of the ground-based test and calibration program to the altimeter and is mainly accomplished with the RSS that provides a full signal simulation of the ocean surface. This paper describes the system design and development of the RSS. Based upon the use of the RSS to simulate the backscatter from the ocean surface, the prelaunch test experiment data are presented to demonstrate that the performance of the "Shenzhou IV" altimeter will meet the specified requirements.

2 RSS Principle

The signal provided by the RSS must realize the real simulation of the ocean return signal. It determines that the simulation model comes from the altimeter pulse's limited measurement geometry, as shown in Fig. 1.

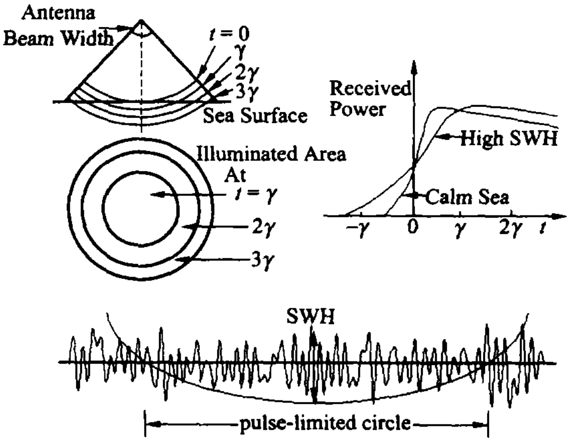


Fig. 1 Altimeter pulse limited measurement geometry

The altimeter averaged received power[1] to be simulated can be represented by the following:

$$P_r(\tau) \approx \begin{cases} \eta P_T P_{FS}(0)\sqrt{2\pi}\sigma_p\left[1+erf\left(\frac{\tau}{\sqrt{2}\sigma_c}\right)\right]/2, & \tau<0 \\ \eta P_T P_{FS}(\tau)\sqrt{2\pi}\sigma_p\left[1+erf\left(\frac{\tau}{\sqrt{2}\sigma_c}\right)\right]/2, & \tau\geq 0 \end{cases} \quad (1)$$

Where, η is pulse compression ratio, P_T is peak transmitting power, σ_p is 3 dB point target response width, $\sigma_c=\sqrt{\sigma_p^2+(2\sigma_s/c)^2}$, σ_s is the RMS height of the specular points relative to the mean sea level, $\tau= t-2h/c$ is the round-trip path time delay of the transmitting pulse, $P_{FS}(\bullet)$ is flat sea surface mean impulse response, $erf(\bullet)$ denotes the error function.

To simulate an ocean return signal by using (1), the relative movement between satellite and ocean surfaces must be considered. So the simulation includes the following effects:

(1) Radar cross section of the ocean surface;

(2) Significant wave height (SWH);

(3) Satellite attitude angle;

(4) Height (round-trip path delay), height rate, and height acceleration;

(5) Speckle statistics of ocean backscatter;

(6) Spatial and temporal correlation of speckle.

By performing the simulation described above, the principle of altimeter validation by RSS is shown in Fig. 2.

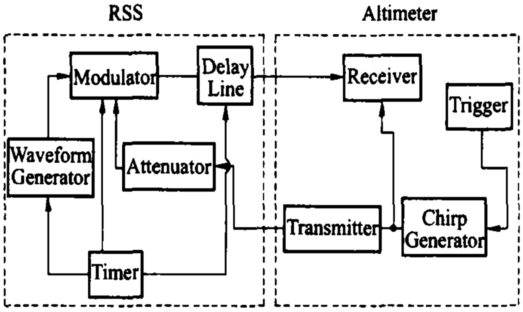


Fig. 2 Functional diagram of altimeter validation by RSS

The pulses from the altimeter transmitter are attenuated by the tunable attenuator and modulated with the signal from the waveform generator precisely controlled by the timer, and passed back to the altimeter receiver through the delay line. The received signal, regarded as the real ocean return signal, is processed by the altimeter. By comparing the results processed by the altimeter with the RSS simulation, the prelaunch altimeter performance will be validated.

3 RSS development

3.1 Hardware design

The block diagram of the RSS system hardware is shown in Fig. 3.

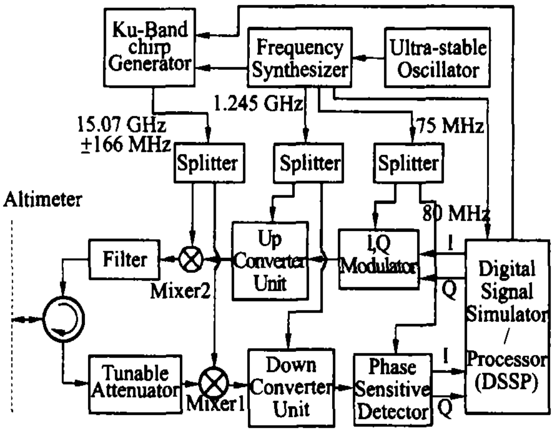


Fig. 3 Block diagram of the RSS system hardware

This system is based upon "chirp regeneration-deramp" concept. The 13. 9 GHz pulse from altimeter transmitter is "full de-ramped" with the RSS Ku-band chirp in Mixer1, the de-ramped signal is down converted to 75 MHz IF, and then detected by the Phase Sensitive Detector (PSD), the I, Q output will be digitized by DSSP. If there exists any time delay between the altimeter pulse and the RSS chirp pulse, I, Q output is a point frequency signal, the frequency is in proportion to time delay. DSSP controls the trigging time to make the time delay vanish, and sequentially, I, Q frequency down to zero, this means the RSS accurately acquired and tracked the altimeter pulse. DSSP records this time as the starting time of the simulation, and also stores the digitized I, Q for duplicating the original altimeter pulse characteristics to make the in succession simulated return signal the same with the real ocean backscatter signal essentially coherent to the altimeter transmission. DSSP can provide both point target response simulation and rough ocean surface return simulation digitally. The simulation results are converted to analog I, Q and modulated in the I, Q Modulator with 75 MHz IF, then up converted and mixed with the same RSS chirp to produce 13.9 GHz RF return signal in Mixer 2, and passed back to the altimeter.

DSSP block diagram is described in Fig. 4. All the timing is synchronized to the 80 MHz clock from Frequency Synthesizer in Fig. 3. The microprocessor is TMS320C30, which communicates with PC computers by PCI bus. All the timing is implemented by the cooperation of FPGA and TMS320C30. The point target response or the rough ocean surface impulse response is simulated by computer software; it's easy to realize the full sea state condition simulation due to the strong function of the recent PC technique. The simulation data are transferred to TMS320C30 and complex multiplied with the stored PSD I, Q data, the results are stored in Dual port RAM in real time. By the timing of FPGA, the data is digital to analog converted and the I, Q outputted to the I, Q Modulator as shown in Fig. 3. The detailed simulation algorithm is described in [2]. Since the time delay is realized by digital technique based upon the "chirp regeneration-de-ramp" method, it's convenient to simulate large round trip path delay from the altimeter to the ocean surface. The range set in this system varies from 1ms to 5 ms, corresponding to a 150 km to 1 500 km height from satellite to the ocean surface.

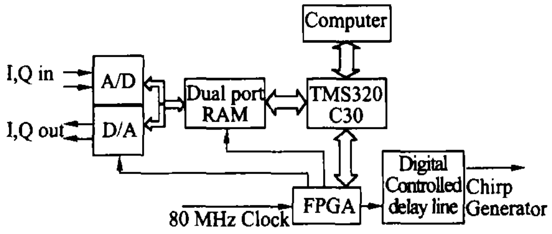


Fig. 4 Block diagram of DSSP

3.2 Function implement

Fig. 5 describes system timing scheduling and function implement.

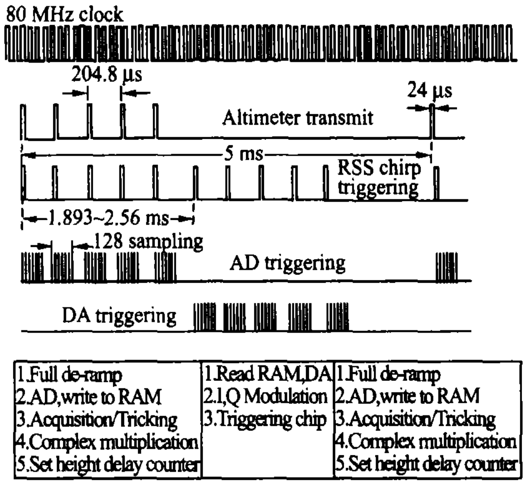


Fig. 5 Timing scheduling and function implement

A "Shenzhou IV" spacecraft altimeter transmitting burst consists of five pulses, and the burst repetition period is 5 ms. Height tracking range is designed at 334 km ±50 km which corresponds to a round trip time delay from 1.893 ms to 2.56 ms. So the RSS must provide the simulation signal burst in a certain time between 1.893 ms and 2.56 ms from the beginning of the transmitting burst of the altimeter. This is realized by the RSS according to the altimeter transmitting timing scheduling as in Fig. 5.

During the altimeter transmission, RSS implement the following steps:

(1) "Full de-ramp" altimeter chirp;

(2) Perform AD conversion of the PSD I, Q output;

(3) Perform Acquisition and Tracking processing;

(4) Perform Complex multiplication of recorded I, Q data with simulation data from PC software and storing the results in the dual port RAM;

(5) Set height delay counter.

Right after the counting of height delay, RSS startup the following steps totally controlled by hardware timing:

(1) DA converters read data from the dual port RAM;

(2) Perform I, Q Modulation;

(3) FPGA triggers chirp generator.

3.3 RSS performance

For altimeter test and calibration, the RSS performance should be better than the altimeter's. TABLE I lists the designed specifications of the RSS system.

Tab. 1 RSS system performance

Time Delay	1-5 ms, Fully variable in intervals of 0.05ns
Delay Precision	±0.1 ns
Delay Accuracy	±0.1 ns
Signal Level	Range 0-70 dB, Variable in < 1 dB steps
Chirp Fidelity	3° RMS
De-ramp precision	±1 kHz

The dominant requirement is de-ramp precision, it determines the overall performance of the RSS system. To achieve the requirement, PSD I, Q output is filtered with a 128 kHz lowpass filter, at 5.333 MHz sample rate, the 24 s altimeter pulse results in 128 complex samples having a spacing of 1 kHz frequency resolution, which corresponds to a 0.07 ns time resolution or 2 cm range resolution. So the altimeter pulse tracking precision and accuracy are less than 0.1 ns. Since the time delay simulation is realized by digital synthesizing method and controlled by the time delay counter in FPGA, the delay precision and accuracy are mainly determined by 80 MHz clock precision, the design requirement is assured by an Ultra-stable Oscillator with 10^{-7} frequency precision and 10^{-10} frequency stability. Furthermore, based upon these, the RSS system can provide an absolute time delay of point target response simulation with 0.1 ns precision and accuracy, and the altimeter absolute calibration of the system time delay can be performed. In addition, 128 complex sampling results in high chirp fidelity of 3° RMS, and by employing digital controlled tunable attenuator, the signal level is accurately simulated.

4 Altimeter test and calibration by RSS

4.1 Point target response test

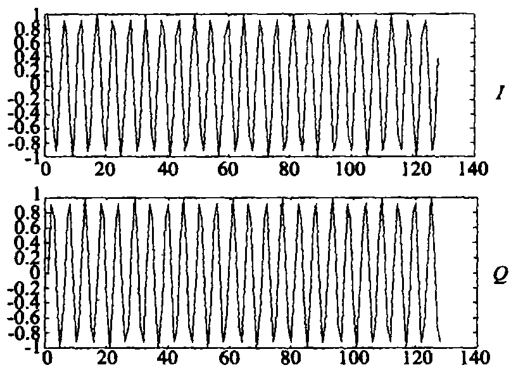
The Frequency Spectrum Analyzer of the "Shenzhou IV" spacecraft Altimeter Tracker has 64 tracking gates, which correspond to the 64 samples of ocean return waveform. The middle gate, index number 32, defined between the sample 32 and 33, is used to track the half power point in the leading edge of an ocean return waveform to form height estimation.

By performing a point target response test, the altimeter system time delay, corresponding to system height bias, can be absolutely calibrated. By using the RSS, the method is rather simple. If the RSS transforms the PSD I, Q data into the RF output with a known time delay t_1, the altimeter tracks this point target signal and sets it in the middle gate in tracking time t_2, and the time difference is the system time delay. If the PSD I, Q data complex multiplies with the point frequency data simulated by DSSP, the altimeter tracker should set this signal in a certain tracking gate whose frequency shift corresponds to the point frequency. If aided by high resolution frequency counter, to measure the I, Q signal of the altimeter tracker, a better result would be obtained.

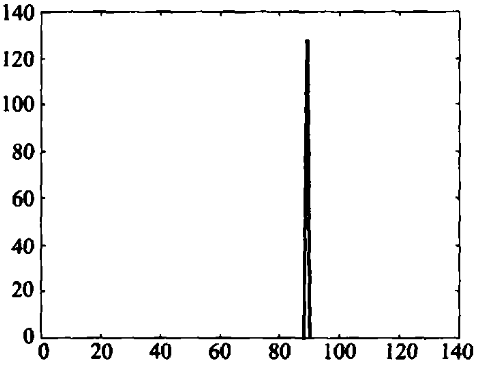
An example of a point target response test is as follows. The RSS simulated signals are shown in Fig. 6.

The signal in Fig. 6 is a simulated 1 MHz point target, and the time delay is set to $t_1 = 2$ ms, which corresponds to a 300 km round trip height. While this signal is accurately tracked by the altimeter, the processed spectrum waveform will appear in the 56th tracking gate.

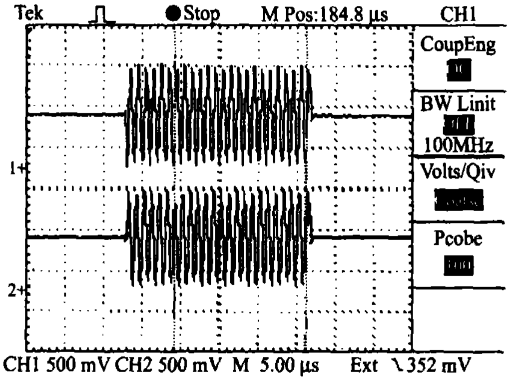
The altimeter tracker processed data is plotted in Fig. 7. The simulated signal is tracked by the 56th tracking gate. In the same time, the height tracking time of the altimeter $t_2 =$



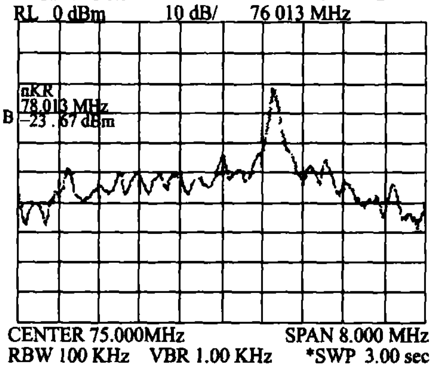
(a) Software simulated 1 MHz point frequency



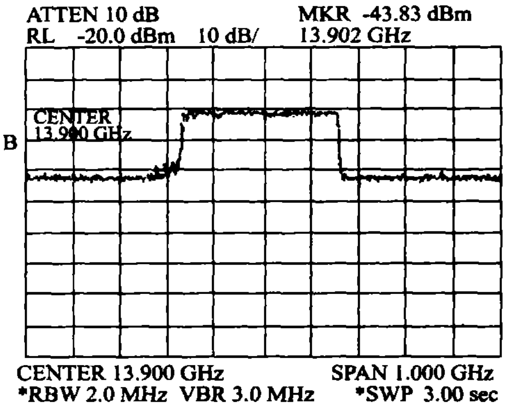
(b) Frequency spectrum of the point frequency



(c) DSSP output I, Q point target signal



(d) I, Q modulator output frequency spectrum



(e) RSS 13.9 GHz RF output frequency spectrum

Fig. 6 Simulated point target response of the altimeter by RSS

2.003 338 ms, less the time delay set in the RSS t_1, is the altimeter system time delay, 3.338 μs. Changing the simulated frequency and averaging all the results, the system time delay is 3.338 μs ±0.1 ns.

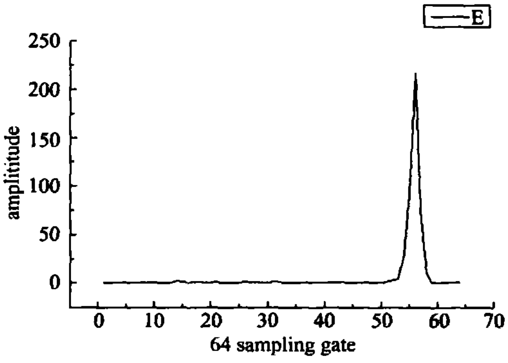
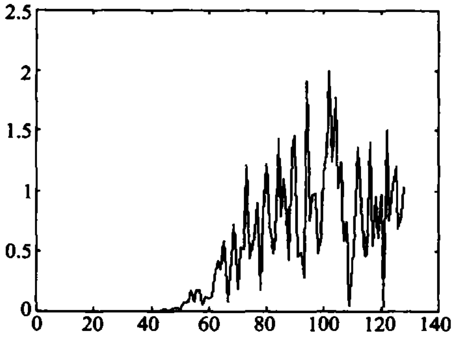


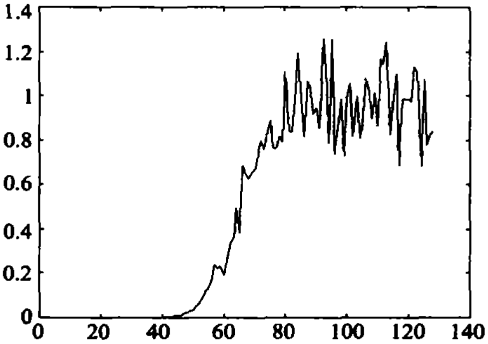
Fig. 7 Altimeter point target signal tracking

4.2 Dynamic performance test

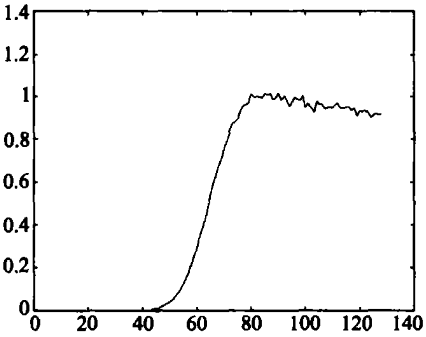
Dynamic performance should be tested over the range of in-orbit conditions before launch. The test program includes thermal vacuum environment tests, vibration tests, acoustic tests, and EMI/EMC tests. Before, during, and after thermal vacuum tests and EMI/EMC tests, the altimeter dynamic performance tests have been conducted by using the RSS simulation. Here is an example of the rough ocean surface return signal simulation to conduct altimeter performance tests during thermal vacuum environment tests, as shown in Fig. 8, Fig. 9, and Fig. 10.



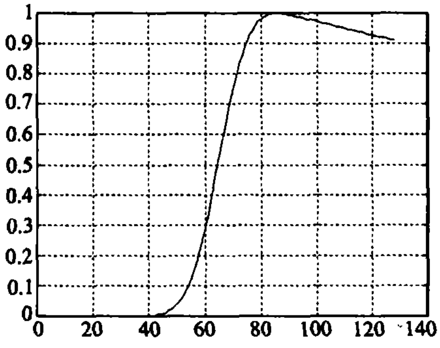
(a) A sample of simulated single pulse (SWH= 5 m, σ^0 = 10 dB, Height= 334 km)



(b) Altimeter 1 tracking period averaging simulated by computer software

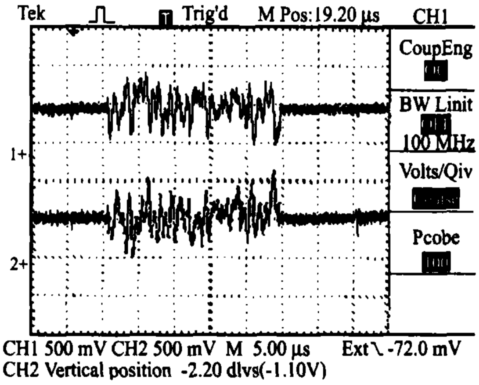


(c) Altimeter 1 second averaging simulated by computer software

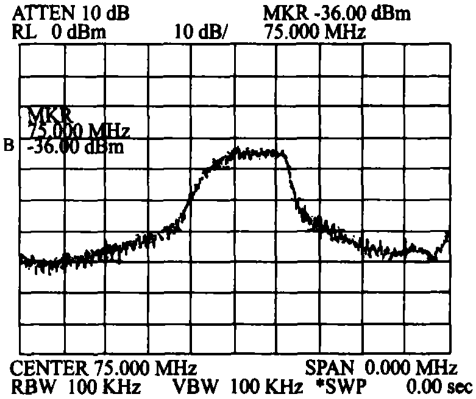


(d) Theoretical averaged return power

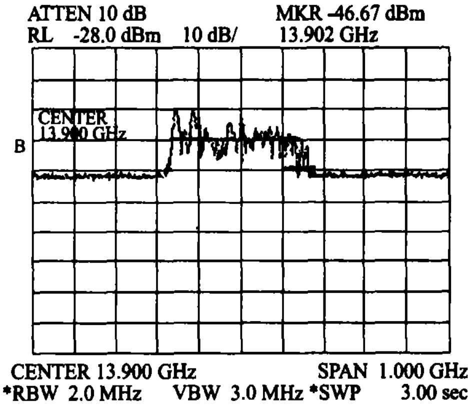
Fig. 8　The computer simulation of rough ocean surface return signal tracked by altimeter



(a) DSSP I, Q output simulating rough surface return



(b) I, Q modulator output frequency spectrum



(c) RSS 13.9GHz RF output frequency spectrum

Fig. 9　The RSS simulation of rough ocean surface return signal

Fig. 8 describes full signal simulation by the DSSP computer software. The simulated height is 334km, SWH is 5 m, and σ^0 is 10 dB. Since the simulation also includes the satellite altitude angle

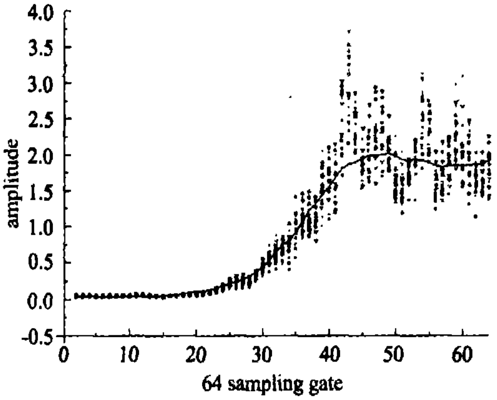


Fig. 10 Rough surface simulation signal processed by altimeter tracker

variation, height rate and height acceleration, speckle statistics of the ocean backscatter, and the spatial and temporal correlation of speckle, the simulated waveforms are random. The Fig. 8 (a) gives a sample of a simulated single pulse. The DSSP software also has the function to simulate altimeter processing, this computer simulation is to validate whether the full signal simulation statistics is the same as in theory.

Fig. 9 describes the signal flow of the RSS simulation.

Fig. 10 describes the altimeter tracker processing. By 1 second averaging, the altimeter height measurement precision is 4. 5 cm, SWH estimation accuracy is 0. 45 m and σ^0 accuracy is ±1 dB.

TABLE II lists altimeter performance tests results of 2 m, 5 m, and 10 m SWH sea states simulation.

Tab. 2 Prelaunch altimeter performance

Sea state SWH (m)	Height standard deviation (cm)	SWH estimation accuracy (m)	σ^0 accuracy (dB)
2	3. 98	0. 235	±0. 5
5	4. 50	0. 450	±1. 0
10	5. 12	1. 020	±1. 0

5 Conclusion

RSS is the most important device for altimeter performance tests and calibrations. In China, theoretical analysis predicted and the prelaunch testing demonstrated the capability of the "Shenzhou IV" spacecraft altimeter to measure the range to the ocean surface with 5 cm accuracy. Flight experiment results also validates this, which will strongly support the further plan for higher performance altimeter development in China.

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