Characteristics of the Passive Hydrogen Masers in Orbit

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***Abstract*—The Passive Hydrogen Maser (PHM) has excellent mid-long term frequency stability. What's more, it's small and light. So it is suitable for global navigation satellite system (GNSS). The Galileo is the first GNSS that equips with PHMs on satellites. The BeiDou Navigation Satellite System deploys PHMs in its third generation (BDS-3) too. The full completion of the BDS-3 constellation deployment has accomplished for almost 1 year. How do the PHMs in Beidou-3 running? The telemetries of PHMs on-board will be analyzed to indicate their running status. They are the typical state parameters, including voltage of Oven Controlled Crystal Oscillator (OCXO), voltage of cavity, amplitude of second harmonic and light intensity of ionization source. By checking, filtering, smoothing and modeling the data, the situations of PHMs and their components is clear. Further, they have been extrapolated to see their status in future. It is verified that the PHMs all work well in orbit, and can work for more than 10 years.**

Keywords—passive hydrogen masers; in orbit; state analysis; telemetries; BeiDou Navigation Satellite System

I. INTRODUCTION

The full completion of BeiDou-3 Navigation Satellite System (BDS-3) constellation deployment accomplished on July 31, 2020[1]. The Passive Hydrogen Maser (PHM) is applied on BDS-3 which is never on BDS-1 and BDS-2. It's the second global navigation satellite system (GNSS) that equips with PHM in the world, after the Galileo.

The PHMs on BDS-3 are all work as maser clocks due to their outstanding frequency stability. How do they work now? How will they work in future? Their working status can be studied through the analysis of the telemetries. And by fitting and extrapolation of the telemetries, the future status could be known.

II. PASSIVE HYDROGEN MASER AND ITS TELEMETRIES

The PHM outputs an accurate and stable frequency reference by lock the Oven Controlled Crystal Oscillator (OCXO) frequency output to the transition frequency of hydrogen atoms. It composed of Physics Package (PP) and Electronics Package (EP). PP supplies the appropriate hydrogen atoms and the transition environment. EP outputs microwave interrogation signal and the controlling voltage of OCXO and microwave resonance cavity according to the transition signal. The frequency reference and telemetries are also generated by EP. The block diagram of PHM is shown in Fig.1.

There are 4 key telemetries in PHM, listed in Fig.1 by blue font. They are amplitude of second harmonic, light intensity, cavity voltage and OCXO voltage. The atomic gain is an important indication of frequency performance of PHM. The amplitude of second harmonic could represent the atomic gain. It is detected by microwave testing circuit. When the molecular hydrogen is ionized to atoms, light is released[2]. The light intensity represents the flux of hydrogen atoms. It can be monitored by photodiode. The frequency output can be regulated according to the transition frequency of hydrogen atoms in real time. It is implemented by adjusting the controlling voltage of OCXO. The resonance frequency of cavity could also be regulated by adjusting the cavity voltage.

The limits of telemetries are shown in TABLE I. If amplitude of second harmonic goes beyond the limits, the atomic gain is too low to maintain PHM's service. If light intensity goes beyond the limits, it's not sure that there is enough hydrogen atoms. If cavity voltage or OCXO voltage goes beyond the limits, the cavity or OCXO is out of control.

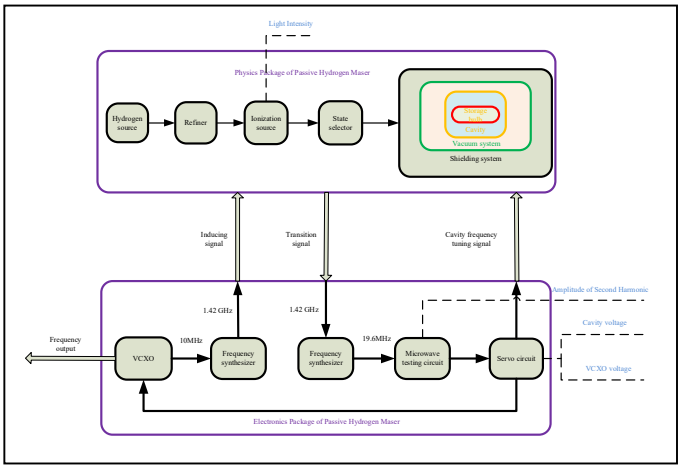

Fig. 1. The block diagram of PHM and its telemetries

TABLE I. LIMITS OF PHMS' TELEMETRIES

Telemetry	Limits
Amplitude of second harmonic	0.7V~3.0V
Light intensity	0.2V~4.5V

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Telemetry	Limits
Cavity voltage	0.1V~2.6V
OCXO voltage	0.1V~1.0V

6 PHMs are analyzed in this paper. They all work on Medium Earth Orbit (MEO). They started up at different date in orbit. The earliest has worked since January 19, 2018, while the latest has worked since November 29, 2019, which is all showed in TABLE II. The following testing curves of telemetries are from January 1, 2020 to January 5, 2021.

A. Amplitude of Second Harmonic

Fig.2 shows the testing curve of amplitude second harmonic. The amplitude of second harmonic of 5 PHMs has begun to decrease. But the rate is very slow. The amplitude of Second Harmonic of PHM on C44 is still increasing because it hasn't worked for long. It fits the aging rule of amplitude of second harmonic, which is rising at first and then turning to fall sometime in future.

B. Light Intensity

The testing curves of light intensity are shown in Fig.3. The light intensity of all 6 PHMs is in falling curves. And the decreasing rate is higher than that of amplitude of second harmonic. The particles including atoms, molecules, ions and

TABLE II. THE STARTING UP DATE OF PHMS

PRN	Starting Up Date
C28	January 19, 2018
C30	April 4, 2018
C26	August 31, 2018
C34	October 21, 2018
C35	October 21, 2018
C44	November 29, 2019

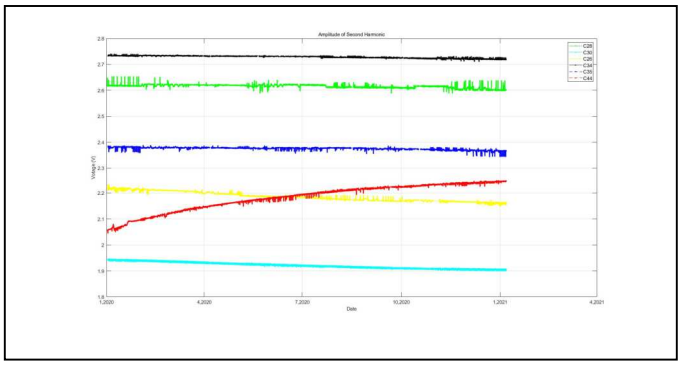

Fig. 2. Testing cureves of amplitude of second harmonic

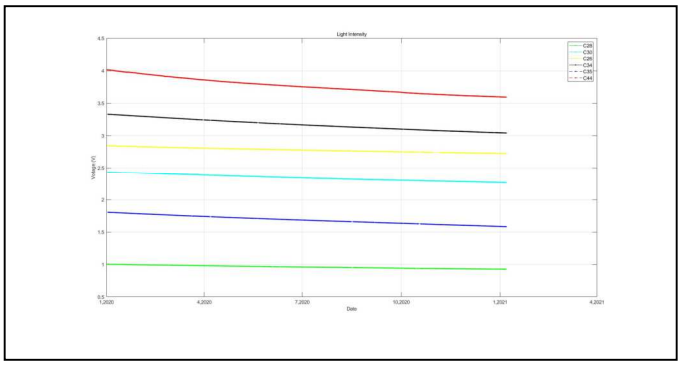

Fig. 3. Testing curves of light intensity

electrons collide with discharge bulb frequently. Collision caused the decline of the light transmittance of discharge bulb. It is the reason of the decreasing of light intensity. It is also can be seen that the deceasing rate is slowed down day after day.

C. Cavity Voltage

Most of testing curves of cavity voltage except C26 in Fig.4 is rising. Assembly stress in PP is released naturally. It leads the falling of the cavity resonance frequency. And it needs to increase cavity voltage tuning cavity frequency back. As assembly stress is released, the rising rate gets lower along with time. The testing curve of cavity voltage of PHM on C26 is almost stable. It can be inferred that its assembly stress is small now.

D. OCXO Voltage

The OCXO voltage is going up or down in different testing curves as shown in Fig. 5. But changing rates are all very low. It indicates that the OCXOs have a ultra-low aging rate.

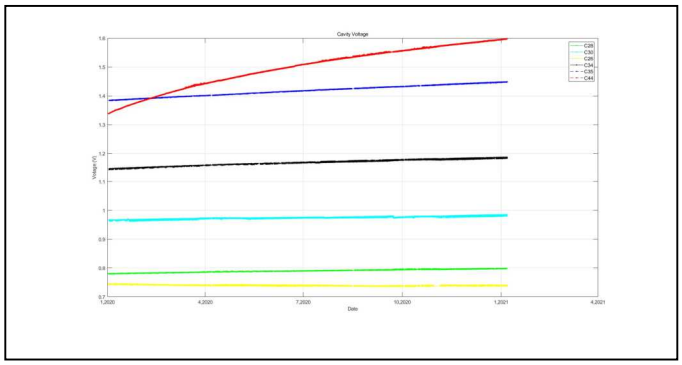

Fig. 4. Testing curves of cavity voltage

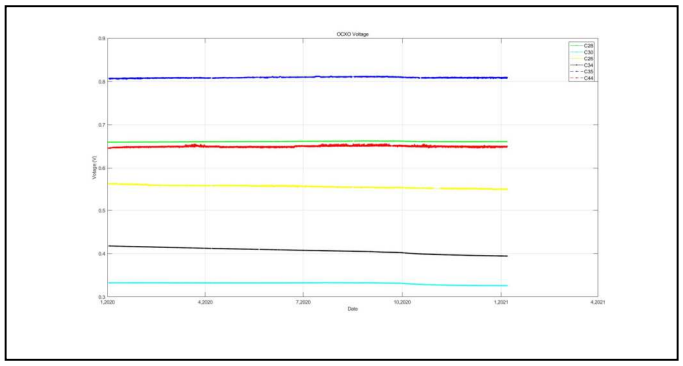

Fig. 5. Testing curves of OCXO voltage

III. FITTING AND EXTRAPOLATION OF TELEMETRIES

It can be seen from the testing curves that all the PHMs work well. It also shows that amplitude of second harmonic, light intensity and cavity voltage get more stable, while OCXO voltage is already stable. So the fitting model will be different for them accordingly.

A. Amplitude of Second Harmonic

The changing rules of amplitude of second harmonic in the testing curves satisfy the power2 function of time. Fig.6 shows the fitting curves and extrapolation curves for 10 years, and TABLE III gives the coefficients. After more than 10 years' work, the amplitudes of second harmonic of all 6 PHMs are still in limits. It shows that the atomic gains are still high. The amplitude of second harmonic of PHM on C44 will increasing continuously according to the extrapolation. But in fact, it will turn to decreasing at last according to the aging rule, which couldn't be predicted by the power2 function. It is confirmed that the amplitude of second harmonic of PHM on C44 will go longer than any of others.

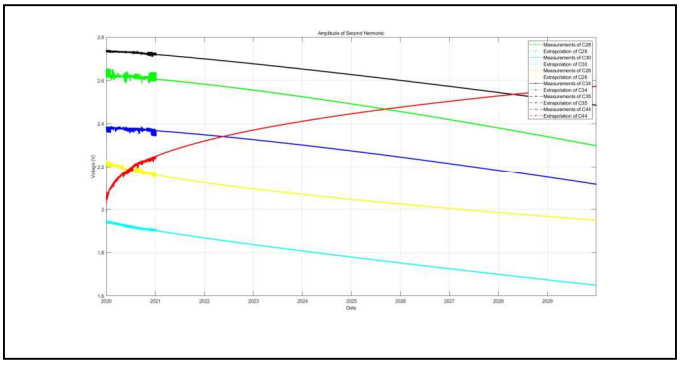

Fig. 6. Fitting and extropolation of amplitude of second harmonic

TABLE III. THE FITTING COEFFICIENTS OF AMPLITUDE OF SECOND HARMONIC

PRN	f(x)=a*x^b+c		
	a	***b***	***c***
C28	-2.288e-12	1.312	2.622
C30	-2.036e-8	0.8426	1.944
C26	-1.71e-6	0.6132	2.228
C34	-1.524e-11	1.202	2.736
C35	-1.873e-12	1.312	2.381
C44	5.464e-4	0.356	1.993

B. Light Intensity

The best fitting of light intensity in the testing curves is the power2. Fig.7 shows the fitting curves and extrapolation curves for 10 years, and TABLE IV gives the coefficients. The light intensity in any of the 6 PHMs has not exceeded the limits after more than 10 years' work. It indicates that the hydrogen atoms are enough.

C. Cavity Voltage

The power2 is a realistic approach for the cavity voltage too. Fig.8 shows the fitting curves and extrapolation curves for 10 years, and TABLE V gives the coefficients. The cavity voltages are all in range after more than 10 years' work. It represents that the microwave resonant cavities in the 6 PHMs are still in control.

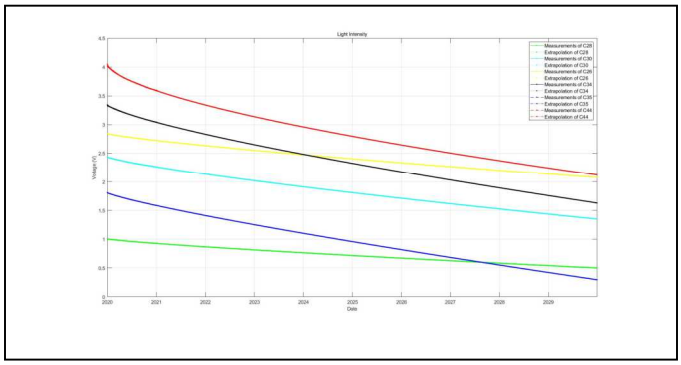

Fig. 7. Fitting and extrapolation of light intensity

TABLE IV. THE FITTING COEFFICIENTS OF LIGGHT INTENSITY

PRN	f(x)=a*x^b+c		
	a	***b***	***c***
C28	-6.839e-8	0.8081	1.005
C30	-1.885e-7	0.7955	2.437
C26	-1.104e-7	0.8051	2.844
C34	-7.053e-7	0.7514	3.345
C35	-1.31e-7	0.831	1.809
C44	-9.879e-6	0.6225	4.05

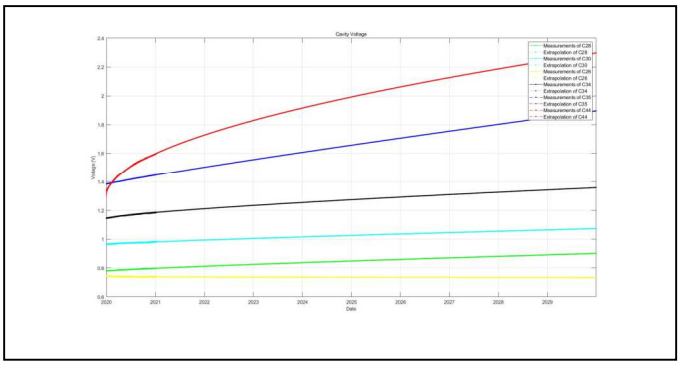

Fig. 8. Fitting and extrapolation of cavity voltage

TABLE V. THE FITTING COEFFICIENTS OF CAVITY VOLTAGE

PRN	f(x)=a*x^b+c		
	a	*b*	*c*
C28	1.153e-8	0.8262	0.7801
C30	7.957e-9	0.8392	0.9658
C26	0.2464	-7.028e-3	0.52
C34	1.573e-7	0.7216	1.145
C35	1.054e-8	0.9045	1.383
C44	3.098e-5	0.5302	1.304

D. OCXO Voltage

Though the changing rates are very small, the OCXO voltages also can be fitted in polynominal1 model. Fig.9 shows the fitting curves and extrapolation curves for 10 years, and TABLE VI gives the coefficients. The OCXO voltages of all 6 PHMs don't go beyond the limits after more than 10 years' work. It can be seen that the OCXOs are still in control.

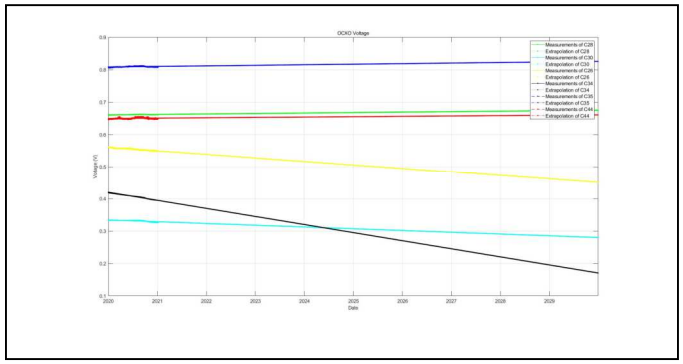

Fig. 9. Fitting and extrapolation of OCXO voltage

TABLE VI. THE FITTING COEFFICIENTS OF OCXO VOLTAGE

PRN	f(x)=p1*x+p2	
	p1	*p2*
C28	4.554e-11	0.6605
C30	-1.718e-10	0.334
C26	-3.481e-10	0.5604
C34	-7.898e-10	0.4196
C35	5.444e-11	0.8082
C44	3.481e-11	0.6494

IV. CONCLUSIONS

The PHMs on BDS-3 have served for 1~3 years. The testing curves of telemetries reveals that they all work well to supply accurate and stable frequency reference. By fitting and extrapolation, it is clear that they all can work for more than 10 years stably and continuously. It satisfies the lifetime requirements on them.

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