Development of a Space Cold Atom Clock

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Abstract: Atomic clocks with cold atoms play important roles in the field of fundamental physics as well as primary frequency standards. Operating such cold-atom clocks in space paves the way for further exploring in fundamental physics, for example dark matter and general relativity. We developed a space cold atom clock (SCAC), which was launched into orbit with the Space Lab TG-2 at 2016. Before it deorbited with TG-2 at 2019, the SCAC had been working continuously for almost three years. During the period in orbit, many scientific experiments and engineering tests have been performed. In this article, we summarize the principle, development and in-orbit results. These works provide the basis for the construction of space-borne time-frequency system in deep space.

Keywords: cold atom clock, in orbit, microgravity, fundamental physics
1 Introduction

Experiments in space provide new opportunities to test fundamental physics, and many great discoveries have been made recently. Space environment offers ultra-high vacuum and infinite microgravity time at a large scale, which are not possible on ground. Recent progress on space science and technology allows us to design advanced space devices to test new physics, for example, the application of cold atoms in space will contribute to the construction of quantum sensors which have extremely high sensitivity [1], and can be of essential help to detect dark matter, gravitational wave, and to test the Standard Model [2].

Atoms can be cooled by laser beams to extremely low temperature [3], and may be even further cooled by further cooling techniques such as evaporative cooling into a macroscopic quantum state such as the famous Bose-Einstein condensation [4,5]. On ground, such cold atoms are strongly affected by gravity not only in the cooling stage but also in the manipulation process, and therefore the physics for cold atoms in space has unique features to be explored.

On the other hand, atomic clocks play more and more important roles in modern society. Since the invention of the atomic clocks, their performance (stability and accuracy) had been improved 1 digit per 5 years until mid-1990s when the traditional atomic clocks almost reached their limit. Thanks to the laser cooling technique, the performance of atomic clocks has been further improved with laser-cooled atoms, with which, not only higher stability is achieved due to a longer interrogation time, but also systematic uncertainties are reduced. Atomic clocks with laser-cooled atoms, so-called cold atom clocks, are now the most precise and accurate frequency standards, and are utilized in the International Atomic Time (TAI).

A typical cold atom clock on ground is the atomic fountain clock [6,7]. Atoms are cooled and trapped in a magneto-optical trap at the bottom of a vacuum setup, then are launched upwards, and eventually fall downwards due to the gravity after reaching their apogee. During the flight, the cold atoms interact twice with microwave field to yield Ramsey fringes, which are used to correct the microwave frequency. Such kind of cold atom clocks have reached a long term stability at \(6 \times 10^{-17}\) level [8], and are now widely used as the most accurate primary frequency standard.

Therefore, sending such a cold atom clock into space has potential applications in many fields. A space cold atom clock (SCAC) can improve the performance of GNSS (Global Navigation Satellite System), facilitate the deep space navigation, and test the fundamental physics. However, although many efforts have been made [9-15], great challenges have impeded the deployment of such a SCAC.

We started a mission called Cold Atom Clock Experiment in Space (CACES) around mid-2000s, which got approved by the China Manned Space Program (CMSP) in 2011. Since then,
under the guidance of the CMSP, we had developed a principle model, an engineering model and a flight model of a SCAC, which had been tested thoroughly on ground. The flight model was launched into orbit on September 15th, 2016 with the Space Lab Tiangong-2 (TG-2), and had been tested in orbit under the regulations of TG-2 until July 19, 2019 when the TG-2 deorbited. During almost 3 years in orbit, the SCAC is kept in operation and has carried out many tests and accumulated a large collection of data.

In this paper, we present the development and results of the SCAC, including the design, manufacture, and tests of both on-ground and in-orbit. Firstly, we discuss the principles of operation and the fundamentals of design for SCAC. Then we describe the details on the engineering side and the basic function of major units, including the tests performed on ground. Moreover, we present the experimental results of in-orbit operation. Finally, we conclude the paper with outlook towards the future.

2 Principle

There are two main differences between on-ground and in-orbit scenarios for the operations of cold atom clock. On ground, gravity drags cold atoms downwards, and thus the cold atom clock can be designed as a fountain, called the atomic fountain. In orbit, however, due to the microgravity environment where gravity is virtually absent, the cold atoms move in uniform rectilinear line after they are launched, and thus the design of fountain-type cold atom clock is not applicable for SCAC.

Another difference is the terrestrial magnetic field. Typically, an atomic fountain is set in a lab, where the terrestrial magnetic field is almost stable. It is relatively easy to shield the stable magnetic field. However, in orbit, the magnitude and direction of terrestrial magnetic field changes during the aircraft’s motion around the earth, and an automatic compensation of the magnetic field is required to keep the magnetic field fluctuation in interaction zone small enough.
Fig. 1 Principle and structure of the SCAC. The laser cooling and trapping zone is a MOT configuration with folded beam design. The ring interrogation cavity is used for the microwave field to interrogate cold atoms. In the detection zone, the cold atoms on both hyperfine states are detected. The clock signal is obtained by feeding the error signal to the microwave system.

The basic principle of a SCAC operating in orbit is shown in Fig. 1. Rubidium (\(^{87}\text{Rb}\)) is chosen for our SCAC partly due to its relatively higher melting temperature, compared to cesium (\(^{133}\text{Cs}\)), which reduces the design complexity of the atomic source for space application. Additionally, the collision shift of \(^{87}\text{Rb}\) is much smaller than that of \(^{133}\text{Cs}\), and thus better performance can be expected with \(^{87}\text{Rb}\) [16]. The atoms are cooled and trapped in a magneto-optical trap (MOT), and then the cold atoms are launched by the moving optical molasses technique. During the launching stage, the cold atoms are further cooled by adiabatic cooling. Because of the microgravity, the cold atoms move in a straight line at a constant velocity. After state selection, the cold atoms are interrogated by the microwave field, and then detected by the laser excited atomic fluorescence.

The SCAC consists of four units: physics package, optical bench, microwave system and control electronics. The main part of the physical package is a titanium alloy vacuum tube whose vacuum is kept below 10\(^{-7}\) Pa. A ring cavity is used for the Ramsey interrogation of cold atoms by the microwave field. Three layers of Mu-metal are used to shield the magnetic field in the interrogation zone, while only one layer surrounds the cooling zone. The magnetic field in the interrogation zone is automatically compensated by regulating the current in the C-field coil through a servo loop, in order to keep total magnetic field stable during the motion of the spacecraft in orbit.
Together with a pair of anti-Helmholtz coils, two cooling laser beams are folded to form a compact MOT in order to reduce the power required for laser cooling. Due to the folded structure, all laser beams intersected in the MOT zone include the transmitting forward part and the backward part. Moreover, the frequencies of the two cooling beams can be controlled separately such that a moving optical molasses may be formed, and thus the cold atoms can be launched at a velocity of

$$v = (\omega_1 - \omega_2) / k,$$

where $\omega_1$, $\omega_2$ are the frequency of the two cooling laser beams respectively and $k$ is the wave vector. After being launched from MOT, the cold atoms are further cooled by the adiabatic cooling below Doppler cooling limit.

The state selection is fulfilled by a combination of microwave excitation and laser pushing method. After cooling and trapping stage, the atoms are concentrated at the state $|F = 2\rangle$ evenly distributed among 5 magnetic sub-states. The microwave power in the state selection cavity is adjusted such that the atoms at $|F = 2, m_F = 0\rangle$ are pumped to $|F = 1, m_F = 0\rangle$ at an efficiency of almost 100%. Then a laser beam pushes all other atoms at $|F = 2, m_F \neq 0\rangle$ states away, and the remained atoms are used for the microwave interrogation.

The Ramsey interrogation of a SCAC requires two cavities separated by a distance $D$, corresponding to the interrogation time $T = D/v$ for cold atoms with velocity $v$ in microgravity. The width of central Ramsey fringe is directly related to the velocity as [17]

$$\Delta \propto v^2 / 2D.$$  

Considering the dead time of the clock cycle combined with the size limitation, we have made the choice of $D = 217$ mm in our SCAC.

The timing sequence of the SCAC is presented in Fig. 2. This process is composed of five stages: cooling and trapping, state selection, interrogation, detection, and feedback. The power and frequency of cooling beams are regulated by the AOMs. Firstly, the rubidium atoms are captured and cooled to lower than 5μK. Secondly, the cold rubidium atoms in state $|F = 2, m_F = 0\rangle$ are distinguished and selected into state $|F = 1, m_F = 0\rangle$ by a microwave field. Thirdly, the selected cold atoms are interrogated by a Ramsey separated oscillating field. Fourthly, the frequency error signal is obtained in the detection zone and is finally fed back to the microwave system.
3 Engineering of SCAC

3.1 Aims of the CACES mission

The European Space Agency (ESA) has developed a cold atom clock, PHARAO, in their mission ACES, which aim to operate a clock system in the International Space Station for the purpose of measuring the gravitational redshift, testing Lorentz invariance and searching the variations of fundamental physical constants [12,14,181-21]. The CACES mission, under the support of the CMSP, is designed to operate a cold atom clock in the Space Laboratory TG-2. The main aims of this mission include:

- to test laser cooling of atoms in microgravity,
- to test the launching and the motion of cold atoms at very low velocity in microgravity,
- to test interrogation of cold atoms via Ramsey microwave fields in microgravity,
- to test the relevant key techniques in orbit, including the frequency stabilization of diode lasers, optical system, fiber-optic coupler, vacuum, temperature control, and etc.,
- to estimate the performance of a SCAC in orbit,
- to accumulate data of the orbital environment for cold atom physics.
Meanwhile, the CACES mission also pioneers the applications of space-borne quantum sensors based on cold atoms, such as cold atom interferometer, cold atom gyroscope, optical clock, cold atom magnetometer, and etc. Moreover, it will be helpful for future development of in-orbit precision measurement experiments for fundamental physics problems, such as the detection of gravitational wave, the search for dark matter, and etc.

3.2 Principle model

Based on the studies of atomic fountain clock, a principle model of SCAC is built to test the main features of a cold atom clock for space application [22]. For the physics package, the principle model uses a ring structure as the Ramsey microwave cavity to simulate the operation of a cold atom clock in microgravity, which is different from an atomic fountain.

Besides the physics package, the optical bench is also an essential ingredient of a cold atom clock operated in orbit. A miniaturized optical bench is developed to test the stability of the most important optical components [23]. Several modules are developed and used in the bench. All units and modules are installed and fixed on an aluminum plate. The variance of output power does not exceed ±5% for 5 months without any adjustment. The bench is employed for cooling, launching and detection of atoms in the SCAC for a long period. And as demonstrated, the number of cooled atoms stays relatively stable at a mean number $8.5 \times 10^6$ with a variation of $0.32 \times 10^6$ for a long period, and temperature of cooled atoms reaches 1.5μK, which is almost the lowest temperature obtained from traditional three-dimensional laser cooling of $^{87}$Rb [24].

3.3 Engineering model

Based on the design and test of the principle model, from 2011 to 2013, an engineering model was developed and all the key engineering technologies were tested thoroughly.

3.3.1 Compact magneto-optical trap

A compact magneto-optical trap (CMOT) was designed and made for the engineering application of the space cold atom clock [25]. The schematic of the CMOT is shown in Fig. 3. In this CMOT, only two cooling laser beams are used instead six in conventional magneto-optical trap. Compared to a conventional one, the CMOT has a series of advantages for space applications especially for SCAC:
Fig. 3 Set of the CMOT mechanical structure. Only two cooling laser beams are used instead of six.

- More compact and efficient. A fold optical path scheme is adopted, two cooling laser beams are input and form six cooling beams through transit mirrors. This design saves about 1/3 in volume and weight, also about 60% in laser power.

- More robust. No additional adjustment is required after the initial adjustment is completed. The whole mechanical structure is more stable and convenient for space applications.

The COMT has passed the thermal cycle tests and the mechanical vibration and shock tests. And the COMT has been implemented in the engineering model and has operated for about six years in the laboratory. The COMT maintained a high performance without necessities of realignment.

3.3.2 Ultra-high vacuum system

An ultra-high vacuum system was developed when the engineering model was manufactured [26], as shown in Fig. 4. The whole system is made of titanium alloy material (Ti-6Al-4V) which is lightsome with high tensile strength and low thermal and electrical conductivity. Also, since this material is non-magnetic, it is especially suitable for manufacturing precision measurement instruments. The vacuum pump system is specially designed with 4 getters at each end of the interrogation cavity, which ensures that the ultra-high vacuum can maintain for a long time even without power supply. This feature can satisfy the requirements of space applications.

Also, with this engineering model of the ultra-high vacuum system, the distribution of the inside pressure was numerically calculated and tested. With these efforts, the vacuum performance of the SCAC was guaranteed.
3.3.3 Highly reliable optical bench

Optical system is one of the key parts in cold atom clocks. For a SCAC, a compact and reliable optical bench is required [27,28]. In this optical bench, all the optical elements are integrated onto a 300mm \( \times \) 290mm \( \times \) 30mm two-side optical table. Its size and weight is greatly reduced compared with the traditional optical system. This optical bench has passed all the space environmental qualification tests to guarantee high reliability.

In the SCAC, preparation and interrogation of the cold atoms are spatially separated and the rubidium atoms’ transition probability is measured by detecting the number of cold atoms on each hyperfine levels via the resonance fluorescence method [28]. The photon emission rate fluctuation resulting from the optical frequency noise is will affect the stability of SCAC during the detection process via Eq. (3).

\[
\sigma_y^2(\tau) = \frac{1}{2\pi Q_{at}} \frac{1}{\tau} \sqrt{\int_{\tau_{det}}^{T_0} \sigma_y^2[f(t) - f(t - \Delta t)] \, dt}
\]  

(3)

where \( \sigma_y^2 \) represents the photon emission rate fluctuation which is related to the laser frequency noise. The subtraction of \( f(t) - f(t - \Delta t) \) represents a reduction of the laser frequency noise’s effect on the SCAC which results from the separate detection of the atom number on the two levels. Consequently, a SCAC with a frequency stability of \( \sim 10^{-13}/\sqrt{\tau} \) requires a laser...
frequency stability better than $\sim 10^{-11}$ from 1 s to 10000 s. The Allan deviation of laser frequency in the highly reliable optical system is of $\sim 10^{-11}$ over averaging times from 1 to 10000s, and even falls into $\sim 10^{-12}$ from 20 to 100s, whose contribution to the stability of SCAC is less than the target level of $\sim 10^{-13}/\sqrt{\tau}$.

3.3.4 Microwave system

Microwave interrogation cavity in SCAC is used to stimulate the clock transition of $^{87}$Rb. Different from the fountain clock on ground, the SCAC’s Ramsey cavity must satisfy the conditions to operate in microgravity, in which the launched cold atoms moves at constant velocity. To meet this demand, a dual-interaction zone interrogation cavity was developed [29]. The principle of the cavity is similar to the one for cesium atoms in the ACES mission [121], but with different guidance structure. The cavity has a ring structure with four rectangular waveguide cavities connected end-to-end, as shown in Fig. 5. The cavity is made of TC4 (Ti-6Al-4V) with silver coating and contains three major parts: bracket, cover and coupled waveguide. The microwave field is feed in from a hole on the coupled waveguide, and propagates in two opposite directions and finally forms a standing wave field which was simulated and tested thoroughly, as discussed in Ref. [29].

![Fig. 5 The ring microwave cavity for SCAC. This picture gives the assembly of the cavity shown in Fig. 1 of Ref. [29] in detail.](https://academic.oup.com/nsr/advance-article/doi/10.1093/nsr/nwaa215/5899773)

The microwave system has two units, including a crystal oscillator which produce a 5 MHz signal, and a synthesizer which convert the 5 MHz signal to the transition frequency 6.834 GHz of the $^{87}$Rb. Then it is fed into the microwave cavity for the interrogation of cold atoms. A phase noise level of $10^{-7} \times f^{-1.5}$ rad$^2$/Hz is realized. Such a microwave noise level guarantees the frequency stability of $1.4 \times 10^{-13} \tau^{-1/2}$ for SCAC operated in orbit [30].

3.3.5 Test of the engineering model

The engineering model of SCAC was manufactured and assembled as shown in Fig. 6. After integration, this model was tested on ground carefully [31]. The engineering model has a good medium-term frequency stability of $1.5 \times 10^{14}$@1000s. Those tests and results provides a basis for
the development of flight model.

![Fig. 6 Photograph of the engineering model for SCAC.](image)

3.4 Flight model

After the success of the engineering model, from 2013 to 2016, a flight model was developed for the flight mission of TG-2, as shown in Fig. 7. An automatic compensation device was added in the flight model in order to keep the magnetic field constant inside the physical package during the flight in the orbit around the earth [32].

![Fig. 7 Photograph of the flight model for SCAC, which contains more details compared to Supplementary Figure 1 of Ref. [33].](image)
The thermal and mechanical tests were carried out according to the regulations of the CMSP. The performance of this model was also tested in those different conditions and met the requirement of space application. About $10^8$ rubidium atoms can be captured and the temperature of them can be lower than 5μK in the flight model’s ground tests. The Ramsey fringe has been obtained with a full-width-at-half-maximum (FWHM) smaller than 10 Hz in laboratory and the frequency stability was obtained by comparing the flight model against an H-Maser even though the performance of the SCAC is degraded due to the gravity on ground. These results satisfy the demands of the CACES project.

The flight model was handed over to the CMSP in May 2016 and went through tests together with all the payloads of TG-2 under unified coordination in June 2016. After the combined tests, the flight model was then installed into the spacecraft in September, 2016.

4 Test in orbit

The TG-2 was launched on September 15, 2016 at the Jiuquan Satellite Launch Center, and the SCAC was switched on during the second day, and started in-orbit tests nearly since then until the time that TG-2 deorbited on July 19, 2019. The in-orbit tests involve the validation of the engineering objectives and exploration of in-orbit scientific phenomena.
Fig. 8 Ramsey fringes vs frequency detuning with different cold atoms' launch velocities.

With the flight model in orbit, time-of-flight signals have been detected in the detection region of the SCAC, and some typical and expected Ramsey fringes have been obtained as shown in Fig. 8. The relation between the FWHM of central Ramsey fringe and the atoms' launch velocity has been determined which is consistent with the calculated results [30,33]. The feed-into microwave power has also been determined from the test, which agree well with the calculated results. The signal-to-noise ratio of the SCAC has been measured at different atom’s launching velocities from which the in-orbit short-term frequency stability of the SCAC has been estimated to be close to $3.0 \times 10^{-13} \tau^{-1/2}$ with a clock period of 2.0 s as shown in Ref. [33]. Also, a closed-loop operation has been carried out by feeding the error signal to the direct digital synthesizer (DDS) of the microwave system to verify the in-orbit long-term operation mechanism [33]. This is particularly useful for the design of next generation cold atom clock, which is expected to operate in Chinese Space Station in the future.
Outlook

The CACES mission has fulfilled all goals before the deorbit of TG-2. The engineering model, as the backup of the flight model, is still working in the laboratory for continuous testing. The successful operation of a SCAC in orbit paves the way for the wide applications of cold atom technologies in spaces, such as cold atom interferometer, cold atom gyroscope, cold atom optical clock and etc. Those quantum sensors based on cold atoms will play a more and more important role in space fundamental physics [1].

Based on the success of CACES mission, in the Chinese Space Station, in-orbit experiments about cold atom clock will be carried out based on the ultra-high precision time-frequency cabinet and the ultra-cold atom physics cabinet which are manufactured adopted many key technologies of the SCAC.

With all the works above, it is expected to achieve time-frequency synchronization between ground and space which will open a new door of the deep space exploration and basic physics research.

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