Features of magnetic field stabilization in caesium atomic clock for satellite navigation system

A A Petrov1, N M Grebenikova1, N A Lukashev1, V V Davydov1,2,3, N V Ivanova2, N S Rodygina2, A V Moroz1

1Higher School of applied physics and space technologies, Peter the Great Saint -Petersburg Polytechnic University, Saint - Petersburg 195251, Russia
2The Bonch-Bruevich Saint - Petersburg State University of Telecommunications, Saint - Petersburg 193232, Russia
3Department of Ecology, All-Russian Research Institute of Phytopathology, 143050, Moscow Region, Odintsovo district, B.Vyazyomy, Russia

alexandrpetrov.spb@yandex.ru

Abstract. In this paper one of several directions of caesium atomic clock modernisation is presented. This paper deals with theoretical model which takes into account features of the development of magnetic field stabilization system for caesium atomic clock and describes the affect of this stabilization system on frequency stability of caesium atomic clock. New magnetic field stabilization system allows eliminating one of the most important perturbing factors affecting on long-term frequency stability. Experimental research of the caesium atomic clock’s metrological characteristics with magnetic field stabilization system showed improvement long-term frequency stability on 10%.

1. Introduction

The accurate measurement of time and frequency is vital to the success of many fields of science and technology. For example atomic physics (atom-photon interactions, atomic collisions, and atomic interactions with static and dynamic electromagnetic fields), geodesy, radio-astronomy (very long baseline interferometry), pulsar astronomy, various communication equipment and metrological services rely on high frequency stability and uniform timescales [1-5]. The same is valid for the operation of satellite navigation systems.

Global navigation satellite constellations such as the European Galileo, Russian GLONASS, and the USA Global Positioning Systems use atomic frequency standards for precision time-keeping and stable frequency generation.

One of the central problems in the satellite system is the problem of mutual synchronization of the satellite time scales up to nanoseconds and less [2, 3, 5]. The error of the navigation signals emitted by the different satellites at 10 ns causes an additional error in determining the location of the consumer to 10-15 meters.

The problem solution of high-precision synchronization of the on-board time scales required the implementation of highly stable on-board caesium and rubidium frequency standards on satellites, as well as the creation of ground-based devices for comparing time scales.
The concept of development of space navigation system and development of the metrological services need to modernize the currently used quantum frequency standards or developing new ones. Development and commissioning of new atomic clock is very long and costly process, which in the most cases hasn’t enough funds and time. Therefore, in most cases, for specific tasks related to the operating conditions of frequency standards modernization is occur [6, 7].

The process of quantum frequency standards modernization includes various directions: changing the weight and dimensions, reducing energy consumption, improvement metrological characteristics. And for frequency standards characterized by the fact that modernization may not be for the whole construction and may be for individual units or blocks. In present work one of the several directions of improvement metrological characteristic is considered.

2. Principles of caesium atomic clock operation

The work of a caesium atomic clock is based on the principle of adjustment a highly stable voltage-controlled quartz crystal oscillator (VCXO) to quantum frequency transition of atoms of caesium-133 [1, 7, 8]. Figure 1 shows a block diagram of a caesium atomic clock.

![Figure 1. Block diagram of a caesium atomic clock.](image)

The output signal frequency 5MHz of the VCXO is supplied to the frequency synthesiser. Frequency synthesiser consists of frequency converter, mixer signals and multiplier signals. In the frequency converter input signal frequency 5MHz is converted to the signal frequency 12,631772 MHz and supplied to the input of mixer signals. In the multiplier signals input signal frequency 5 MHz is multiplied to the frequency 270 MHz and then to frequency 9180 MHz. This signal frequency 9180 MHz is also supplied to the input of mixer signals. As a result, the output signal of the frequency synthesiser is the signal of ultrahigh frequency 9192,631772 MHz. This signal is supplied in the Ramsey cavity.

In caesium atomic clock with the help of magnet polarizer 2 the atoms are prepared such that they are either in the |$F=4, m_F=0>$ or in |$F=3, m_F=0>$ state. Afterwards the atoms interact with an electromagnetic field that induces transitions into the former unoccupied state.

A magnetic field is used to separate energetically the otherwise degenerate magnetic sub-levels in order to allow the excitation of the clock transition |$F = 3,m_F = 0> \rightarrow |F = 4,m_F = 0>$ isolated from the other transitions. By convention such a field is referred to as the C field as it is applied between the fields of the polariser and the analyser.

The magnitude of the C field is chosen as a compromise between two conflicting requirements. First, it has to be large enough to separate the otherwise overlapping resonances. Second, the C field shifts the resonance frequency quadratically which has to be corrected. However, in a larger field the
frequency of the clock is influenced to a larger extent by fluctuations of the magnetic field. In the scheme of a commercial Cs clock the C field is often generated by a coil with windings in the paper plane wound around the Ramsey resonator and hence, points perpendicularly to that plane. Owing to the dependence of the frequency of the clock transition from the magnetic field, efficient magnetic shielding has to be provided in order to attenuate the ambient magnetic field and the magnitude of the associated fluctuations.

The atoms in the former unoccupied state are detected and allow one to determine the frequency of the interrogating field where the transition probability has a maximum. The observed transition frequency is corrected for all known frequency offsets that would shift the transition frequency from the unperturbed transition and is used to produce a standard frequency or pulse per second every 9192631772 cycles [1, 7, 8].

Scanning the frequency $\nu$ of the atomic resonance leads to a detector current like the one shown on the figure 2. The signal shows the Ramsey resonance structure on a broader, so-called, Rabi pedestal.

![Figure 2. Ramsey resonance structure on the Rabi pedestal.](image)

The central feature with the maximum at the transition frequency $\nu_0$ is used to stabilize the frequency of the crystal oscillator to the atomic transition frequency. To this end, the frequency from the synthesizer is modulated across the central peak. The signal from the detector is phase-sensitively detected in the servo electronics, integrated and this servo signal is used for stabilising the frequency of the VCXO. From this suitable output frequencies are derived, such as 5MHz or a 1 PPS signal.

3. Features of C field stabilization

The stable isotope Cs-133 has a two hyperfine states $F = 4$ and $F = 3$ which are split in the magnetic field into 16 components. In accordance with the selection rules seven transitions between the components of hyperfine sublevels are possible [9, 10]. These are presented in figure 3.
Figure 3. Microwave resonances in the Ramsey cavity.

The central resonance $|F=3, m_F=0\rangle \rightarrow |F=4, m_F=0\rangle$ (marked on the figure 3 as a «1») due to the Zeeman effect expose a quadratic frequency shift. With the help of formula (1) we can calculate a frequency shift.

$$\Delta f_{B^2} \approx 4.2745 \times 10^{-2} \text{ Hz} \times \left(6\times10^{-6}\text{T} \mu\text{T}^{-1}\right)^2 = 1.5388 \text{ Hz}.$$ (1)

For a typical value of C field equals 6 $\mu$T the frequency shift equals 1,5388 Hz. This frequency shift corresponds to a relative frequency shift of $3 \times 10^{-10}$.

How we can see from formula (1) the accuracy of the output signal of quantum frequency standard is dependent on the shift of the central resonance. It should be noted that not only the central resonance is exposed the frequency shift, but also all six transitions $(3, m_F) \leftrightarrow (4, m_F)$, which $\Delta m_F = 0$. To express these changes as a function of magnetic induction $B$ and atomic constants use the equation Bright Rabi:

$$E(F, m_F) = -\frac{\hbar v}{2(2l+1)} - g_I\mu_B B m_F + \frac{\hbar v}{2} (1 + \frac{4m_F}{2l+1} x + x^2)^{1/2},$$

where $E(F, m_F)$ is the change energy of atoms in the ground state; $I$ is the quantum number of nuclear spin; $g_I$ is the factor Lande for electron; $\mu_B$ is the Bohr magneton; $m_F$ is the magnetic quantum number; $x = \frac{(g_I+g_L)\mu_B B}{\hbar v}$.

The relation (2) can be used for calculation the frequency shift of any transition between two hyperfine sublevels, depending on the magnetic field. Revealing this expression, we find that the first member is proportional to the magnetic field $B$. For caesium beam primary frequency standards we must consider the quadratic member of this expression.

In theory, the frequency shifts can be taken into account in the calculation of the functional dependence on magnetic field values and the atomic constants using equation Bright-Rabi. But in practice, any changes of the magnetic field shift the resonance frequency. And values of these frequency shifts cannot be accounted for in advance.

Thanks to the development of a new frequency synthesiser design [7, 8, 10, 11] the range of generated output frequencies has been expanded. It allowed detuning output synthesiser’s frequency to
the neighboring resonance frequency of spectral line that makes it possible to adjust the C-field in quantum frequency standard.

Now in caesium atomic clock the magnetic field is maintained by the active stabilization system. For this purpose the neighboring transition $|F=3, m_F=1\rangle \leftrightarrow |F=4, m_F=1\rangle$ (marked on the figure 3 as a «2») is used. The method of C-field adjustment is similar to the method of frequency adjustment to the main maximum. For this purpose, the average value of the sampling frequency $v_i$ is changed from the value of the $v_{Cs}$ to $v_{Cs} + \Delta \nu$, where $v_{Cs}$ is the frequency of the main transition of the caesium atom, $\Delta \nu$ - difference between the transitions for a preset value of the magnetic field. Then the value of magnetic field is adjusted in a such way that the frequency of transition $|F=3, m_F=1\rangle \leftrightarrow |F=4, m_F=1\rangle$ match the preset frequency. This adjustment set up automatically several times per minute. The value of the applied field is automatically maintained at a predetermined level. In this case effects associated with any changes in the magnetic field (for example, long-term drift of the current source, temperature dependence, effect of external magnetic field, etc.) are excluded.

This feature gave us the opportunities to close the ring-locked loop frequency oscillator on the neighboring resonance transition.

Alternately closing the ring-locked loop at the central and the neighboring transition we adjust the frequency of the VCXO to the frequency of the central atomic transition, and support the constant value of the magnetic field inside the Ramsey cavity.

4. Experimental research of caesium atomic clock output signal

Experimental research of caesium atomic clock output signal consisted of measuring the output frequency and calculation the Allan variance, which allows to evaluate the frequency instability. But before that, the correct functioning of the magnetic field stabilization system was verified. The figure 4 shows the dependence of the coil current change, which determines the value of the magnetic field from the temperature change.

![Figure 4. Dependence of the coil current change from the temperature change.](image)

From this figure 4 we can see that in different external temperatures the operation modes of atomic clock are different. As a result of temperature changes, the temperature-dependent parameters of all electronic components are change. The output frequency of the frequency synthesizer, which corresponds to the frequency transition of caesium atom-133 is shifted. Magnetic field stabilization
system begins to change the coil current so as to compensate shift of the central resonance frequency of caesium atom -133.

Thanks to the magnetic field stabilization, the current value stabilizes at a constant level after external temperature changes. Also in this way frequency shifts associated with any magnetic field changes are excluded.

Figure 5 shows Allan variance ($\sigma_\gamma$) via time (t) for caesium atomic clock with magnetic field stabilization system (2) and previous design (1).

![Figure 5. Allan variance via time for caesium atomic clock with magnetic field stabilization system (2) and previous design (1).](image)

From these results it is clear that the use of magnetic field stabilization system make it possible to obtain a better long-term frequency stability of quantum frequency standard output signal. It is mainly achieved through by compensating the frequency shift of central resonance of caesium-133.

5. Conclusion

Frequency shifts associated with magnetic field changes and features of magnetic field stabilization in caesium atomic clock are considered. Magnetic field stabilization system for caesium atomic clock is developed. New magnetic field stabilization system allows eliminating one of the most important perturbing factors affecting on long-term frequency stability. Experimental research of correct functioning of the magnetic field stabilization system was successfully verified. Experimental research of the caesium atomic clock’s metrological characteristics with magnetic field stabilization system showed improvement long-term frequency stability on 10%.

6. References

[1] Riechle Fr 2004 *Frequency Standards. Basics and Applications* (WILEY-VCH Verlag GmbH Co.KGaA, Weinheim)
[2] C. Audoin and B. Guinot 2002 *Measurement of Time, Time Frequency and the Atomic Clock* (Cambridge University Press, Cambridge, UK).
[3] McClelland T, White Y and Wilson D 2011 Proc 43rd Annual PTTI Systems and Applications Meeting (California) vol 1 (USA, Hyatt Regency Long Beach) p 325-340
[4] Davydov R V, Saveliev I V, Lenets V A, Tarasenko M Yu, Yalunina T R, Davydov V V, Rud’ V Yu 2017 Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) 10531 LNCS 177-183.
[5] Pakhomov A A 2007 Journal of Communications Technology and Electronics 52 1114 – 1118
[6] Petrov A A, Davydov V V, Myazin N S, Kaganovskiy V E 2017 Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) 10531 LNCS 561-568.
[7] Petrov A A, Davydov V V 2015 Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) 9247 739-744
[8] Petrov A A, Davydov V V 2017 Journal of Communications Technology and Electronics 62 289 – 293
[9] Semenov V V, Nikiforov N F, Ermak S V, Davydov V V 1991. Soviet Journal of Communications Technology and Electronics 36(4) 59-63
[10] Petrov A A, Vologdin V A, Davydov V V, Zalyotov D V 2015 Journal of Physics: Conference Series 643(1) 012087
[11] Petrov A A, Davydov V V 2016 Journal of Physics: Conference Series 769(1) 012065