5-6 Applied Researches in T & F Fields

5-6-1 The Detection of Gravitational Red Shift by Transportation of Atomic Clocks

KOTAKE Noboru, SHIMIZU Yoshiyuki, IMAMURA Kuniyasu, KANEKO Akihiro, KURIHARA Noriyuki, and HOSOKAWA Mizuhiko

According to the theory of general relativity, the proper frequency of the clocks in lower altitude becomes lower than that in higher altitude, because of the effect of gravity. This phenomenon is called as gravitational red shift. We have transported some Cesium clocks from CRL Tokyo headquarters to two LF frequency standard stations, Mt. Ootakadoya and Mt. Hagane. The altitudes between the headquarters and the stations differ by several hundred meters. The frequencies of the clocks before and after the transportation were measured. Averages of the observed shifts for these two stations are about $+7.7\times10^{-14}$ and $+13.0\times10^{-14}$, respectively, which show the good agreement with the theoretically expected shifts of $+7.8\times10^{-14}$ and $+9.0\times10^{-14}$, respectively.

Keywords

Gravitational red shift, Cesium frequency standard, Portable clock, GPS (Global Positioning System) common view method

1 Introduction

The theory of general relativity is important in understanding various physical phenomena, and today has become indispensable as a basic theory of precise space and time measurement. The gravitational red shift is one of the important relativistic effects. In the detection of this shift, accuracy and frequency stability are critical. In the past, a number of well-known experiments used rockets and aircraft to detect relativistic effects, including the gravitational red shift, using an atomic frequency standard[1][2]. In one case, detection was performed by Iijima et al. in Japan in conjunction with transportation of atomic clocks to Mt. Norikura aboard a vehicle[3]. For details of the theoretical aspects of this phenomenon, please refer to paper 2-3, "Relativistic Effects in Time and Frequency Standards," in this special issue [4].

At Koganei headquarters, a highly stable frequency standard with a stability in the order of 10^{-14} is generated, and frequency comparison featuring precision in the order of 10^{-15} is routinely performed using cesium frequency standards (clocks featuring excellent frequency stability) and the GPS common-view method of time transfer. Moreover, recently, LF frequency standard stations have been established with cesium frequency standards near the summits of Mt. Ootakadoya in Fukushima prefecture and Mt. Hagane, located on the border between Fukuoka and Saga prefectures[5]. Taking advantage of the opportunity offered by the transportation of the atomic clocks from the Koganei headquarters in preparation for the establishment and operation of these stations, we endeavored to observe the gravitational red shift by analyzing data obtained in the course of transportation[6][7]. Data were obtained in the course of routine maintenance and operation, including the regular publication of Japan Standard

Time by the Koganei headquarters.

This paper reports on the actual measurement results of the gravitational red shift (frequency shift) of these cesium frequency standards. In Section **2**, the basic principles will be briefly introduced and a theoretical value for the frequency variation will be calculated. In Section **3**, outlines of apparatuses and facilities used for this measurement, transportation of the clocks, and other details will be given. The data obtained will be analyzed in Section **4** and the results will be summarized.

2 Principle of gravitational red shift and theoretical value

According to the theory of general relativity, the gravitational red shift causes a clock placed at a lower altitude, where gravity is strong, to run more slowly than a clock placed at a higher altitude, where gravity is weaker (Fig.1). In other words, the time generated by a frequency standard is affected by position-dependent changes in the gravitational potential. As described in a separate paper (**2-3** [4]) in this special issue, this is attributed to the fact that the gravitational potential bends space and time, affecting the values of metric tensor components.

The frequency shift caused by gravity in the movement of a clock near the Earth's surface is expressed by the following equation, based on the theory of general relativity.

$$\Delta f / f = 1.1 \times 10^{-16} \Delta h \qquad (1)$$

where $\Delta f/f$ is the frequency shift and Δh (in units of m) is the difference in altitude before and after transportation[8]. (1) Table 1 shows the theoretical values of the gravitational red shift calculated using equation (1) from the difference in altitude between the clock room at Koganei headquarters (Koganei-shi, Tokyo; geoid surface altitude of 84 m above geoid surface) and the clock rooms in which the atomic clocks of the respective LF frequency standard stations are kept. As can be seen from the results of this equation, the value of the expected gravitational red shift is close to 10^{-13}, which is considered sufficiently detectable.

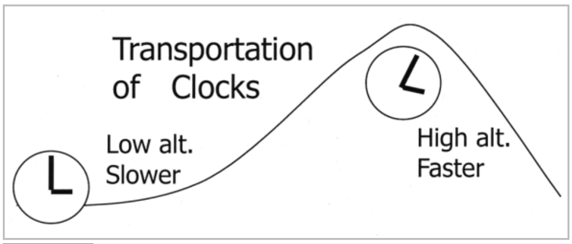

Fig.1 Effect of difference in altitude on the frequency of a clock

3 Outline of experiment

3.1 Measurement principles

An overview of the procedures we used in the experiments to detect gravitational red shift is as follows. First, at the Koganei headquarters, the frequency difference Δf_1 between the frequency of the cesium frequency standard to be transported $f_{clock}(h_1, \tau_1)$ and the reference frequency $f_{ref}(\tau_1)$ was measured.

$$\Delta f_1 = f_{clock}(h_1, \tau_1) - f_{ref}(\tau_1) \qquad (2\text{-}1)$$

where h_1 represents the altitude of the Koganei headquarters and τ_1 is the measurement period. Next, the cesium frequency standard was transported to the LF frequency standard station, and the same measurement was performed to obtain Δf_2.

$$\Delta f_2 = f_{clock}(h_2, \tau_2) - f_{ref}(\tau_2) \qquad (2\text{-}2)$$

where h_2 is the altitude of the Koganei headquarters and τ_2 is the measurement period. Coordinated Universal Time (UTC) was adopted as the frequency reference standard, as will be described later.

The gravitational red shift $\Delta f_{r.s}$ is expressed by the following equation using equations

Table 1 Theoretical value of gravitational red shift

	Mt. Ootakadoya	Mt. Hagane
Altitude from CRL Tokyo(84m)	710 m	816 m
Gravitational red shift (Frequency shift)	$+7.8 \times 10^{-14}$	$+9.0 \times 10^{-14}$

(2-2), (2-1).

$$\Delta f_{r.s} = f_{clock}(h_2,\tau_2) - f_{clock}(h_1,\tau_2)$$

$$= \{\Delta f_2 - \Delta f_1\} + \{f_{clock}(h_1,\tau_1) - f_{clock}(h_1,\tau_2)\} \quad + \{f_{ref}(\tau_2) - f_{ref}(\tau_1)\} \quad (3)$$

where $f_{\mathrm{clock}}(h_1, \tau_2)$ is the assumed frequency of the cesium frequency standard were it to have remained at the Koganei headquarters during the measurement period τ in question. In order to detect the gravitational red shift, measurement errors in the terms on the right side of the equation (3) must be sufficiently small relative to the assumed extent of gravitational red shift (approximately 10^{-13}).

3.2 Estimation of measurement errors

3.2.1 Measurement system

Δf_1 and Δf_2 were measured as follows.

At the Koganei headquarters, time differences among one-second signals generated by 12 cesium frequency standards are measured every four hours directly by a time interval counter. The Koganei headquarters generates UTC (CRL) based on the obtained time-difference data. For details on the system for generating UTC (CRL), please refer to paper **5-1** [9] of this special issue. The time differences among UTC (CRL) and 12 cesium frequency standards are also measured every four hours. From these time differences, the frequency of UTC (CRL) $f_{UTC(CRL)}(\tau_1)$ is calculated, while the frequency of UTC serving as a reference $f_{ref}(\tau_1)$ is estimated from a report referred to as the "Circular T," which is published by the Bureau International des Poids et Mesures (BIPM).

Equation (2-1) is replaced with the following equation.

$$\Delta f_1 = \{f_{clock}(h_1,\tau_1) - f_{UTC(CRL)}(\tau_1)\} - \{f_{UTC(CRL)}(\tau_1) - f_{ref}(\tau_1)\} \qquad (4)$$

Error in the first term on the right side of equation (4) comes from the time interval counter measurement of one-second signals (with a measuring resolution of 30 ps), and this measurement error in the indicated term is on the order of 0.1 ns. If the measurement period is set to 20 days, measurement error will become 0.6×10^{-16} due to frequency conversion.

Error in the second term on the right side of equation (4) is the comparison error of UTC (CRL) and UTC. According to the Circular T from the BIPM, the precision of the international frequency link[10] is about 1.5×10^{-15} for a 20-day averaging time.

Measurement performed at the LF frequency standard stations is the same as that performed at Koganei headquarters, enabling GPS (Global Positioning System) common-view comparison between the values for the Koganei headquarters and individual LF frequency standard stations. For further details, please refer to paper **4-2**[11] of this special issue.

In both LF frequency standard stations, one of the cesium frequency standards is used as a reference oscillator for the long-wave standard wave. Coordinated Universal Times of the Ootakadoya LF frequency standard station and of the Hagane LF frequency standard station, generated based on these frequency standards, are referred to as UTC (Fukushima) and UTC (Kyushu), respectively (Table 2).

The frequencies of the cesium frequency standard after transportation, UTC (Fukushima) or UTC (Kyushu), UTC (CRL), and UTC are represented as $f_{clock}(h_2,\tau_2)$, $f_{UTC(LF)}(\tau_2)$, $f_{UTC(CRL)}(\tau_2)$, and $f_{ref}(\tau_2)$, respectively, Δf_2 is expressed by the following equation.

$$\Delta f_2 = \{f_{clock}(h_2,\tau_2) - f_{UTC(LF)}(\tau_2)\} - \{f_{UTC(LF)}(\tau_2) - f_{UTC(CRL)}(\tau_2)\}$$

$$- \{f_{UTC(CRL)}(\tau_2) - f_{ref}(\tau_2)\} \qquad (5)$$

An error in the first term on the right side of equation (5) comes from the time interval counter measurement of one-second signals, as in the case of the equation (4), and the measurement error of this term is in the order of 0.1 ns, which results in a frequency equivalent of 0.6×10^{-16} (20-day averaging).

The second term on the right side of equation (5) is the result of GPS common-view comparison between the Koganei headquarters and one of the LF frequency standard stations.

The error is about 1.5×10^{-15} (with 20-day averaging), equivalent to the precision of the international frequency link, as in the case of equation (4).

The third term on the right side of equation (5) is the comparison error between UTC (CRL) and UTC; this error is about 1.5×10^{-15} (20-day averaging), equivalent to the precision of the international frequency link, as with the second term.

Therefore, the error in the first term of equation (3) is expressed by the square root of the sum of squares of the first and second terms of equation (4) and the first, second, and third terms of equation (5), which becomes 2.6×10^{-15}; sufficiently small compared with the expected amount of gravitational red shift.

3.2.2 Cesium frequency standard

The cesium frequency standards used were the 5071A model from Agilent Technologies. Either a high-performance tube or a normal tube can be used as the beam tube of this type of cesium frequency standard. The high-performance tube is superior in stability, but the normal tube excels in economical efficiency and long life. Fig.2 shows the catalog specification values[12] and actual measurement values of their frequency stability. Although the values of the normal tube are around two or three times worse than those of the high-performance tube, it is very likely that stability of about 10^{-14} may be obtained if averaging of actual measurement values is performed for 20 days or more. This provides sufficient stability for the detection of the gravitational red shift. Therefore, the error in the second term on the right side of the equation (3) is sufficiently small.

At the Koganei headquarters, 12 cesium frequency standards with high-performance tubes are in operation, generating the standard time UTC (CRL)[9]. The clock rooms in which the cesium frequency standards are kept are temperature-controlled to 23±0.5˚C; they are also shielded from electromagnetic fields, and provided with a fail-safe power supply system.

Three cesium frequency standards using normal tubes are installed at the Ootakadoya and Hagane LF frequency standard facilities and are used as time and frequency references for the long-wavelength band standard wave. The clock rooms are temperature-controlled to 25±0.5˚C, and shielding is provided here as well against electromagnetic fields.

The catalog specification value[12] of the temperature characteristics of the cesium frequency standard is 1.8×10^{-15}/˚C for the normal tube and 1.5×10^{-15}/˚C for the high-performance tube in the temperature range from 0 to 55 ˚C. Fig.3 shows one example of the measured temperature characteristics for the 5071A

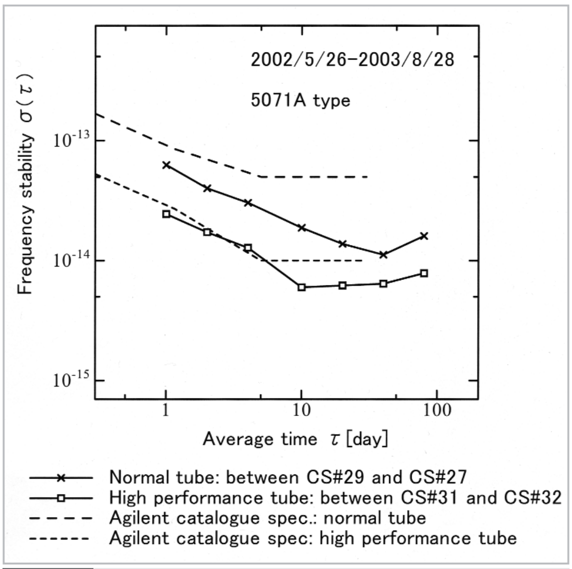

Fig.2 Stabilities of frequency standards

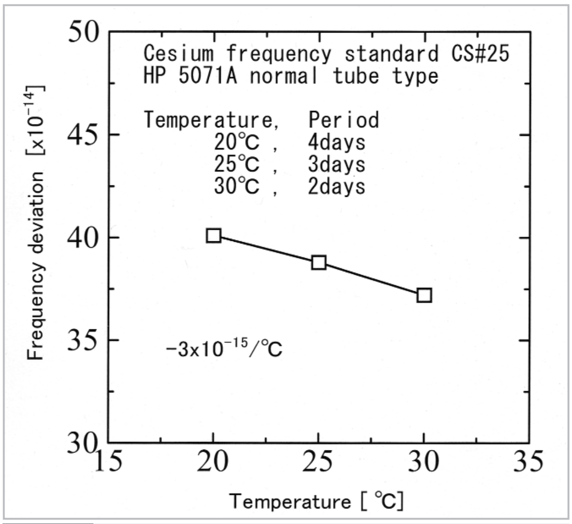

Fig.3 Temperature characteristics of frequency standard

with a normal tube. Based on this measurement, the temperature coefficient was calculated as -3×10^{-15}/°C. Since the temperature change in the vicinity of the frequency standard before and after transportation was 2°C, the effect of temperature change is estimated as -6×10^{-15}. This estimated temperature effect is of a lesser order than the detection frequency of the theoretically predicted gravitational red shift. Therefore, the error in the second term on the right side of the equation (3) is sufficiently small.

3.2.3 Reference frequency

In order to measure the variation in frequency, it is necessary to prepare a frequency reference sufficiently stable with respect to the variation to be measured. UTC (CRL) is in principle a good candidate. However, UTC (CRL) is used not only as a frequency standard but also as a time standard, and it is subject to frequency adjustment on the order of 10^{-14} depending on its deviation from UTC. This reference is therefore not ideal.

The UTC itself—the international standard for time and frequency—may act as a bridge between UTC (CRL) and the variation to be measured. UTC is a highly precise standard that has attained frequency stability in the order of 10^{-16} and accuracy of approximately 2×10^{-15} with the help of primary frequency standards of multiple countries and an averaging time of 30 days. However, time data can only be obtained every five days, and the accuracy of the international frequency link is about 6×10^{-15} with a five-day averaging time, as described above; these characteristics are somewhat problematic. However, with 20-day averaging, stability of 1.5×10^{-15} may be expected.

As another possible candidate, a method is available whereby only the frequency of the Koganei headquarters cesium frequency standards are averaged for better stability and used as a reference. It has been shown in other research that with this method, a frequency reference as stable as on the order of 5×10^{-15} could be obtained by five-day averaging by establishing an ensemble of 10 to 12 atomic frequency standards which undergo equivalent weighted averaging[13]. With 20-day averaging, a stability of 2.5×10^{-15} could be expected. This ensemble time system is hereinafter referred to as the EWE (Equal Weight Ensemble).

As discussed above, error of any frequency reference standard is estimated to be smaller than the assumed amount of the gravitational red shift, or less than approximately 10^{-13}. Therefore, both UTC and EWE will be selected and analyzed as potential frequency references for measurement, and the results will be compared.

3.2.4 Other effects

In addition to the above-mentioned measurement errors, errors caused by temperature variation during the transportation of the cesium frequency standard and variation in the magnetic field were expected. Since temperature data during transportation and the magnetic-field data for the clock rooms were not available, it was impossible to estimate these error values, but these errors were considered to be sufficiently small based on the catalog specification values[12]. In Section **4.2**, these

Table 2 *Altitude, latitude and longitude of three stations*

	Tokyo Koganei CRL	Fukushima Mt. Ootakadoya	Kyushu Mt. Hagane
Altitude	84m	794m	900m
Latitude Longitude	N 35 deg 42'24" E139 deg 29'19"	N 37 deg 22'10" E140 deg 51'09"	N 33 deg 27'56" E130 deg 10'34"
Straight line distance	---	238 km	1066 km
UTC(k)	UTC(CRL)	UTC(Fukushima)	UTC(Kyushu)

Table 3 Conditions of the transportations

Clock ID	Beam tube type	Transportation course	Necessary time	Transportation date
CS#28	Normal	CRL→ Mt. Ootakadoya	5hours	2000 April 27
CS#30	Normal	CRL→ Mt. Hagane	2days	2001 May 22
CS#25	Normal	CRL→ Mt. Hagane	2days	2001 July 21
CS#26	Normal	CRL→ Mt. Hagane	2days	2001 July 21
CS#31	High perform.	CRL→ Mt. Ootakadoya	5hours	2002 April 24
CS#31	High perform.	Mt. Ootakadoya→CRL	3hours	2002 May 23

effects will be estimated by statistical analysis using actual measurement results.

3.3 Outline of transportation

Geographical specifications of the Koganei headquarters, the Mt. Ootakadoya LF frequency standard station, and the Mt. Hagane LF frequency standard station involved in the experiment are shown in Table 2, and an outline of the transportation (cesium beam tube type, travel route, time traveled, and date of transportation) are shown in Table 3.

Trucks were used to transport all of the standards, and during transportation the cesium frequency standards were connected to batteries and were run continuously. The truck used toll expressways for a major part of the distance traveled, and the speed of the truck was 100 km/h on these expressways. It took two days for the truck to transport the 5071A standards from the Koganei headquarters to the Mt. Hagane LF frequency standard station, since the distance is over 1,100 km on the expressways alone. This was the first attempt by the CRL to transport the 5071A standards over a long distance by truck.

Furthermore, in 2002, transport was carried out between the Koganei headquarters and the Mt. Ootakadoya LF frequency standard station, which was remarkable in two respects: It was the first time for CRL to transport the 5071A cesium frequency standards with high performance tubes, and it was the first time to conduct two-way transport.

4 Comparison between experimental results and theory

4.1 Frequencies before and after transportation

Based on the transportation experiments shown in Table 3, variation in the time difference between the CS#30 and UTC before and after transportation to the Mt. Hagane LF frequency standard station was obtained (see Fig.4), and that for the CS#31 and UTC before and after transportation to the Mt. Ootakadoya LF frequency standard station (see Fig.5). In Fig.4, gaps extend over the course of approximately two months, because the CS#30 cesium frequency standard was lent out for manufacturer testing and the measurement system was not available before the opening of the Mt. Hagane LF frequency standard station.

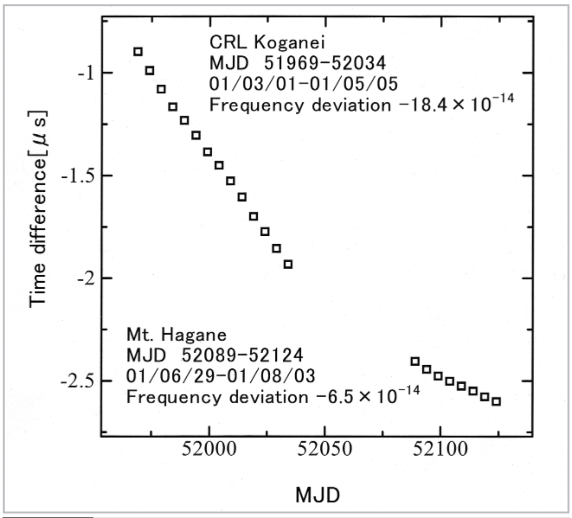

Fig.4 Time difference between CS#30 and UTC: in the case to Mt. Hagane

In Fig.4 and Fig.5, the rate of change in time difference, i.e., the gradient in the graph, shows a frequency deviation. The frequency

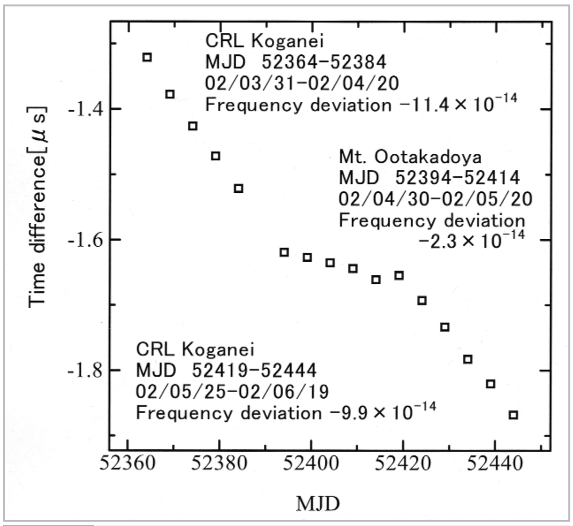

Fig.5 *Time difference between CS#31 and UTC: in the case to and from Mt. Ootakadoya*

deviations between the CS#30 and UTC before and after transportation to Mt. Hagane were -18.4×10^{-14} and -6.5×10^{-14}, respectively, resulting in a frequency shift of $+11.9\times10^{-14}$ (Fig.4). The frequency deviations between the CS#31 and UTC before and after the transportation to Mt. Ootakadoya (outbound trip) were -11.4×10^{-14} and -2.3×10^{-14}, respectively, resulting in a frequency shift of $+9.1\times10^{-14}$ (Fig.5). Furthermore, the frequency deviations between the CS#31 and UTC before and after transportation from Mt. Ootakadoya (return trip) were -2.3×10^{-14} and -9.9×10^{-14}, respectively, resulting in a frequency shift of $+7.6\times10^{-14}$ (Fig.5). These values indicate that the frequency deviation relative to standard UTC clearly changed in the course of transportation.

4.2 Comparison with theoretical values

A comparison between theoretical and measured values of the gravitational red shift for the Mt. Hagane LF frequency standard station and for the Mt. Ootakadoya LF frequency standard station are shown in Table 4. The table illustrates both the case in which UTC was used as the reference for the time difference and the case in which the EWE was used, as described above. The difference in the frequency-shift value between these two references was $\pm0.9\times10^{-14}$. These frequency shifts are in good agreement with values expected from estimations of the respective stabilities, which indicates that these frequency standards may serve equally well as excellent reference standards. In the following analysis, UTC is chosen as a typical reference.

The difference between the measured value (CS#30) and the theoretical value in transportation to the Hagane LF frequency standard station was $+2.9\times10^{-14}$. Due to natural occurrences preventing travel during transport to the LF frequency standard station in June 2001, the CS#25 and CS#26 were returned to the Koganei headquarters temporarily, and then successfully transported again to the LF frequency standard station in July. It can be surmised that the thermal environment during actual transportation in July was subject to rougher variation than in the clock rooms. The reason for the large error between measured values at this time and theoretical values is attributable to the effects of the thermal environment during the two days of transportation from Tokyo to Fukuoka prefecture. The average of the six measurements

Table 4 *Comparison of frequency shift value between theoretical and measured values*

Clock ID	$\Delta f_{r.s}$ (Ref. EWE)	$\Delta f_{r.s}$ (Ref. UTC)	$\Delta f_{r.s}$ (Theoretical value)
CS#25	19.7	20.2	Mt. Hagane
CS#26	6.3	7.2	
CS#30	12.6	11.9 (see Fig. 4)	9.0
CS#28	6.4	6.2	Mt. Ootakadoya
CS#31(go)	8.8	9.1 (see Fig. 5)	
CS#31(return)	8.2	7.6 (see Fig. 5)	7.8

of the Mt. Hagane LF frequency standard station shown in Table 4 is $+13.0\times10^{-14}$, which differs from the theoretical value by $+4.0\times10^{-14}$.

The difference between the measured value at the Mt. Ootakadoya LF frequency standard station (CS#31; round-trip average: $+8.4\times10^{-14}$) and the theoretical value was $+0.6\times10^{-14}$. Since the CS#31 uses a high-performance cesium beam tube, its performance is approximately three times better in terms of frequency stability (one day) than that of a CS#28 with a normal tube[12]. The average of the six measurements for the Mt. Ootakadoya LF frequency standard station shown in Table 4 is $+7.7\times10^{-14}$, differing from the theoretical value by -0.1×10^{-14}, showing extremely excellent agreement. These results thus indicate that the difference between the measured value and the theoretical value in the case of transportation to the Mt. Ootakadoya LF frequency standard station was smaller than in the case of transportation to the Mt. Hagane LF frequency standard station. This difference in observed precision is assumed to be attributable to the different transportation times involved (and the resultant differences in thermal environments).

Further errors caused by temperature, magnetic fields, and vibration during transportation cannot be estimated due to lack of relevant data. However, when these errors are estimated based on the catalog specification values of the 5071A cesium frequency standard and the maximum assumed environmental change, each of these errors is shown to be smaller than approximately 10^{-13}. More specifically, it can be assumed that the error value of the Mt. Ootakadoya LF frequency standard station is smaller than that of the Mt. Hagane LF frequency standard station because the former involves a shorter transportation distance and therefore the clock can be transported more quickly. Measurement results support this hypothesis.

5 Concluding remarks

Taking advantage of the transportation of the atomic frequency standards to LF frequency standard stations, we attempted to detect gravitational red shift in the atomic frequency standards based on data obtained before and after transportations. Although results varied depending on the specific conditions of transportation, it was clear that in the case of transportation to the Mt. Ootakadoya LF frequency standard station (a relatively easy trip), measured and theoretical values nearly agree, while in the case of the Mt. Hagane LF frequency standard station (involving longer travel), measured and theoretical values differ by about 4×10^{-14}; an error equivalent to nearly half of the theoretical value itself. According to observation results, deviations were noted among measured values, depending on the cesium frequency standard used. Potential causes include changes in environmental conditions around the clock during transportation (i.e., variations in temperature and magnetic field), vibrations, methods of establishing a reference for the calculation of time difference data during transportation, and more; further analysis in this area is thus required.

To summarize, the system for generating, maintaining, and supplying Japanese Standard Time is highly precise and highly stable, and is sufficient to detect the gravitational red shift with a frequency variation of the order of 10^{-14}. Now that the theory of relativity has been demonstrated in a number of experiments, our detection of the gravitational red shift does not carry much scientific novelty; however, considering that it was extremely difficult to detect this effect only 40 years ago, we cannot fail to note the enormous progress in the technology of time and frequency standards. In addition, it is extremely significant that in the course of this research, methods of daily routine work were re-confirmed through the detection of this effect, and the limits of the accuracies of the comparison and the measurement of the time and frequency were investigated in many processes.

We intend to continue to improve the precision and reliability of Japan Standard Time, and will work to improve techniques of measurement and data analysis, so that we will have the tools to measure a given cesium frequency standard to the maximum limit of precision whenever similar transportation opportunities arise.

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KOTAKE Noboru

Researcher, Japan Standard Time Group, Applied Research and Standards Division

Time and Frequency Standard

SHIMIZU Yoshiyuki

Visiting Researcher, Japan Standard Time Group, Applied Research and Standards Division

IMAMURA Kuniyasu

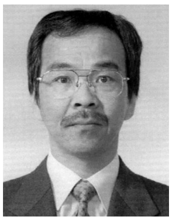
Senior Researcher, Japan Standard Time Group, Applied Research and Standards Division

Time and Frequency Standards

KANEKO Akihiro

Reseacher, Time Stamp Platform Group, Applied Research and Standards Division

Standard Time and Frequency



KURIHARA Noriyuki

Leader, Japan Standard Time Group, Applied Research and Standards Division

Time and Frequency Standards, Space Measurement

***HOSOKAWA Mizuhiko**, Ph. D.*

Leader, Atomic Frequency Standards Group, Applied Research and Standards Division

Atomic Frequency Standards, Space Time Measurements