Status Report to the 21st meeting of the CCTF on Time and Frequency Activities at KRISS

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1. Atomic Fountain Frequency Standard

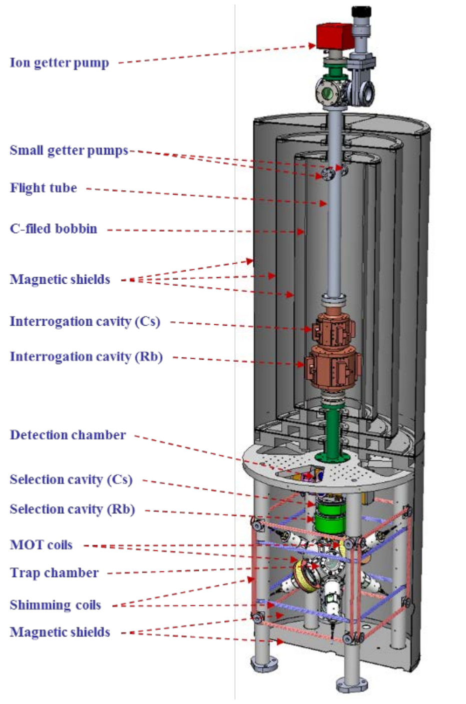

Fig. 1. Cs/Rb dual foutain clock at KRISS

KRISS is developing an atomic fountain frequency standard, KRISS-F1. The atomic fountain clock at KRISS is a Rb/Cs double fountain [1]. We will trap two species of atoms simultaneously with cooling laser beams of (111)-geometry. However, as the laser system only for cesium was presently prepared, we have been experimenting with a Cs fountain. Cs atoms are trapped and cooled with MOT and optical molasses, respectively. We installed two cylindrical TE_{011} cavities for ^{133}Cs and ^{87}Rb interrogation that are newly designed to minimize the distributed cavity phase (DCP) shift error collaborating with The Pennsylvania State University [2, 3]. We are currently evaluating the cold collision and DCP shifts for an accuracy evaluation of the Cs fountain standard. We aim for a total uncertainty of KRISS-F1(Cs) at the low 10^{-16} level. After completing accuracy evaluation of the atomic fountain, we hope it will contribute to the generation of TAI and be used as a reference standard for frequency comparison of an Yb optical lattice clock under development at KRISS.

2. Optical Frequency Standard

After the 20th meeting of CCTF, there have been significant improvements to reduce the systematic uncertainty of the Yb lattice clock at KRISS. The optical lattice was formed by a build-up cavity (finesse ~220) to enhance the maximum lattice trap depth (U_0) up to ~2500 E_r, where E_r is the recoil energy. This will be beneficial for a better evaluation of the hyper-polarizability shift. The signal-to-noise ratio of the probe light fluorescence at 399 nm has been enhanced by using a lens at nearer distance from the lattice trap and also by the black coating (Aquadag) at the inner surface of the main chamber. A flag-type atom shutter based on a rotating lever that is driven by a bender piezoelectric actuator was developed, and was installed in the

Yb lattice clock [4].

We measured the differential shift by interleaving the high (335(3) E_r) and low (161(2) E_r) lattice depth for each frequency of the lattice light to evaluate the lattice light shift. The magic frequency for the electric dipole (E1) polarizability was determined to be 394 798 264.7(84) MHz. The E1 lattice shift was 82(18) mHz considering that the operating condition for the lattice laser was at 394 798 222.9 MHz, U_0 = 163(2) E_r, and the average vibrational quantum number $\bar{n}$ = 1.1(1). The nonlinear light shift was estimated to be 35(19) mHz, by using the measured values of U_0, $\bar{n}$, and the known values of the multipolar polarizability coefficient and the hyperpolarizability coefficient. To evaluate the collisional frequency shift at the atomic density ρ, we alternated the high and low atomic density by changing the Zeeman slowing laser power. The density shift could be fitted to $-55(12)$ mHz $\times\, \rho/\rho_0$, where ρ_0= 1×10^9/cm^3. The operating condition for the atomic density was $7(4)\times10^8$/cm^3, thus, the shift was estimated to be -38(21) mHz. The details of the other systematic uncertainty evaluation was reported in Ref. [5]. The uncertainty budget for the absolute frequency measurement in 2016 is summarized in Table 1 [5]. The current total systematic uncertainty of the Yb lattice clock at KRISS has decreased to 1.1×10^{-16}. Currently, the experimental setup is being modified, aiming at the 10^{-17} uncertainty level. We have a plan to measure the frequency shift coefficients for a fully independent frequency uncertainty evaluation. For example, the coefficient of the Quadratic Zeeman shift has been measured to be -6.74(13) Hz/mT^2 with the uncertainty of the coefficient has been reduced by a factor of 7 compared to the previously reported value.

The absolute frequency of the clock transition ($^1S_0$–$^3P_0$) of ^{171}Yb atom referenced to the SI second was measured during ten consecutive days from MJD 57734 to MJD 57743 [5]. The clock operation covers 34% of the total measurement duration. The relative frequency offset of the hydrogen maser, which was used as a frequency reference of the optical frequency comb, from TAI (International Atomic Time) was calculated by using BIPM Circular-T No. 348 and the time comparison data between the hydrogen maser and UTC(KRIS). As summarized in Table I, the absolute frequency of the clock transition relative to the SI second was determined to be 518 295 836 590 863.38(57) Hz whose uncertainty was dominated by the link to TAI. The measured absolute frequency value in this work agrees well with the CIPM recommendation in 2015 with the uncertainty decreased by 14-fold compared with our previous measurement in 2013 [6].

Also, the measured absolute frequency has been confirmed by a direct comparison with a ^{87}Sr lattice clock at National Institute of Information and Communications Technology (NICT) in Japan via a carrier-phase two-way satellite time and frequency transfer technique. The measured frequency ratio was in a good agreement with the calculated value using each absolute frequency within the total uncertainty, the result of which will be presented in EFTF2017 [7].

The systematic uncertainty limit of the current Yb lattice clock is expected to be about 5×10^{-17} due to the BBR shift. To overcome this limit and for the systematic uncertainty level of 10^{-18}, we have designed a new

Yb optical lattice system, and this is currently being constructed. The key idea is to adopt a blackbody-like spectroscopy chamber, the temperature of which is actively controlled at the outer surface of the vacuum chamber. The temperature distribution homogeneity was measured to be as small as 20 mK, which corresponds to the BBR shift uncertainty level of 10^{-18} [8]. This spectroscopy chamber has also ITO coatings at the BK7 windows to shield the stray electric field and to evaluate the DC Stark shift.

A clock laser system with 10^{-16} relative frequency stability was designed to enable rapid uncertainty evaluation of KRISS Yb optical lattice clock. A ULE cuboid-type 30-cm-long cavity was adopted with fused silica mirrors and mirror coating material with low thermal noise. The vertical, longitudinal, transverse vibration sensitivity was calculated by finite element analysis to determine the optimum support position [9].

An erbium-doped fiber comb was stabilized to the clock laser at 578 nm by using an electro optical modulator (EOM) inside the fs laser cavity. The stability of the repetition frequency of this optical comb was compared to the synthesized RF frequency from a cryogenic sapphire oscillator (CSO), which will be used as a local oscillator of Cs fountain clock, and a stability of 5×10^{-15} at 1 s average time was obtained [10]. This will be beneficial for rapid absolute frequency measurement by the Cs fountain clock.

Table I. Uncertainty budget for the absolute frequency measurement of the ^{171}Yb clock transition.

Effect	Relative Shift $\times10^{-16}$	Relative Uncertainty $\times10^{-16}$
Lattice ac Stark (scalar)	1.6	0.4
Nonlinear lattice shift	0.7	0.4
Density shift	-0.7	0.4
Blackbody radiation	-23.3	0.6
Second-order Zeeman	-10.2	1.5
Probe light	0.2	0.04
AOM phase chirp	-	0.03
Servo error	-	0.7
Static Stark shift	-	0.1
Yb total	-31.8	1.8
Statistics	-	4.0
Gravitational red shift	81.4	0.3
H-maser dead-time	-	5.0
H-maser - TAI	945.8	6.5
TAI dead-time	-	5.2
TAI - TT	-12.4	2.2
Total	983.0	10.9

3. Time and Frequency Transfer

In order to contribute to the generation of TAI and keep UTC(KRIS) traceable to UTC, KRISS is operating GNSS and TWSTFT time transfer systems. Time transfers using P3 code, precise point positioning, and C/A code of GNSS are being carried out with two Ashtech Z12T receivers, a Septentrio PolaRX2eTR, two Septentrio PolaRX3eTR and a multi-channel GPS receivers (Topcon Euro-80) (Fig. 2). Recently, three Dicom GTR51 and one PikTime TTS-4 GNSS receivers were introduced for time transfer using GPS, GLONASS, GALILEO and SBAS (or WAAS). It is highly expected that the Dicom GTR51 or PikTime TTS-4 receivers will play the main role of the time comparisons substituting for current Ashtech Z12T in the near future. For this purpose, we performed the GNSS receiver calibration campaign prepared by BIPM for a Dicom GTR51 and a PikTime TTS-4 receivers. The calibration results will be provided sooner or later. After calibrate the two receivers by using the calibration results, we will execute some experiments and replace the Ashtech Z12T. The GIPSY-OASIS II Ver.6.1 software is currently used for PPP computations and it was used to compare the frequencies of optical clocks between KRISS and NICT. Also, we operated Bernese Ver. 5.2 for GPS and Galileo CPs and the Bernese software will be used to calculate ray-path ionospheric delay for increasing time comparing performance of TWSTFT CP by compensating the non-symmetric ionospheric delays between up and down links.

For TWSTFT links, three sets of TWSTFT system configured with SATRE 2-ch modem have been settled in the laboratory and the rooftop of the building. Currently, two sets of the systems are utilizing. One of them is for Asia-link via the Eutelsat-172A (old GE-23) satellite and used not only for TWSTFT system using the SATRE modem but also for the SDR receiver from TL and the TWCP modem from NICT. The other is for Europe-link via the AM22 satellite temporally. Although the antenna is mainly pointed to the AM22 satellite, at now, we carried out a feasibility test using the ABS-2A satellite for the next Eu-Asia link after AM-22 decommission. At present, the time comparison using the Asia-link is performed according to the provided schedule and the results are going to be uploaded to the corresponding BIPM directory. The Europe-link is being carried out various experiments for the selection of the appropriate satellite.

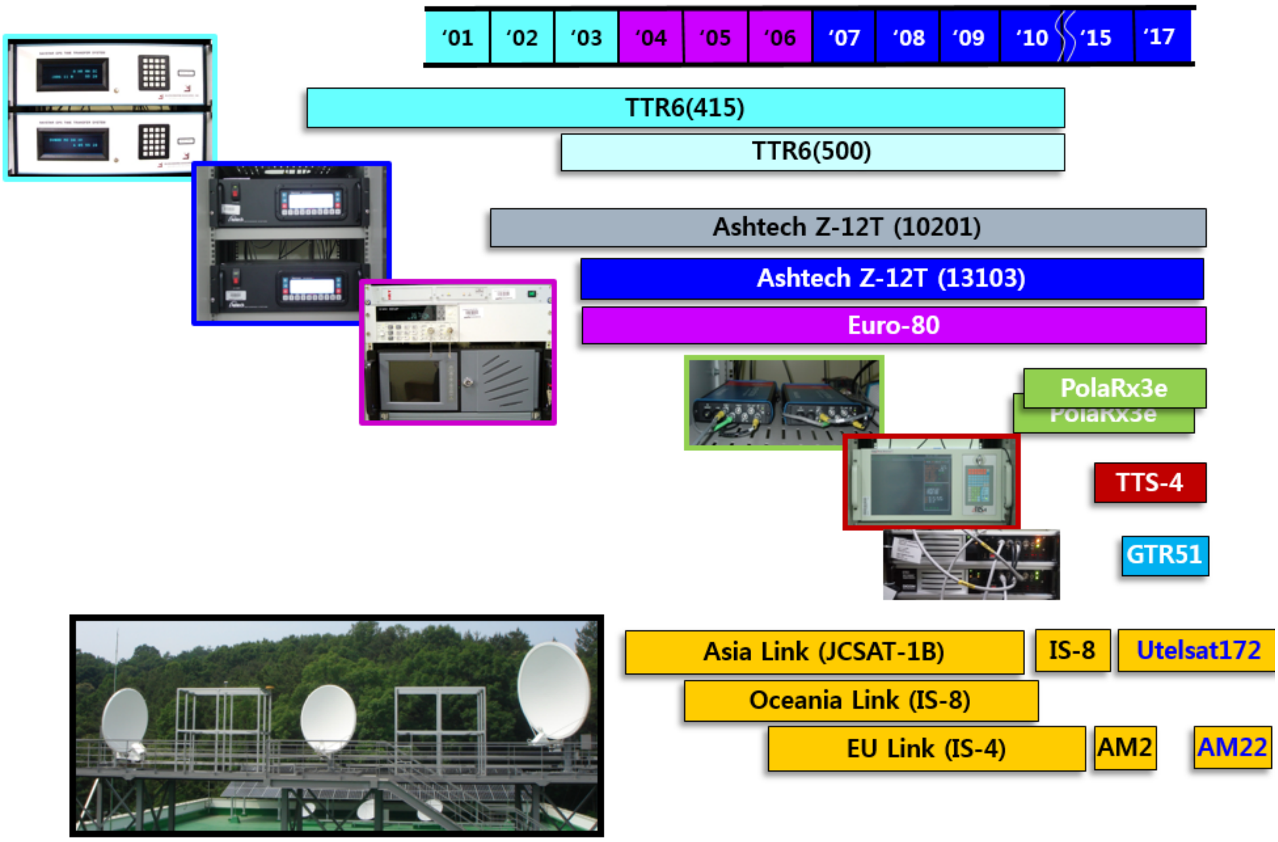

Fig. 2. Time Transfer system at KRISS.

We also implemented a fiber-optic dissemination system of time and frequency between two buildings connected by about 1 km underground optical fiber inside KRISS campus. This optical link was used to confirm stable operations of H-masers relocated to a new building by comparison with H-masers in the old building. For the frequency transfer, the laser intensity is modulated at 1 GHz synthesized from the H-maser and the fiber noise is actively compensated. In case of the time transfer, the commercial time code generator is used to encode timing signals on the laser pulse and the change of propagation delay in the fiber was compensated by post-processing.

For advanced time and frequency transfer, it has been nowadays conceived to use VLBI for space geodesy (operated by National Geographic Information Institute) or SLR (operated by Korea Astronomy and Space Science Institute) which are located about 30 km away from KRISS. Although the delivery of the optical carrier frequency itself has shown best performance in distance and stability, it always requires a frequency comb for the practical use, so we decided to transfer a radio-frequency (RF) to these sites. Because fiber links to these facilities were not established yet, we tested other research fiber network called Korea Research Environment Open Network (KREONET) operated by Korea Institute of Science and Technology

Information (KSITI). It is a pair of 56-km dark fibers going from KRISS to the local station located in the other city (Cheongju-si). This is not a favorable link for the frequency transfer because its one-way loss is as high as 20 dB and most of connectors are PC type, leading to high Fresnel reflections. To avoid unwanted reflections, we used lasers with different wavelength and filtered out unwanted light using optical bandpass filters before the photodetectors. The fractional frequency instability after noise compensation was 5×10^{-14} at an averaging time of 1 s and 1.2×10^{-16} at 1000 s. Recently, we also have a plan to increase the amplifier gain more than 30 dB by using a Fiber Brillouin Amplifier (FBA) for signals passed through about 100 km distance.

4. Dissemination of Time and Frequency

We are operating two NTP time servers and provide a software (UTCk3.1) allowing users to synchronize their computer clocks via the internet. Currently, we limit the number of requests per second below 3000 to avoid the heavy traffic from degrading network capability.

A 5 MHz broadcasting station (call sign: HLA) has been in operation to disseminate Korea Standard Time (KST) and Korea Standard Frequency (KSF) since 1984. Form 2015, we started to build a long-wavelength broadcasting station to disseminate the same timing signal. This project is scheduled for five years to design and build a key system for broadcasting. We completed the design draft to investigate an optimum carrier frequency, modulation technique, infrastructure for broadcasting not only for timing information but also for necessary public information. We are planning to construct a site and station building to broadcast timing and public information nationwide.

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