BIPM Capacity Building & Knowledge Transfer Programme
2025 BIPM - TÜBİTAK UME Project Placement

REPORT

Project Name	Knowledge acquisition and transfer, capacity building and professional development in the creation and operation of a time and frequency standard, Time Dissemination System, time and frequency measurements by various methods
Description	This project is necessary for the profound modernization of the Secondary Standard of Time and Frequency and the reference laboratory, as well as progressive measurement methods taking into account modern world experience
Author, NMI	Oleh Meshcheriak, State Enterprise "All-Ukrainian state research and production center for standardization, metrology, certification and consumers' right protection" (SE "UKRMETRTESTSTANDART"), Ukraine
Mentor at TÜBİTAK UME	Adem Gedik, Dr. Efendi Fidan, Time and Frequency Laboratory, TÜBİTAK UME, Türkiye
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MOTIVATION & INTRODUCTION

The Time and Frequency Laboratory of SE "UKRMETRTESTSTANDART" is one of the leading laboratories in Ukraine in the field of time and frequency measurements. The Laboratory performs verification, calibration, and testing of measuring instruments for other laboratories throughout Ukraine. Currently, the Laboratory requires modernization and replacement of its reference equipment. Figures 1 and 2 show the main components of the Secondary Standard of Time and Frequency Units (ВЕТУ 07-01-03-10), which require partial replacement (or repair) and a modern solution for their operation.

Fig. 1. Atomic clock and Distribution Amplifier Secondary Standard of Time and Frequency Units (ВЕТУ 07-01-03-10)

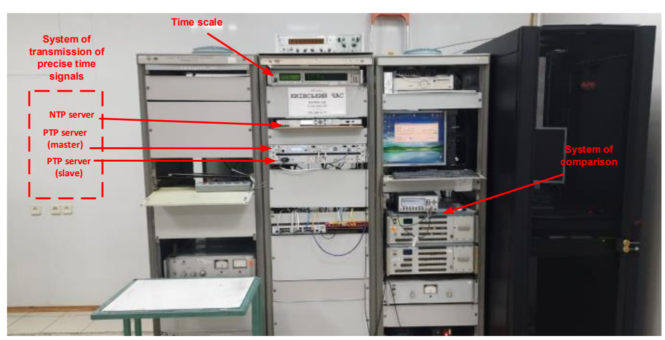


Fig. 2. Time scale system, systems of comparison and transmission of precise time signals Secondary Standard of Time and Frequency Units (ВЕТУ 07-01-03-10)

Project Objectives

The project aimed to acquire new knowledge on modern approaches to building a time and frequency standard using new, commercially available equipment, to master measurement automation in the field of time and frequency, and to master the calibration of rubidium frequency standards using the direct frequency measurement method.

Acquiring this knowledge will enable informed and justified decisions regarding the upgrade of the SE "UKRMETRTESTSTANDART" Secondary Time and Frequency Standard, the replacement of the laboratory's outdated reference base with new modern units, the implementation of automation, the revision of calibration procedures, and the reduction of measurement uncertainty.

RESEARCH

1. Ensuring the Operational Maintenance of the Secondary Standard of Time and Frequency Units (ВЕТУ 07-01-03-10)

During the internship, leveraging the operational experience of the TÜBİTAK UME Time and Frequency Standard (Fig. 3,4), a functional diagram for upgrading the Secondary Standard of Time and Frequency Units (ВЕТУ 07-01-03-10) was developed (Fig. 5).

Fig. 3. TÜBİTAK UME Time and Frequency Standard (General view)

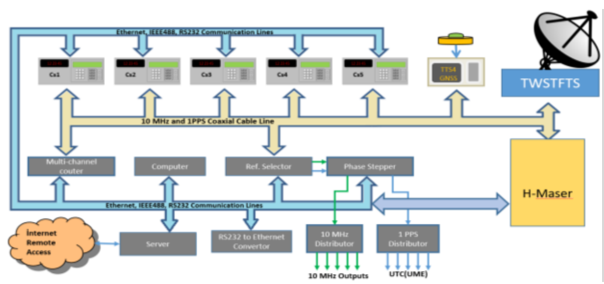


Fig. 4. TÜBİTAK UME Time and Frequency Standard (Functional diagram)

The diagram (Fig. 5) illustrates the main components:

- **Hydrogen Maser** - provides extremely high short-term stability and is used as the master clock; cesium clocks ensure long-term stability.
- **Distribution Amplifier (Frequency and Pulse Distribution System) (first stage)** - ensures proper distribution of signals from the atomic clocks without power loss for subsequent input to the Atomic Time Scale Ensemble System, and also allows the connection of measuring instruments for atomic clock signal verification.
- **Atomic Time Scale Ensemble System** (e.g., Microchip SyncSystem 4380A or a similar system from another manufacturer) is the key element of this solution. It also includes two separate modules: a **Phase Measurement Module** for precise measurement of relative phases/shifts of 5/10 MHz signals and a **Time Interval Counter** for precise measurements of 1 PPS signals and time intervals. Thus, the Atomic Time Scale Ensemble System collects measurements from several "free-running" high-precision clocks (three cesium clocks and the maser), compares them, applies a built-in time scale generation

algorithm (KAS-2), and produces a single, more accurate and stable frequency (time) — superior to any individual member of the ensemble.

- **Time Correction Generator** - a unit that provides correction of the precise time signal after receiving data from comparisons with a higher-level standard (the BIPM bulletin). It is after this unit that precise time signals, synchronized with UTC, are provided to the laboratory's users via a Distribution Amplifier (Frequency and Pulse Distribution System) (second stage) — either through physical cable connections or via the internet using PTP and NTP servers.

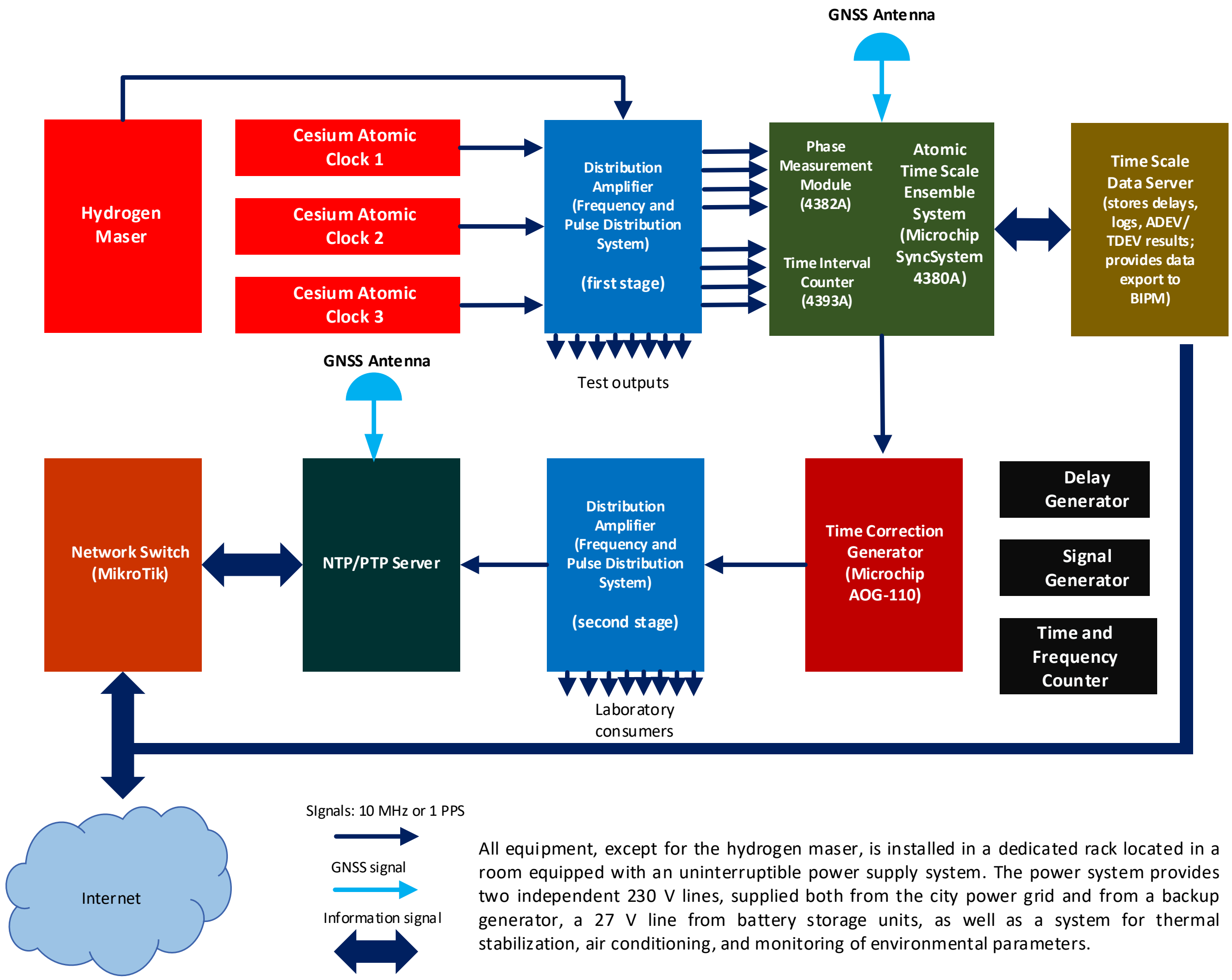


Fig. 5. Upgrade diagram for the Secondary Standard of Time and Frequency Units (ВЕТУ 07-01-03-10)

Thus, the proposed solution is based on a new key component — the **Atomic Time Scale Ensemble System**. It involves the complete replacement of obsolete comparison and time scale systems, which have reached the end of their service life, with modern, higher-performance equipment, making it cost-effective and sufficiently efficient.

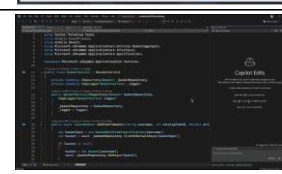
2. Mastering the Automation of Time and Frequency Instrument Calibration

During the internship, the experience of the TÜBİTAK UME Time and Frequency Laboratory in automating the measurement of metrological characteristics for frequency counters, generators, and spectrum analyzers was acquired.

The implementation of automation significantly reduces calibration time, minimizes operator errors, and ensures high measurement repeatability, all of which are critical for enhancing the accuracy and reliability of Calibration and Measurement Capabilities (CMCs).

The principles of automation (three steps) are presented in Table 1.

Table 1. Principles of Measurement Automation

Step	Tools / Technology	Description	Foto
1. Physical Connection	GPIB-USB Cable	Establishes the link between the computer and the instruments.	
2. Communication Layer	NI-VISA Driver	Software standard for device discovery and low-level communication.	
3. Programmatic Control	Python (PyVISA) in MS Visual Studio	Used to write automated code (SCPI commands) for execution of tests and measurements.	

To gain practical experience in automated measurement specifics, under the guidance of mentor Dr. Efendi Fidan, measurements of the metrological characteristics of the instruments listed in Table 2 were performed.

Table 2. Instruments Used for Automated Metrological Measurements

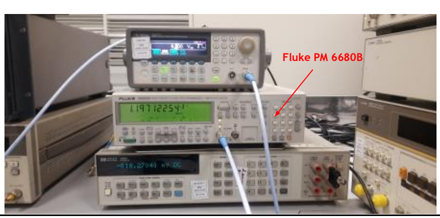
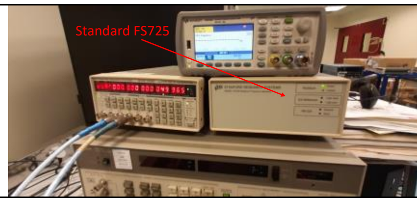
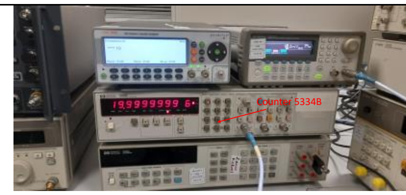
Instrument Name	Photo	Instrument Name	Photo
Fluke PM 6680B High-Resolution Programmable Timer/Counter		Keysight E4440A Spectrum Analyzer	

Table 2. (continuation)

Instrument Name	Photo	Instrument Name	Photo
E8267D PSG Vector Signal Generator (100 kHz to 44 GHz)		AFG31000 Arbitrary Function Generator	
Rubidium Frequency Standard FS725		Universal counter 5334B	

3. Calibration of a Rubidium Frequency Standard Using the Direct Frequency Measurement Method

3.1 At SE "UKRMETRTESTSTANDART," the calibration of rubidium frequency standards is performed not by the direct frequency measurement method, but by comparing the phases of two signals (the reference and the device under test) using a phase comparator, followed by the conversion of phase difference measurement results into frequency characteristics.

Mastering the direct frequency measurement method used by the TÜBİTAK UME Time and Frequency Laboratory will simplify the calibration procedure and eliminate the need to purchase new, expensive phase comparators, as reference frequency counters are already available.

To master this method, a frequency standard model FS725, manufactured by Stanford Research Systems (SRS), USA, was selected (Fig. 6).

The measurements were performed automatically with a 1-second averaging interval, according to the diagram shown in Fig. 7.

Fig. 6. Frequency Standard FS725, manufactured by Stanford Research Systems (SRS), USA

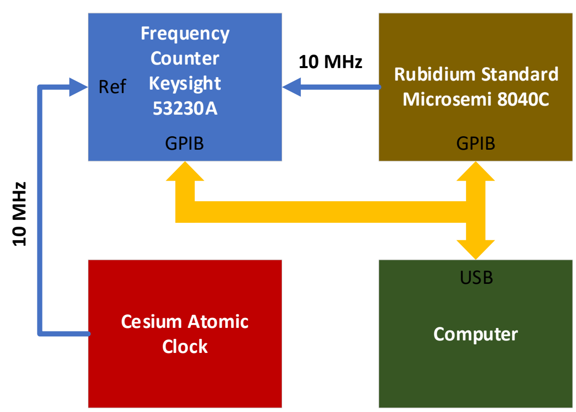


Fig. 7. Frequency variation diagram of the rubidium standard 8040

A total of 298 175 measurements were performed, yielding a mean frequency value of 9 999 999,999 799 Hz and a standard deviation (over 100 s) of 0,000 038 Hz.

3.2 Uncertainty Calculation

The TÜBİTAK UME methodology was used for the uncertainty calculation.

3.2.1 Model function

$$F_x = F_S\left(1 + \frac{\Delta f}{f} + \delta\frac{\Delta f}{f} + \delta F_{SIS} + \delta F_{RES}\right) + \delta F_{DR},$$

where:

F_x: The reported measurement result;

F_S: The average of the values read from the frequency counter;

$\frac{\Delta f}{f}$: The time base accuracy of the frequency counter. Since the counter is locked to the TFS which is traceable to UTC (UME), this value is taken to be zero. The error of the value is transferred into its uncertainty;

$\delta\frac{\Delta f}{f}$: The effect of frequency counter/TFS aging, line voltage and temperature factors. Its value is zero. Its effect is taken into account in the uncertainty value;

δF_{SIS}: The systematic effect of the counter;

δF_{RES}: The resolution effect of the counter. It is also named as the random uncertainty effect;

δF_{DR}: The display resolution of the counter.

3.2.2 Components and Uncertainty Budget

Uncertainty Components:

u_{F_S}: The standard uncertainty resulting from the standard deviation. It is also called repeatability uncertainty. Its distribution is normal;

$u_{\frac{\Delta f}{f}}$: The uncertainty of the time base accuracy of the counter. It is normally distributed. Since the counter is locked to TFS, which is traceable to UTC (UME), this value is obtained from the Circular T data;

$u_{\delta\frac{\Delta f}{f}}$: The uncertainty component of the counter's oscillator, which consists of aging, line voltage and temperature factors. Its distribution is rectangular;

$u_{\delta F_{SIS}}$: The systematic uncertainty of the counter;

$u_{\delta F_{RES}}$: The resolution (random) uncertainty of the counter;

$u_{\delta F_{DR}}$: The display resolution uncertainty. Its distribution is rectangular.

Table 3. Uncertainty budget

	Source of Uncertainty	Value (Hz)	Type	Distribution	Conversion Factor	Standard Uncertainty (Hz)
1	Standard Uncertainty (u_{F_S})	$6{,}77\text{x}10^{-7}$	A	Normal	1	$6{,}77\text{x}10^{-7}$
2	Time Base Accuracy Uncertainty ($u_{\frac{\Delta f}{f}}$)	$1{,}03\text{x}10^{-6}$	B	Normal	1	$1{,}03\text{x}10^{-6}$
3	Uncertainty of Oscillator Aging, Temperature, and Line Voltage Effects ($u_{\delta\frac{\Delta f}{f}}$)	$1{,}01\text{x}10^{-7}$	B	Rectangular	$1/\sqrt{3}$	$5{,}83\text{x}10^{-8}$
4	Systematic Uncertainty $u_{\delta F_{SIS}}$)	$2{,}00\text{x}10^{-7}$	B	Rectangular	$1/\sqrt{3}$	$1{,}15\text{x}10^{-6}$
5	Resolution (Random) Uncertainty ($u_{\delta F_{RES}}$)	$4{,}68\text{x}10^{-7}$	B	Rectangular	$1/\sqrt{3}$	$2{,}70\text{x}10^{-7}$
6	Display Resolution Uncertainty ($u_{\delta F_{DR}}$)	$5{,}00\text{x}10^{-8}$	B	Rectangular	$1/\sqrt{3}$	$2{,}89\text{x}10^{-8}$
Combined Uncertainty		$\sqrt{(u_{F_S})^2 + \left(u_{\frac{\Delta f}{f}}\right)^2 + \left(u_{\delta\frac{\Delta f}{f}}\right)^2 + (u_{\delta F_{SIS}})^2 + (u_{\delta F_{RES}})^2 + (u_{\delta F_{DR}})^2} = 1{,}709\text{x}10^{-6}$				
Expanded Uncertainty (k=2)						$3{,}42\text{x}10^{-6}$

3.2.3 Calibration results

To process the results, software Stable 32, available on the IEEE (Institute of Electrical and Electronics Engineers) website was used

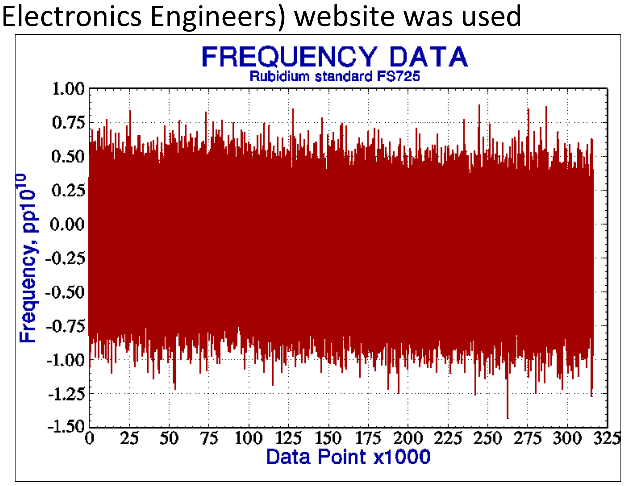


Fig. 8. Raw Data of Relative Frequency Deviation. Each data point corresponds to a measurement averaged over a 1-second interval for the FS725 rubidium standard

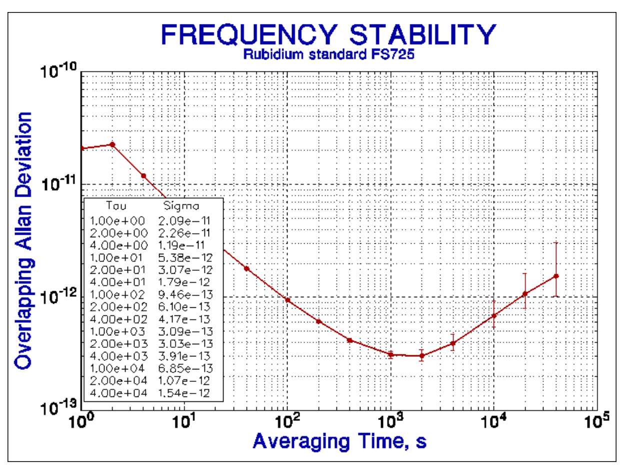


Fig. 9. Frequency Stability Characteristic of the FS725 Rubidium Standard. The plot shows the Allan Deviation, EsEy (τ), as a function of the averaging time, τ, on a log-log scale

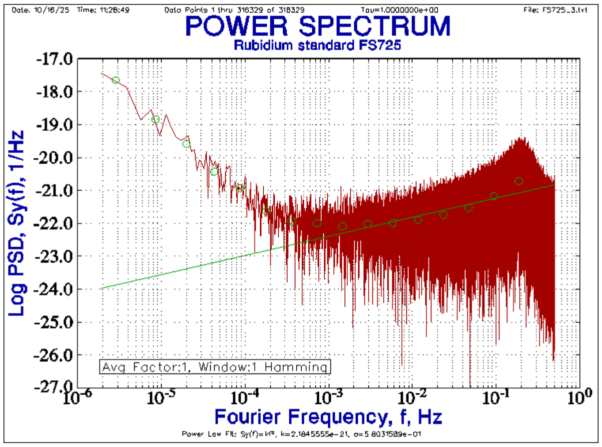


Fig. 10. Power Spectral Density of Relative Frequency Fluctuation (Sy(f)) for the FS725 rubidium standard. The graph shows the logarithmic dependence of Sy(f) on the Fourier frequency f, including a Power Law Fit approximation

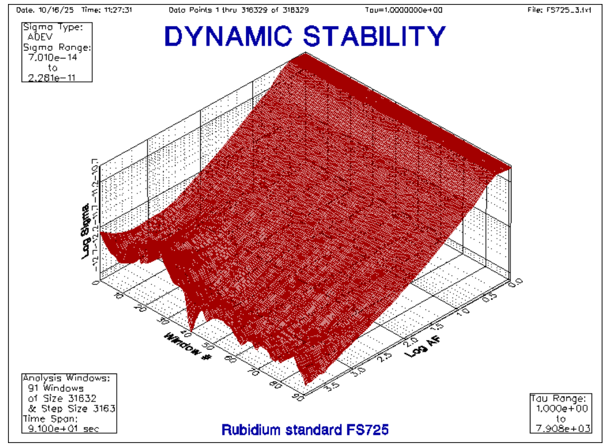


Fig. 11. A 3D plot of dynamic stability for the FS725 rubidium standard. The graph shows the change in Log Sigma (measured as Log ADEV) as a function of the time window number (Window #) and the logarithm of the acceleration factor (Log AF)

Table 4 Measurement accuracy

Nominal frequency	Measured absolute frequency value	Relative frequency value ($\frac{\Delta f}{f}$)	Expanded uncertainty
10 MHz	9 999 999,999 799 Hz	$-2{,}01 \cdot 10^{-11}$	3 μHz (Absolute) $3 \cdot 10^{-13}$ (Relative)

Table 5 Stability measurements

Averaging time, s	Stability (Allan deviation) $\sigma(\tau)$	Uncertainty	
		Lower limit $\sigma(\tau)$	Upper limit $\sigma(\tau)$
1	$2{,}09 \cdot 10^{-11}$	$2{,}09 \cdot 10^{-11}$	$2{,}10 \cdot 10^{-11}$
2	$2{,}26 \cdot 10^{-11}$	$2{,}25 \cdot 10^{-11}$	$2{,}27 \cdot 10^{-11}$
4	$1{,}19 \cdot 10^{-11}$	$1{,}19 \cdot 10^{-11}$	$1{,}20 \cdot 10^{-11}$
10	$5{,}38 \cdot 10^{-12}$	$5{,}35 \cdot 10^{-12}$	$5{,}42 \cdot 10^{-12}$
20	$3{,}07 \cdot 10^{-12}$	$3{,}05 \cdot 10^{-12}$	$3{,}08 \cdot 10^{-12}$
40	$1{,}79 \cdot 10^{-12}$	$1{,}78 \cdot 10^{-12}$	$1{,}81 \cdot 10^{-12}$
100	$9{,}46 \cdot 10^{-13}$	$9{,}27 \cdot 10^{-13}$	$9{,}65 \cdot 10^{-13}$
200	$6{,}10 \cdot 10^{-13}$	$5{,}93 \cdot 10^{-13}$	$6{,}28 \cdot 10^{-13}$
400	$4{,}17 \cdot 10^{-13}$	$4{,}01 \cdot 10^{-13}$	$4{,}35 \cdot 10^{-13}$
1000	$3{,}09 \cdot 10^{-13}$	$2{,}88 \cdot 10^{-13}$	$3{,}33 \cdot 10^{-13}$
2000	$3{,}03 \cdot 10^{-13}$	$2{,}72 \cdot 10^{-13}$	$3{,}42 \cdot 10^{-13}$
4000	$3{,}91 \cdot 10^{-13}$	$3{,}36 \cdot 10^{-13}$	$4{,}67 \cdot 10^{-13}$

CONCLUSIONS AND FUTURE WORK

During the internship, I gained extensive theoretical and practical experience in the design and operation of a time and frequency standard, calibration of time and frequency measuring instruments, automation of measurements, and evaluation of measurement uncertainty.

The acquired knowledge will be applied in the modernization of the Secondary Standard of Time and Frequency and laboratory equipment, in the automation of measurements, and in the wide-scale implementation of software solutions. Furthermore, I will definitely apply this experience in the training of metrology specialists in the field of time and frequency measurements.

ACKNOWLEDGEMENTS

I would like to express my deep gratitude to everyone who made my internship "BIPM–TÜBİTAK UME Project Placement" possible. Many thanks to Mr. Chingis Kuanbaev and Mr. Mustafa Çetintaş for organizing this Project, and to Ms. Müge Atam, who coordinated the activities before and during the internship and provided valuable support in resolving any issues.

In addition, I would like to sincerely thank the staff of the Time and Frequency Laboratory, who generously shared their calibration experience and with whom it was a great pleasure to work. Special thanks go to Mr. Adem Gedik and Dr. Efendi Fidan for sharing their expertise and theoretical knowledge in time and frequency measurements, for demonstrating the practical application of these skills, for their clear explanations, and for their attention and support.