Geodetic Measurements and Quantitative Evaluation for Reduced Gravitational Redshift Uncertainty of NICT Optical Frequency Standards

ICHIKAWA Ryuichi, HACHISU Hidekazu, SEKIDO Mamoru and IDO Tetsuya
National Institute of Information and Communications Technology
Koganei, Japan
richi@nict.go.jp

HIRAOKA Yoshifumi, HARIMA Eiichirou, FUKAYA Shuntaro, MATSUO Koji and NAKASHIMA Masahiro
Geospatial Information Authority of Japan
Tsukuba, Japan

AOYAMA Yuichi, HATTORI Akihisa, and FUKUDA Yoichi
National Institute of Polar Research
Tachikawa, Japan

The National Institute of Information and Communications Technology (NICT) has developed optical ion clocks employing In+ and Ca+, as well as a Sr optical lattice clock that provides TAI calibration data to BIPM. We have started geodetic measurements near these NICT optical atomic clocks to evaluate vertical ground movements, where centimeter-level uncertainties correspond to 10^{-18}-order frequency shifts.

Keywords—optical atomic clock, geodesy, leveling, gravity, GNSS and ground water

I. Introduction

The frequency accuracy of optical atomic clocks has dramatically increased over the past 15 years, improving by more than two orders of magnitude from 16 digits of precision to 18 or even 19 digits of precision [1,2,3]. Around 2015 researchers from around the world began to consider a redefinition of the second based on optical atomic clocks. Since then, the development of optical atomic clocks has progressed and the recent results demonstrated the detection of frequency changes with 18 digits of precision [4]. In terms of elevation differences, this provides centimeter-order precision [5], showing the chronometric leveling can now be realized with the same level of accuracy as conventional leveling, and that in the future it will be possible to take real-time elevation difference measurements regardless of distance. Such relativistic geodesy, applying optical atomic clocks to the determine global height standards is now being actively discussed.

On the other hand, the redefinition of the second requires the stable operation of optical atomic clocks, and so it is important to understand frequency changes caused by solid-earth tides that often range from 10 to 20 cm in amplitude, by oceanic tidal loading, crustal deformations due to earthquakes, and ground movements with groundwater changes. NICT, in collaboration with partners including the Geospatial Information Authority of Japan (GSI), the National Institute of Polar Research (NIPR), the National Institute of Advanced Industrial Science and Technology (AIST), and several universities, has begun observations and data analysis to evaluate how these effects interact with optical atomic clocks. In this paper, we describe the recent geodetic measurements and preliminary results.

II. Geodetic measurements and preliminary results

Since early 2021, NICT and the Geospatial Information Authority of Japan (GSI) have been jointly conducting leveling surveys and relative gravimeter observations at the NICT's headquarters in Koganei. These observations reduce the contribution of gravitational redshift to the total uncertainty of the NICT-Sr1 optical lattice clock has been reduced to the 10^{-19} level.

With the support of the National Institute of Polar Research (NIPR), absolute gravity measurements were performed in August 2019 and May 2022 to evaluate the effects of the March 11, 2011 Tohoku megaquake on coseismic vertical crustal displacement (See, Figure 1). The obtained absolute gravity change between the two periods was −43.8 μGal. This matches the trend of GNSS result obtained by the GNSS Earth Observation Network system (GEONET) of GSI, which show a vertical displacement of up to 31.5 mm from August 2019 to May 2022, equivalent to about −10 μGal gravity change, even though the values do not agree precisely.

We have introduced the Micro-g LaCoste's gPhoneX gravimeter for continuous gravity measurements near by the optical clocks at the end of 2021 (Figure 1). The preliminary results over seven months detects stable gravity change due to solid earth tide with about 22 μGal precision. We are also monitoring vertical crustal displacement by geodetic GNSS measurement.

III. Concluding Remarks and Outlook

Geodetic measurements such as leveling, gravity survey, and continuous GNSS observation help manage uncertainties of optical atomic clocks at NICT. The results of a new leveling survey reduce the uncertainty due to gravitational redshift. The absolute gravity change over two intervals of two and ten months is consistent with the vertical crustal displacement due to the Tohoku megaquake on March 11, 2011.

We have started studying the effects of ground water variation at Koganei, and will continue to investigate uncertainties due to vertical movements caused by solid earth tide, non-tidal ocean loading, groundwater variation and other phenomena using continuous gravity and GNSS measurements nearby the optical atomic clocks.

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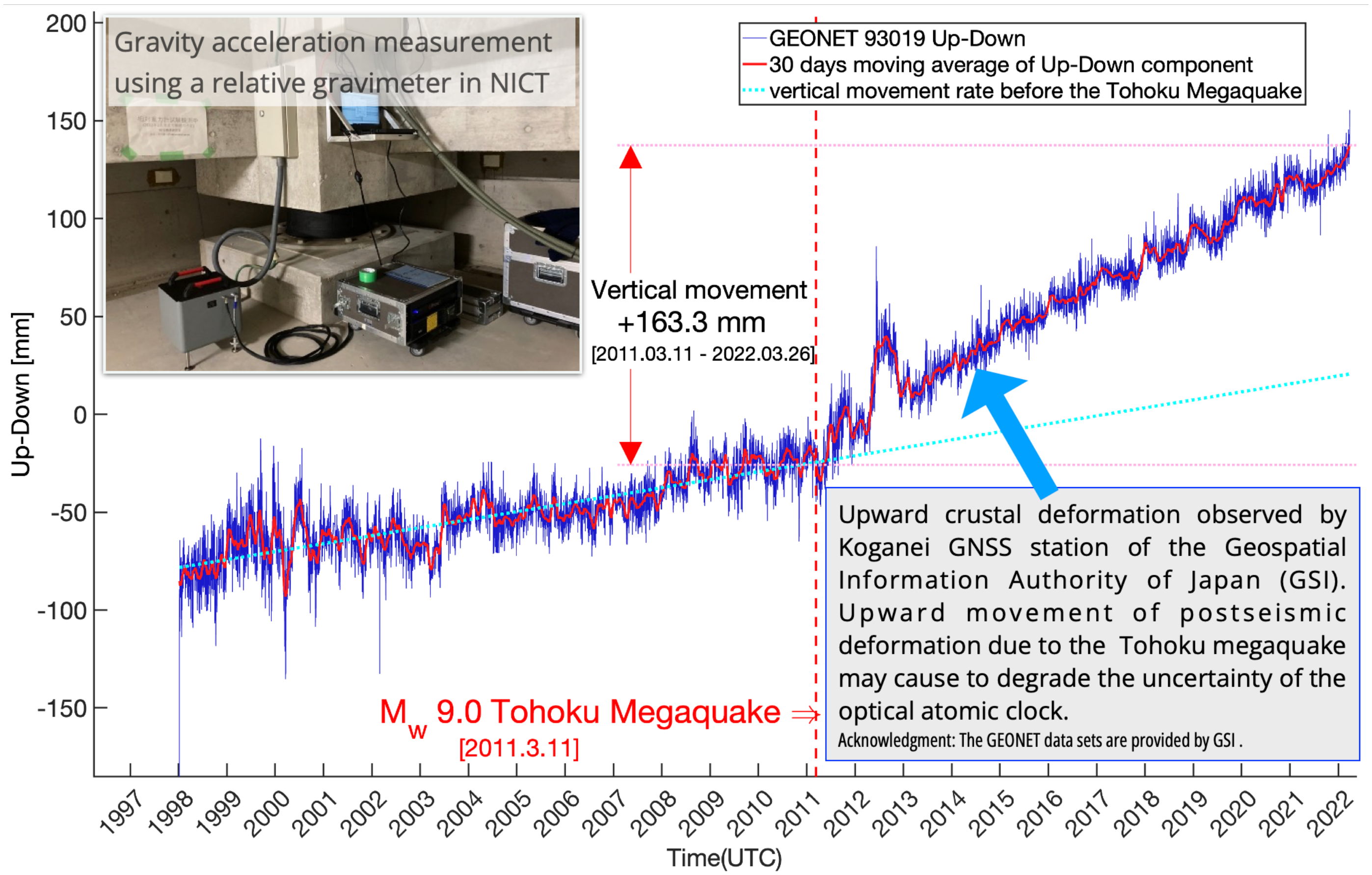

Fig. 1 Time series of upward displacement obtained by GEONET GNSS measurement at NICT headquarters. The inset photo shows the relative gravity measurement.