

# The Role and Future of Leap Seconds in International Atomic Timekeeping

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Time serves as a critical element in modern society, influencing numerous and diverse sectors such as finance and digital governance, telecommunications, navigation, and emerging technologies like Artificial Intelligence, and the Internet of Things (IoT). To ensure precise timekeeping, the ensemble of extremely accurate atomic clocks generate International Atomic Time (TAI) based on atomic frequency standards. However, the dynamic nature of the Earth's rotational speed introduces variations in earlier used time scale, Universal Time (UT1), which relies on the Earth's rotational dynamics. Therefore, to establish synchronization, Coordinated Universal Time (UTC) was formed, incorporating leap seconds to closely align with UT1. This paper explores the factors that sustain the link between UT1 and UTC, discusses the pros and cons of the leap second system, and highlights potential issues if it remains unaddressed.

**Keywords:** Coordinated Universal Time (UTC); UT1; TAI; BIPM; Leap seconds

## 1 Introduction

International Atomic Time (TAI) is the globally accepted time scale managed by International Bureau of Weights and Measures (BIPM) which collects time data from various National Measurement Institutes (NMIs), designated institutes (DIs) and observatories worldwide. It is an atomic time scale derived from the definition of the SI second. Fundamentally derived from TAI is the Coordinated Universal Time (UTC) is the timescale that acts as the reference time scale for civil purposes. Maintained by BIPM, UTC differs from TAI by an integral multiple of seconds (known as leap seconds) and is closely linked to UT1, which is determined by the Earth's rotation. Occasionally, a leap second is inserted into UTC to ensure it stays in phase with UT1, also known as astronomical timescale. Defined by Earth's rotation, Universal Time (UT1) is the time scale used in astronomical measurements and celestial navigation. Due to the irregular rotation periodicity of Earth, UT1 keeps on deviating from UTC. The link connecting UT1 and UTC is presently being maintained by insertion of leap second to UTC time scale whenever the gap between UT1 and UTC nears 0.9 seconds. The leap second was introduced to address the requirements of celestial navigation by minimizing the discrepancy between atomic time and solar time<sup>1</sup>.

The speed at which the Earth rotates varies. Three different kinds of variations exist: A gradual deceleration, random fluctuations and periodic variation<sup>2</sup>. It was explained that the primary cause of the Earth's secular deceleration in its rotation rate is tidal forces exerted by the Moon<sup>3</sup>, which leads to a change in the Moon's orbital velocity due to the conservation of angular momentum. According to Stephenson & Morrison<sup>4</sup>, the length of day (LOD) has surged by an average of 1.7 milliseconds per day every century over the last 2700 years. Also, moon's tidal deceleration should account for an increment of 2.3 milliseconds per day per century, according to geophysical studies of tidal deceleration. The Earth's shape altering in consequence to glacial isostatic adjustment is thought to be the cause of the disparity of 0.6 milliseconds per day every century. The periodic fluctuations in the Earth's rotation rate are influenced by multiple factors. The exchange of angular momentum between the air and the solid Earth is a major contributor, particularly on shorter timescales. However, on inter-annual timescales, fluctuations in zonal core flows are significant, with a recurring 6-year oscillation being a dominant feature. These core dynamics contribute notably to the observed periodic variations in the Length of Day (LOD)<sup>5</sup>. The seasonal fluctuation in the duration of the day is approximately 0.5 milliseconds per day which is linked to the circulation of the atmosphere<sup>6</sup>.

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The Earth rotates slowly in May by around 30 milliseconds and quickly in November by roughly the same amount. Additionally, variations in the Earth's LOD of less than a few tenths of a millisecond each day occur frequently and appear to be random. Usually, these variations last for a decade<sup>7</sup>. The difference, UT1-UTC, is used to determine the changes in the Earth's rotation. This discrepancy is ascertained using Very Long Baseline Interferometry (VLBI) measurements of the Earth's orientation relative to the celestial frame of reference<sup>8</sup>. Apart from this very gradually increasing difference between UT1 and UTC, there also exist a short term fluctuations which leads to the inconsistency in the period between insertions of leap seconds.

This paper explains the disadvantages of the present definition of UTC timescale and the discontinuities which is created by the leap second insertion. Over the years only positive leap seconds have been added to UTC. However, recent data indicates an increase in the Earth's angular rotation rate, which could eventually necessitate the addition of a negative leap second to UTC<sup>9,10</sup>.

## 2 History of Clocks and Time Scales

Clocks are composed of a time reckoner and a time reference, delineating interval and epoch attributes. Celestial bodies and sundials played pivotal roles as time reckoners throughout history. Mechanical clocks, introduced in the 14th century, marked a significant advancement by establishing consistent-hour durations<sup>11</sup>. The 20th century witnessed the development of quartz and atomic clocks, driven by advancements in radio technology<sup>12</sup>. Notably, the first atomic clock, built in 1948 by Harold Lyons, utilized ammonia's microwave transition to stabilize a quartz oscillator. It was built at the National Bureau of Standards (NBS), Washington, D.C. (now the National Institute of Standards and Technology (NIST), Gaithersburg)<sup>13</sup>. Subsequently, caesium<sup>14-16</sup> and hydrogen maser clocks<sup>17</sup> were introduced, further refining time measurement precision. International timekeeping standards were established, overseen by organizations like BIPM, culminating in the continuous maintenance of atomic time since 1955<sup>18-20</sup>.

Throughout history, the rotation of the Earth has served as the basis for societal timekeeping. In order to comprehend the current timekeeping problems, it is crucial to grasp the specifics of both clock time and astronomical time as they have been used since the middle of the twentieth century. The methods of measuring time have evolved with the advancement

of clocks sophistication and precision. For contemporary physics, astronomy and engineering applications, three main methods for measuring time have been widely used<sup>1</sup>: The Universal Time (UT), Ephemeris Time (ET) and Atomic Time (AT).

### 2.1 Universal Time: Astronomical Time Derived from the Rotation of Earth

The rotation of the Earth about its axis with respect to the Sun serves as the basis for the Universal Time (UT1), a measurement of astronomical time. It is supposedly equal to mean solar time, which is measured from midnight and is based on the Greenwich meridian<sup>21</sup>. The term "mean solar day" often refers to the interval of time between consecutive transits of the hypothetical mean Sun over a specific meridian. Mean solar day is precisely divided into 86,400 units known as seconds<sup>22</sup>. Although it cannot equal the accuracy attained with atomic clocks, it is the oldest functioning timescale still in use for civil timekeeping<sup>3,23</sup>. In principle, the measurement of Universal Time is made using the observation of celestial objects and a standard equation that expresses UT1 in terms of Greenwich Mean Sidereal Time (GMST). In 1956, The IAU began recognizing three components of Universal Time: UT0 (Greenwich mean solar time recorded anywhere on Earth), UT1 (UT0 adjusted to account for the rotating pole's motion in relation to the surface of the Earth's), and UT2 (UT1 adjusted to take into consideration the observed seasonal variation in Earth's rotational speed)<sup>9,24</sup>. UT1 is normally described as being linearly related to the Earth rotation angle, as it most accurately depicts the instantaneous position of the Earth's surface with respect to its axis of rotation<sup>25</sup>. For the astronomical compendium, the IAU proposed using the term "Universal Time" in 1928 instead of GMT or GCT. The term 'Universal Time' was then officially designated<sup>26</sup>. Currently, observation of celestial object (quasars) using Very Long Baseline Interferometry (VLBI) is the main method employed to estimate UT1. Despite estimations of UT1 being provided by GPS satellite tracking and satellite laser ranging, VLBI offers the only accurate calculation of UT1 due to the mobility of orbital nodes of satellite in space<sup>27</sup>.

### 2.2 Ephemeris Time: Astronomical Time Determined from Solar System Motions

The complexity of Earth's rotation made it clear that a time scale based solely on it could not guarantee consistency, thus in 1948 the International

Astronomical Union (IAU) was entrusted with researching a new definition of the SI second. The demand for a more consistent timescale based on astronomical time, independent of the rotation of the Earth, led to the initial conception of a timescale based on the dynamic motions of solar system objects. Newcomb's Tables of the Sun, published in 1895, established a new time scale based on the Earth's revolution period around the Sun, was proposed by Clemence<sup>28</sup>. This timescale, introduced by Clemence, is known as Ephemeris Time (ET). In 1950, The International Astronomical Union (IAU) was recommended at the Conference on the Fundamental Constants of Astronomy, held in Paris, that the new time standard should be based on Ephemeris Time. In 1952, this proposal was approved by the IAU at its 8th General Assembly in Rome<sup>29</sup>.

International Astronomical Union (IAU) decided to adopt the ephemeris second's duration in relation to the tropical year 1900 in 1952. According to the calculation of Newcomb's formula, the tropical year of 1900 comprises 31556925.9747 seconds. This led to the CIPM defining the ephemeris second as "the fraction  $1/31,556,925.9747$  of the tropical year for January 0, 1900, at 12 hours ephemeris time" in 1956, using the authority granted by the 10th CGPM in 1954<sup>2,30</sup>. This definition was accepted by the 11th CGPM in 1960 under the 9th resolution<sup>31</sup>.

Starting in 1960, Ephemeris Time replaced the position of UT1 as the independent variable which was used in astronomical ephemerides<sup>27</sup>. In 1976, the notion of ET time scales, which was dependent on the planetary system's dynamics, was modified. During the 16th General Assembly in Grenoble in 1976, the IAU established time-like arguments to differentiate coordinate systems having origins at the of the Earth's and solar system's centers, respectively, in line with the general theory of relativity<sup>32</sup>. These time scales were named Terrestrial Dynamical Time (TDT) and Barycentric Dynamical Time (TDB) in 1979<sup>33</sup>. Further detail about relativistic modifications of ET can be found in<sup>34</sup>. Present days, only for specialized research and the formation of astronomical ephemerides dynamical time scales are utilized.

### 3 International Atomic Time

Despite having a consistent time scale, Ephemeris Time was difficult to realize and disseminate. In an effort to create a more uniform timescale, scientists and researchers were developing molecular and atomic clocks at approximately the same time when

astronomers were working on the idea of Ephemeris Time. Physicists began exploring ways to harness alkali atoms' energy level transitions to establish a consistent frequency for clocks, instead depending on celestial or astronomical processes to create the repetitive events that define the time period.

A new timescale was necessary in order to reap the advantages of this work. Atomic clocks' quick development enabled them to define time in yet another way<sup>35</sup>. Essen & Parry at the National Physical Laboratory (NPL) in the United Kingdom developed the first usable caesium beam clock in 1955, and the following year saw the introduction of commercial caesium beam frequency standards<sup>16,36</sup>.

The Atomichron caesium clock standard and a quartz-crystal clock were the primary components at the Naval Research Laboratory (NRL) upon which the US Naval Observatory (USNO) first established its A.1 atomic time scale on September 13, 1956<sup>37</sup>. Beginning on October 9, 1957, the National Bureau of Standards (NBS) in Boulder, United States, also started maintaining the NBS-A atomic time scale<sup>38</sup>. In<sup>1</sup>, the specifics of how these scales evolved into the present standard International Atomic Time (TAI) are described in detail. On January 1st, 1959, the A.1 time scale was made available for usage worldwide. By 1961, the functioning of atomic resonators at nine laboratories, including USNO, NRL, NBS, and USNO etc., served as the basis for A.1<sup>39,40</sup>. In 1969, BIH had developed an atomic time scale derived from the average of multiple primary laboratory standards once uninterrupted atomic time had been established at several laboratories. This scale was adopted as the International Atomic Time (TAI) in 1971<sup>18</sup>. The 13th CGPM in October 1967 established the atomic second as the main unit of time in the International System of Units<sup>41,42</sup>. It was defined as "The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom".

International Astronomical Union (IAU) Commissions 4 and 31 suggested in 1967 that time scale be unified using an atomic timescale and that the BIH establish an international atomic time scale that combines the individual time scales of the main national time systems<sup>43</sup>. CIPM's Comit'e Consultatif pour la D'efinition de la Seconde (CCDS) recommended TAI standards in 1970, endorsed by the 14th CGPM in 1971, establishing International Atomic Time (TAI) and its abbreviation<sup>44-46</sup>. In 1988,

control over TAI maintenance was assigned to the BIPM from the BIH<sup>27</sup>. TAI has been computed at the BIPM since 1988 as an outcome of international collaboration<sup>48</sup>.

#### 4 Coordinated Universal Time (UTC) and role of Leap seconds

Despite being considered as an atomic timescale, TAI has never been explicitly disseminated or accepted as the global standard for timekeeping. In the case of Coordinated Universal Time (UTC), this distinction is maintained. The dissemination of time to customers who required astronomical time, notably for sea navigation and other practical applications, was at the time a prominent obstacle to TAI's widespread adoption. At the same time, engineers and physicists in time and frequency laboratories preferred a completely uniform time scale aligned with the most precise clocks. Coordinated Universal Time (UTC) was developed in an effort to serve the demands of both communities. Although there has been a discrete amount of seconds' difference between UTC and TAI since 1972, but UTC remains the internationally recognized time scale<sup>49</sup>.

In 1955, atomic clocks utilizing the resonance frequency of a cesium atom transition were introduced, and the UK began transmitting radio time signals based on these atomic clocks<sup>9</sup>. Over time, the time scale progressed, and the time broadcasting system soon came to be known as Coordinated Universal Time. The BIH coordinated annual rate offsets and determined when time steps needed to be added to these broadcasts to stay in step with the astronomical time<sup>48</sup>. In 1967, during the 13th General Assembly, IAU Commissions 4 and 31 passed a resolution authorizing the designation "Coordinated Universal Time (UTC)"<sup>48</sup>.

BIPM is a global standard for determining and maintaining time intervals and accumulated time. The International Earth Rotation and Reference System Service (IERS) is the international agency in authority and oversees the calculation and implementation of time based on Earth orientation observations. Prior to 1972, short wave radio timing signals and civil time scales used rate steering and stepping of up to 0.1 s to reflect astronomical time. The UTC system used frequency offsets and time stepping up to 0.1s. Important systems, particularly those involved in radio communications, utilised this frequency<sup>50</sup>. However, this led to variable broadcast second lengths differing from the SI second, challenging

timekeeping oscillator calibration from broadcast timing signals. Maintaining a consistent frequency offset at the expense of frequent and/or longer time steps became the main timekeeping goal<sup>51</sup>.

Winkler<sup>52</sup> & Essen<sup>51</sup> independently suggested the idea of the leap second at a CIPM meeting that was conducted at the BIPM in 1968. The same year, the CCIR Study Group 7 met in Boulder, Colorado, and considered the possibility of changing UTC. It was suggested that coded data signals be added to transmissions in order to satisfy navigators' needs and give a more accurate measurement of the difference between UT2 and UTC<sup>53</sup>. To keep UTC and UT2 closely related, the first alternative discussed was to make steps in UTC of 0.1 or 0.2 seconds. The second option was to replace UTC with a timescale that makes no modifications, and the third option was to make steps adjustments in UTC of one second<sup>54</sup>. Thereafter, Study Group 7 prepared set of recommendations that were accepted in January 1970 in New Delhi, India at the 12th Plenary Assembly of CCIR<sup>55</sup>. The approved recommendation serves as the foundation for the current concept of the global civil timeframe. It was mandated that radio transmission time intervals and frequencies align precisely with the atomic second, defined by the cesium transition frequency. Secondly, to ensure the step corrections approximately in accord with UT, it must be precisely one second. And finally, there should be data on the gap between UT and UTC in standard time transmission signal<sup>56,57</sup>. These suggestions led to the creation of the UTC time scale, with the SI second as its fundamental unit<sup>19</sup>. The International Earth Rotation and Reference Systems Service (IERS), the successor to the BIH since 1988, monitors Earth's rotation as a collaborative initiative between the International Union of Geodesy and Geophysics (IUGG) and the IAU to determine and establish the timing leap seconds<sup>58</sup>.

On January 1, 1972, the CCIR made the decision to implement the new UTC structure in its Recommendation 460. To ensure that the gap between TAI and UTC was an integer, a time step of -0.107 7580 seconds was added before the new UTC was implemented on January 1, 1972. The offset between TAI and UT1, which had accumulated to approximately 10 seconds since TAI's establishment in 1958, was designated as the defining epoch of January 1, 1972, at 0 hours, 0 minutes, and 0 seconds UTC<sup>59-61</sup>. The maximum UTC deviation from UT1 was extended from 0.7 seconds to 0.9 seconds in 1974

by CCIR Recommendation 460-1. The transmission signals were to include a second correction code,  $DUT1 = UT1 - UTC$ , with integral multiples of 0.1 s, which, when combined with UTC, would provide a more accurate estimate to UT1. In 1975, the 15th CGPM concluded that the usage of UTC can be strongly promoted and endorsed<sup>45</sup>. The International Earth Rotation and Reference Systems Service (IERS) is responsible for determining and publishing the UTC leap second dates<sup>62</sup>. Numerous international organizations have advocated for the usage of UTC, which serves as the foundation for legal times in the majority of nations<sup>49</sup>. The time difference between TAI and UTC at present (February 2023) is 37 seconds<sup>63</sup>.

## 5 Leap Second and its operational challenges over the years

By introducing the leap second, the primary goal was to meet the needs of astronomical and celestial navigation while minimizing the discrepancy between atomic and astronomical time. However, the necessity for this has decreased with the development of sophisticated navigation systems, and the challenges of maintaining accurate and flawless timekeeping systems have made the addition of leap seconds increasingly difficult and expensive. Currently, some working groups within international scientific organizations are reviewing the necessity of the leap second, given its technical challenges<sup>50,64,65</sup>. It is also being considered whether it would be preferable to simply end the close association of Earth's rotation with atomic timekeeping.

The concept of UTC may not have any implications for systems and applications that rely on time elapsed with an epoch which is defined by user. Examples include asynchronous communications in which users can constitute a shared epoch cooperatively. Although the Global Positioning System (GPS) time intervals are not specifically linked with celestial phenomena or frequency standards, GPS time is widely used as a reference. The GPS and UTC time scales are identical, with the exception of how epochs are labelled. The second of GPS is not an ideal frequency reference for a precision that only matters for a small number of applications. An accurate measurement of a standard time interval, based on a consistent epoch that remains stable and does not change arbitrarily, is essential for astrodynamics and astronomy. Some elements of such fields would be considerably

affected by a change to UTC. The synchronization of astronomical time with atomic time standards is a matter of speculation, agreement, and execution. The outcomes will have significant scientific, legal and technological consequences<sup>66</sup>.

The most debated and contentious topic in timekeeping towards the end of 1999 was the proposal to modify the definition of UTC to include leap seconds and perhaps eliminate their use<sup>67</sup>. Fast growing and complex technologies have their basis in majority of the reported problems with leap seconds, notably those in the information technology field<sup>68-70</sup>. However, dialogues among the stakeholders of the institutions and organizations that dealt with challenges in time keeping had not reached a noticeable conclusion. According to a relevant ITU-R Study groups, many significant stakeholder institutions and organizations were still unable to come to a consensus or somewhat neutral about it on the matter of redefinition of UTC<sup>71,72</sup>. In recent times, the applications of time and its community of users have undergone profound changes. Satellite signals which are directly connected to atomic standards are beginning to replace the conventional radio transmission of time signals. These standards are used to synchronize high-speed computer networks. International telecommunication, economic and financial infrastructure now heavily depends on international time scales. Modifications in the time scales constitute a big financial investment and there are strong economic aspects to consider, therefore, this connection can make change more challenging. Leading worldwide scientific organizations' working groups were examining whether it was necessary to continue using the leap second despite its technological limitations and whether it would be preferable to break the conventional connection between timekeeping and the rotation of the Earth<sup>69</sup>. Numerous reports, articles and publications have documented arguments against and in favour of elimination of leap seconds, with diverse levels of information and interpretations. Several leading IT companies including Facebook, Alibaba, Amazon, and Google, have expressed support for the removal of the leap second<sup>73-77</sup>. Their rationale often revolves around the operational disruptions that the leap second can cause in various technology systems, particularly those that rely on precise and synchronized timekeeping. These disruptions can impact glitches in software and data processing, financial transactions, communication network,

internet of things (IoT) and other critical functions that are highly time-sensitive.

**6 Trend reversal in UT1-TAI / UT1-UTC: A possibility of negative leap second requirement**

Alongside the numerous problems related to the future of leap second, a new trend reversal in the UT1-UTC data is being observed. Which clearly indicates that the Earth’s rotation has been accelerating particularly and distinctly from 59000 MJD (31st May 2020) approximately (Fig. 1).Infact, if we analyse the Earth Orientation Parameters (EOP) beginning from the introduction of leap second (i.e. from MJD 41317), one can observe that the LOD (Fig. 2) began to decrease around the same time, which led to the more frequent insertion of leap seconds.

If we look at the UT1-TAI plot (Fig. 3) at around MJD 51000 (mid of 1998), the acceleration became

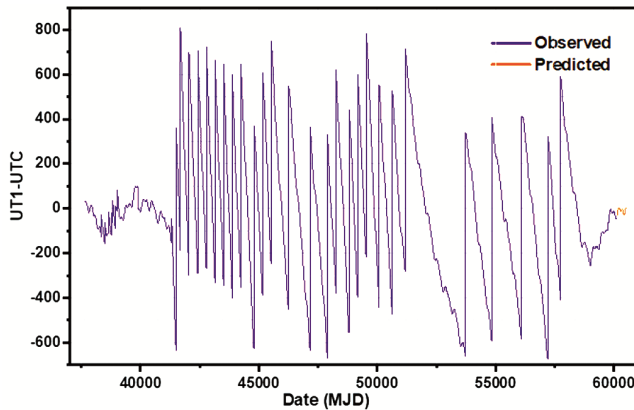


Fig 1 — UTC and UT1differences. The Modified Julian Date (MJD) is shown in the abscissa. A positive leap second is introduced when the difference (UT1-UTC) approaches -0.6s approximately. The introduction of leap second to UTC started from MJD 41317. The data is obtained from Earth Orientation Centre

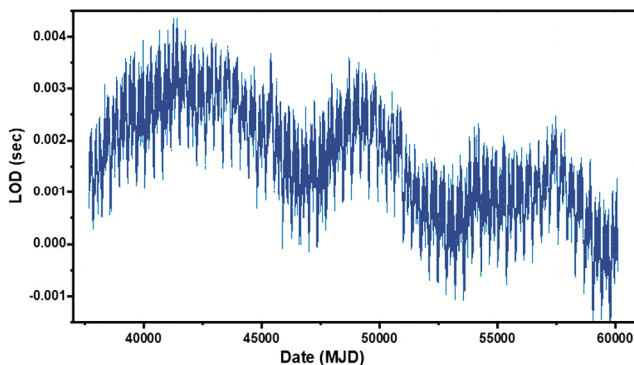


Fig 2 — Difference in Length of the Day (LOD) as a function of MJD. The data is obtained from Orientation Center of the Earth

extremely evident and it has been persistently increasing since the last insertion of leap second (Fig. 1), which was introduced at MJD 57753 (31st December 2016).As a result, the Earth's rotation is accelerating, which could necessitate the usage of a hitherto unheard-of negative leap second.

Although adding positive leap seconds to UTC has been a method for more than 50 years, numerous reports of system failures during leap second insertion still persist<sup>77,78</sup>. This issue is made worse by the potential of a negative leap second. Since these situations have never occurred, it is quite predictable that there will be numerous mistakes made while realizing negative leap second<sup>79</sup>. Also, there is no uniformity in the variation of UT1 and hence there is no algorithm to precisely predict the need of leap second insertion.

Expanding the tolerance range can be regarded as a prudent interim measure, warranting reassessment in light of future discoveries and enhanced comprehension (such as<sup>82</sup>), which may yield a more optimal solution<sup>79</sup>. By widening the tolerance range, we allow for greater flexibility in accommodating variations, uncertainties, or potential errors within the current understanding. The accurate prediction of leap seconds necessitates extensive research and long-term observations over several decades. At present, our available data is insufficient to establish a clear trend and develop a precise algorithm for leap second predictions.

Recent studies<sup>80,81</sup> highlight the critical role of core dynamics and climate change in driving variations in LOD. The study demonstrate that these factors are interdependent, necessitating an integrated approach to accurately model and predict their combined

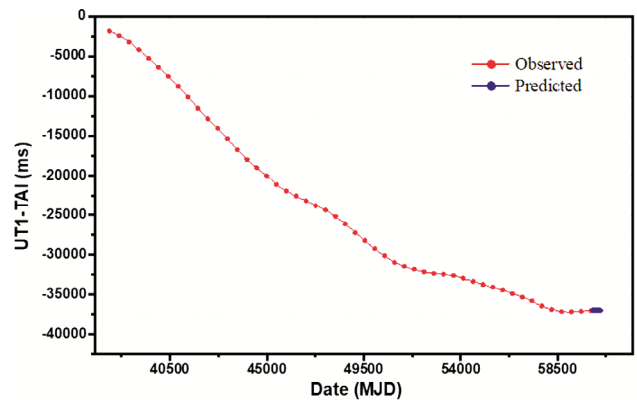


Fig 3 — Difference between UT1 and TAI. The Modified Julian Date (MJD) is shown in the abscissa. The observed and predicted data is obtained from Orientation Center of the Earth

effects. Future studies should focus on refining prediction models to account for this complex interaction, which will have implications for precise timekeeping and geophysical research.

### 7 Gradual acceleration in earth's rotation and its co-relation with Earth's inner core moment

While the intricate motion of the Earth and its interactions with various celestial bodies still lack a fully predictive algorithm, recent research focusing on Earth's core has made significant progress<sup>82</sup>. This study has unveiled a robust correlation among the observed variations in the length of day ( $\Delta$ LOD) and the dynamic interactions transpiring among different layers of the Earth. In this comprehensive study, conducted by Yi Yang and Xiaodong Song, a detailed investigation was carried out to analyse and elucidate the rotational behaviour exhibited by the innercore of the Earth over considerably extended temporal spans. It is believed that there is a dynamic connection between the Earth's inner core and its outer layers, primarily through electromagnetic coupling with the outer core and gravitational coupling with the mantle<sup>83,84</sup>.

Several studies have demonstrated that the rotation of the inner core exhibits multi-decadal fluctuations and oscillations, with a periodicity of roughly seven decades<sup>85,86</sup>. The research draws upon seismic wave analysis, geophysical observations, and geodynamic models to understand the mechanisms and interrelations between Earth's rotation and the multi-decadal variations in the inner core's rotation.

The observed slight disruption in rotation around 2009, along with a previous overturn in the early 1970s, and a relatively consistent rotation in the intervening period, suggests that the inner core is likely undergoing a cyclical oscillation with a period of approximately seven decades, the detailed study of which can be found in<sup>78</sup>. Significant geophysical patterns, in particular the fluctuations in the magnetic field and the length of day (LOD) - both of which exhibit dominant frequencies of six to seven decades, coincide with the inner-core rotation's multi-decadal periodicity<sup>85,87,88</sup>.

In the study<sup>78,86</sup>, a significant correlation coefficient was found between the amount of rotation in the Earth's inner core between 1964 and 2021 and the observed variations in the length of day ( $\Delta$ LOD) across six to seven decades. Hence, it is suggested for the International Astronomical Union (IAU) and the

International Earth Rotation and Reference Systems Service (IERS) to incorporate these findings and establish a correlation between the aforementioned studies. This could help refine the accuracy of prediction models for UT1-UTC or UT1-TAI. This integration of research could significantly improve the accuracy of Earth's rotation rate forecasts, potentially influencing resolutions pertaining to the inclusion of leap seconds in Coordinated Universal Time (UTC). However, it is essential to recognize that, despite this promising finding, the complete prediction of Earth's motion remains an ongoing challenge in the field of geophysics and planetary science.

Recent studies emphasize the increasingly significant impact of climate change on LOD variations. The melting of glaciers and polar ice sheets due to global warming causes mass redistribution from polar to equatorial regions, altering Earth's moment of inertia and increasing its oblateness. These barostatic processes induced an LOD trend of approximately 1 ms/century during the 20th century. Projections indicate that this trend may accelerate to 2.62 ms/century by the end of the 21st century under high greenhouse gas emission scenarios<sup>89</sup>. This rate would surpass the secular tidal friction trend, becoming the dominant driver of long-term LOD variations. While our study focuses on UT1-UTC trends, it is important to acknowledge this limitation and the need for further analysis integrating climate-induced effects<sup>89</sup>.

### 8 Summary and Conclusions

In conclusion, the future of UTC and the leap second remains a subject of ongoing debate and consideration. The unpredictable nature of leap seconds and their disruption to precise timekeeping systems have led to calls for their elimination. However, maintaining a connection to the rotation of Earth and astronomical phenomena is still a point of discussion. Proposals have been made to allow UT1 and UTC to gradually drift apart over time, with the CGPM suggesting a period of at least a century without adding leap seconds. However, further consultations and decision-making processes involving international organizations are needed to determine the extent to which UT1 and UTC can diverge. Different countries have expressed varying viewpoints, with some advocating for the removal of leap seconds before 2035, while others propose a later date to address technical challenges. The International Telecommunications Union's stance on the matter

could also influence the plans for a leap second-free system<sup>75</sup>.

The growing reliance on time signals from GNSS satellites as the main source of time poses a challenge to the dominance of UTC. This shift may shift the general definition of time from international bodies to GNSS operators, necessitating the provision of instant access to the DUT1<sup>89</sup>.

The potential need for negative leap seconds in the future raises implementation challenges, emphasizing the urgency of making informed decisions. Establishing a time scale that balances the requirements of time and frequency users while aligning with astronomical phenomena requires careful consideration and trade-offs.

In summary, the future of UTC and the leap second requires continued evaluation and discussion. Although there are arguments for abolishing leap seconds, the link to Earth's rotation and persistent concerns call for further investigation. Decisions on the acceptable discrepancy between UT1 and UTC, access to real-time data, and the role of international organizations will shape the evolution of precise timekeeping.

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### Conflict of Interest Statement

The authors of this research article declare that there are no conflicts of interest that could influence the objectivity, impartiality, or integrity of the research findings and their interpretation.

### Data Availability Statement

The datasets/database generated during and/or analysed during the study/research are available from the corresponding author on reasonable request.

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