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# Aging of ground Global Navigation Satellite System oscillators

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## Highlights

- A comprehensive analysis of global navigation satellite system clocks is presented.
- First research on the effect of aging on ground clocks was described and discussed.
- Changes in clock stability over time are proven.
- There are no specific changes for the type of oscillator (internal, rubidium, caesium, hydrogen maser).

## Abstract

Global Navigation Satellite System (GNSS) are widely used in many areas of human life and activity. The proper functioning of GNSS systems depends on several factors, the most important of which is the correct knowledge of time. The position indirectly is based on the knowledge of the distance, which is determined based on time with the knowledge of the speed of the electromagnetic wave. Thus, proper (accurate) knowledge of time (GNSS clock stability) is a key to precise positioning. In this text, the long-term stability of the GNSS station clocks covering the years 1994-2020 was analysed. For this purpose, the corrections of the clocks at selected permanent stations were used, and their stability was determined for all years separately. Then the change of clock stability over time and the search for correlation were analysed. As the results showed, there are clearly differences between four of the type of oscillators analysed. In case of the comparison on an annual basis, no change over time was found.

## Keywords

clock, GNSS, oscillator, positioning, time.



## 1. Introduction

GNSS (Global Navigation Satellite System) clocks are the core of navigation and positioning, where it is very important to ensure continuous and reliable operation in a wide range of applications, e.g. autonomous vehicles [8], dynamic displacements [26] or real-time positioning [25] and many others [12]. As research shows it has a main impact on the inaccuracy of results if clock are modelled incorrectly [5, 7, 13, 17]. Each GNSS satellite is equipped with a precise atomic oscillator (clock), usually a rubidium (Rb) or hydrogen maser (H-maser), and it is rarely a caesium (Cs) clock [9]. The ground clock is usually an internal quartz oscillator or a higher precise external clock (Cs, Rb, H-maser) [23]. Precise knowledge of time is very important in various engineering fields [19, 27]. The carrier phase measurement are used in the most accurate applications, it is described by observation equations and contains receiver and clock biases [21, 28]:

$$\lambda_l \varphi_m^j(t) = \rho_m^j(t) + c\cdot\delta t_m(t) - c\cdot\delta t^j\left(t-\tau_m^j\right) + T_m^j(t) - I_m^j(t) - \lambda_l N_m^j(t) + \lambda_l \varphi_m^j(0) + dM_m^j - dR_m^j + \varepsilon_m^j \quad (1)$$

$$\rho_m^j(t) = \left\| \left(\vec{r}^{\,j}\left(t-\tau_m^j\right) + d\vec{r}^{\,j}\left(t-\tau_m^j\right)\right) - \left(\vec{r}_m(t) + \vec{dr}_m(t)\right) \right\| \quad (2)$$

where $m$ denotes the receiver, $j$ the satellite, $t$ . the epoch time, $c$ the speed of light in a vacuum, $\lambda_l$ the wavelength of the carrier phase, $\varphi_m^j$ the carrier phase observation, $\delta t_m$ and $\delta t^j$ the receiver clock and satellite clock biases, $T_m^j$ the tropospheric delay, $I_m^j$ the ionospheric delay, $N_m^j$ the integer ambiguity, $\varphi_m^j(0)$ the initial fraction of carrier phase, $dM$ the multipath effect on the carrier phase, $dR$ the relativistic effect error, $\varepsilon_m^j$ the noise of carrier phase measurement, and $\rho_m^j$ . the geometric distance between satellite position $\left(x^s, y^s, z^s\right)$ at the signal emission time and GPS receiver position $(x, y, z)$ at the signal arrival time.

In GNSS positioning correct and precise time allows for the determination of the objects with the appropriate accuracy and quality, and also enables the use of GNSS systems in all areas of satellite positioning, e.g., train monitoring, 3D models, or time series analysis. In a similar regard regarding GNSS clock analysis, ground clock is often a stable reference [20], and in case of the external clock performance are better than the space clock [2]. The ground GNSS clock was not an object of the wide spectrum of the research. Usually, the object of research is satellite clocks, due to the fact that errors in reference stations are eliminated in the first place when differentiating observations or constitute one of the unknowns in observations processing [29]. There are only a few positions regarding the issue analysed in this text [22]. Ground clocks are the core of absolute positioning, while in

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differential positioning they are eliminated [15, 31] and in a real-time positioning [3]. In the PPP (Precise Point Positioning) usage of clocks corrections and other precise products allows for determination user's position with cm accuracy [30]. Each clock is characterised by a noise type, and similar analyses are also used for the coordinate time-series analysis [16]. Research shows a mainly random phase walk and due to white frequency noise that affects the stability of space clocks [4]. However, regarding the analysed period and clock types, other noises such as flick or random frequency walk are expected [24].

In this paper, the author makes an analysis of the type and time of the ground GNSS clock operation mounted in the permanent reference stations. For a stability clock analysis, Allan (and related) variations are used [6]. Among four different the less stable were internal oscillators because of a weakest frequency standard, usually quartz. This is first such complex analysis allows also for determination stability and reliability of the GNSS clocks, similar analysis were conducted already, but only for general characteristics [10], evolution of clock quality [11] or in real-time precise positioning [14]. The results of the comparison of the next three clock types are comparable, but – what to expect – the most accurate were external H-maser. An analysis of the changes on an annual basis of the same clock showed no changes with the passage of time.

## 2. Methods

Based on commonly available IGS (International GNSS Service) clock corrections, annual correction files of IGS reference station clocks were created with an interval of 5 minutes, leading to more than 100,000 records per year. gure 1 shows a current distribution of the IGS network stations; only part of them have a clock correction published, due to their status in the IGS. For a determination of the oscillator types of the stations, its changes and the date of the inclusion station logs were analyzed.

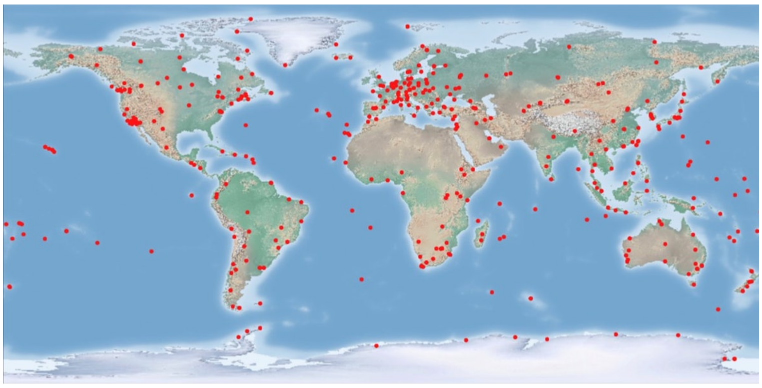

*Fig. 1. IGS stations (https://www.igs.org/station-resources)*

Since the 1980s until the end of 2020, more than 500 stations have been included in the IGS. Based on the information about frequency standards from the logs, there were more than 1,195 records for such a network, which leads to a ~2.5 changes of the oscillator type for each permanent station during its lifetime. The types of oscillators are divided almost in half: 610 external ones, 585 internal ones, and 22 of them unknown (log is not properly filled by the moderator, Table 1). Among external clocks, the majority of them are H-maser (315 external clocks), caesium (140), and rhodium (130), 22 do not have a detailed description of the external clock type (No record).

*Table 1. Statistics of the standard type number and mean lifespan in the IGS network*

| Standard-type | | Number of clocks | Mean lifespan |
|---|---|---|---|
| External | Quartz | 3 | 5,1 |
| | Caesium | 140 | 5,4 |
| | H-maser | 315 | 4,6 |
| | Rubidium | 130 | 4,4 |
| | There are no records. | 22 | 5,2 |
| Internal | | 585 | 9,7 |
| ∑ | | 1 195 | 7,2 |

Among all the stations analysed, Table 2 shows the top 10 with the longest uninterrupted operations of a single oscillator and the top 10 stations with the longest permanent periods on a single oscillator. The majority of the are internal, due to the simplest way of the mountain and low cost. The longest period is more than 30 years (PIN1 station, Pinyon Flats, USA).

Since beginning of IGS a several hundred stations belonged or belongs to an IGS till now. Therefore, a criterion related to the selective choice of several stations to present in this paper was made. Criterion was based on the selection of the 3 oscillators with the longest uninterrupted operation of each of the 4 types (Table 1) and the available clock products (Table 3). According to the standard types in the IGS network, 12 representative clocks were selected for detailed analyses, which will be further analysed.

Figure 2 shows a raw clock product of the sample of each oscillator type. In these graphs, a different kind of correction changes is clearly seen. Moreover, each graph has a different y-axis scale, thus in addition to the trends, magnitudes also differ.

The first part of the processing was the removal of outliers and gaps from a raw observation. For this purpose, an MAD (median absolute deviation) was calculated and a criterion of 5 MAD was adopted [1]. Figure 3 shows raw (left) and cleaned (right) data for the IRTK station.

*Table 2. Top 10 stations with the longest uninterrupted operating single oscillators*

| # | Station | Clock | Clock-type | From | To | Days | Years |
|---|---|---|---|---|---|---|---|
| 1 | PIN1 | Internal | | 09.01.1990 | 24.11.2020 | 11 277 | 30,9 |
| 2 | JPLM | External | Rubidium | 20.03.1990 | 30.11.2018 | 10 482 | 28,7 |
| 3 | VNDP | Internal | | 25.05.1992 | 24.11.2020 | 10 410 | 28,5 |
| 4 | INEG | Internal | | 19.02.1993 | 24.11.2020 | 10 140 | 27,8 |
| 5 | ONSA | External | H-Maser | 01.07.1991 | 02.04.2019 | 10 137 | 27,8 |
| 6 | NLIB | External | H-Maser | 05.03.1993 | 24.11.2020 | 10 126 | 27,7 |
| 7 | BRMU | Internal | | 12.03.1993 | 24.11.2020 | 10 119 | 27,7 |
| 8 | ZIMM | Internal | | 01.05.1993 | 24.11.2020 | 10 069 | 27,6 |
| 9 | MAW1 | Internal | | 01.01.1994 | 24.11.2020 | 9 824 | 26,9 |
| 10 | BLYT | Internal | | 13.01.1994 | 24.11.2020 | 9 812 | 26,9 |

*Table 3. Statistics of the standard type number and mean lifespan in the IGS network*

| # | Station | City | Country | Clock | Clock-type | From | To | Days | Years |
|---|---|---|---|---|---|---|---|---|---|
| 1 | JPLM | Pasadena | USA | External | Rubidium | 20.03.1990 | 30.11.2018 | 10 482 | 28,7 |
| 2 | ONSA | Onsala | Sweden | External | H-Maser | 01.07.1991 | 02.04.2019 | 10 137 | 27,8 |
| 3 | NLIB | North Liberty | USA | External | H-Maser | 05.03.1993 | 24.11.2020 | 10 126 | 27,7 |
| 4 | BRMU | Town of St. George | UK | Internal | | 12.03.1993 | 24.11.2020 | 10 119 | 27,7 |
| 5 | ZIMM | Zimmerwald | Switzerland | Internal | | 01.05.1993 | 24.11.2020 | 10 069 | 27,6 |
| 6 | MAW1 | Mawson | Antarctica | Internal | | 01.01.1994 | 24.11.2020 | 9 824 | 26,9 |
| 7 | IRKT | Irkutsk | Russia | External | H-Maser | 16.09.1995 | 24.11.2020 | 9 201 | 25,2 |
| 8 | SUWN | Suwon-shi | South Korea | External | Rubidium | 03.02.1998 | 24.11.2020 | 8 330 | 22,8 |
| 9 | KIRU | Kiruna | Sweden | External | Caesium | 08.07.1993 | 19.02.2013 | 7 166 | 19,6 |
| 10 | VILL | Villafranca | Spain | External | Caesium | 12.11.1994 | 27.12.2012 | 6 620 | 18,1 |
| 11 | TSKB | Tsukuba | Japan | External | Caesium | 15.12.1993 | 14.09.2011 | 6 482 | 17.7 |
| 12 | JOZE | Jozefoslaw | Poland | External | Rubidium | 10.11.1994 | 30.06.2005 | 3 885 | 10,6 |

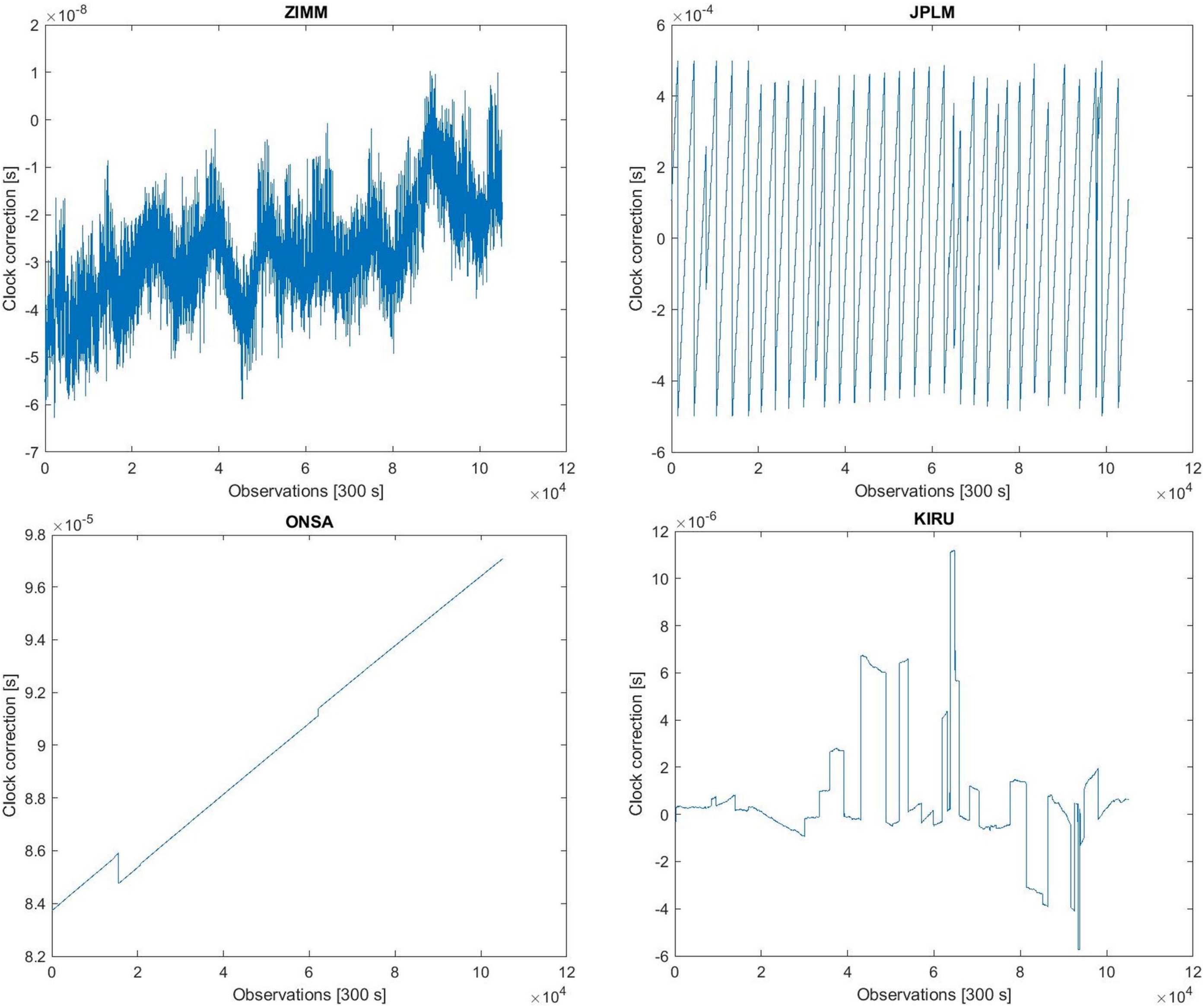


*Fig. 2. Raw clock corrections for 2015 of 4 different types of oscillators: ZIMM (internal), JPLM (rubidium), KIRU (caesium), and ONSA (H-maser) for each available period*

For the calculation, daily clock files for each clock mentioned in Table 3 were divided into years, for a simplification, only years with at least 80% of the cover (at least 292 days/year). For the possible identification of change in time in HDEV (Hadamard deviation) and frequency drift (aging) in yearly periods were calculated. Such as-

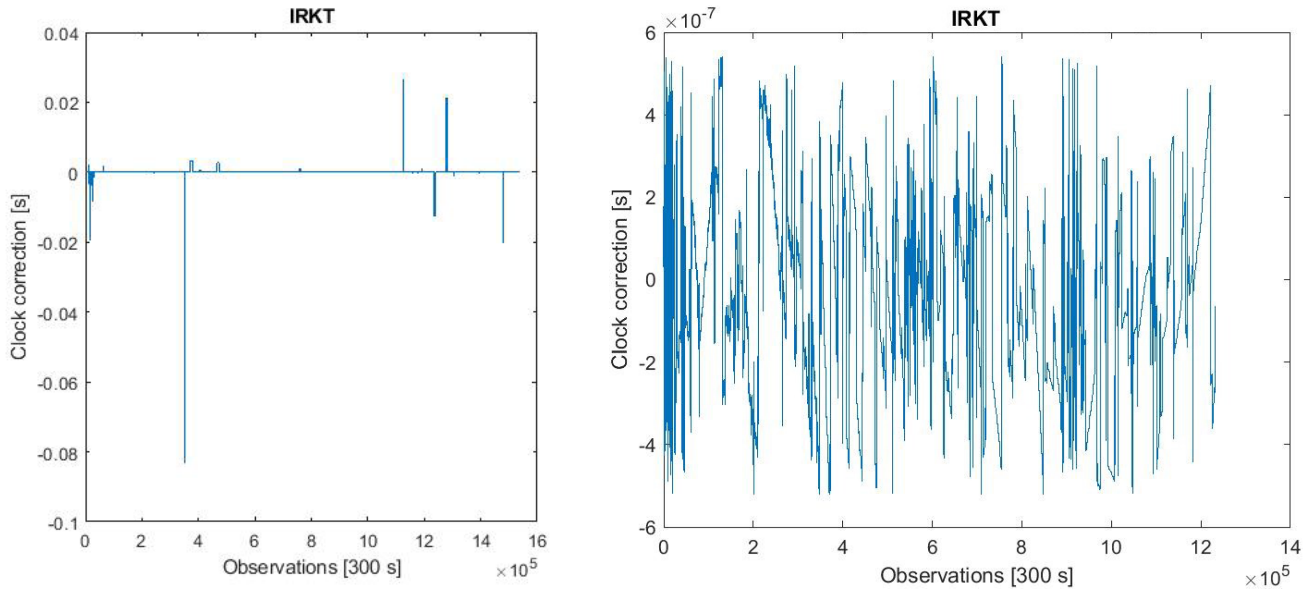


*Fig. 3. Clock corrections of the IRKT station for the 1994-2005 period: raw (left) and with removed outliers (right)*

sumption allows to reject frequency drift, and handles divergent noise, compared to the standard or other Allan variation (and related) [18].

## 3. Results

Based on the calculation, Figure 4 shows an HDEV for each year and each clock shown in Table 3. For the best possible interpretation, the X- and Y-axis scales are the same for each. The first row shows 3 internal oscillators, the second - rubidium ones, the third - caesium, and the fourth h-maser ones. When comparing results in a row, there is a small repeatability of the clocks in a type. For example, for the BRMU station, there is clearly no dependence between each analysed year. While for a MAW1 clock, there is high compatibility and repeatability of the results obtained comparing years among each other. These situations appear in the case of the rubidium and cesium clocks. For h-maser clocks, these results are more comparable to each other and compared year-to-year (IRKT & NLIB). The greatest consistency

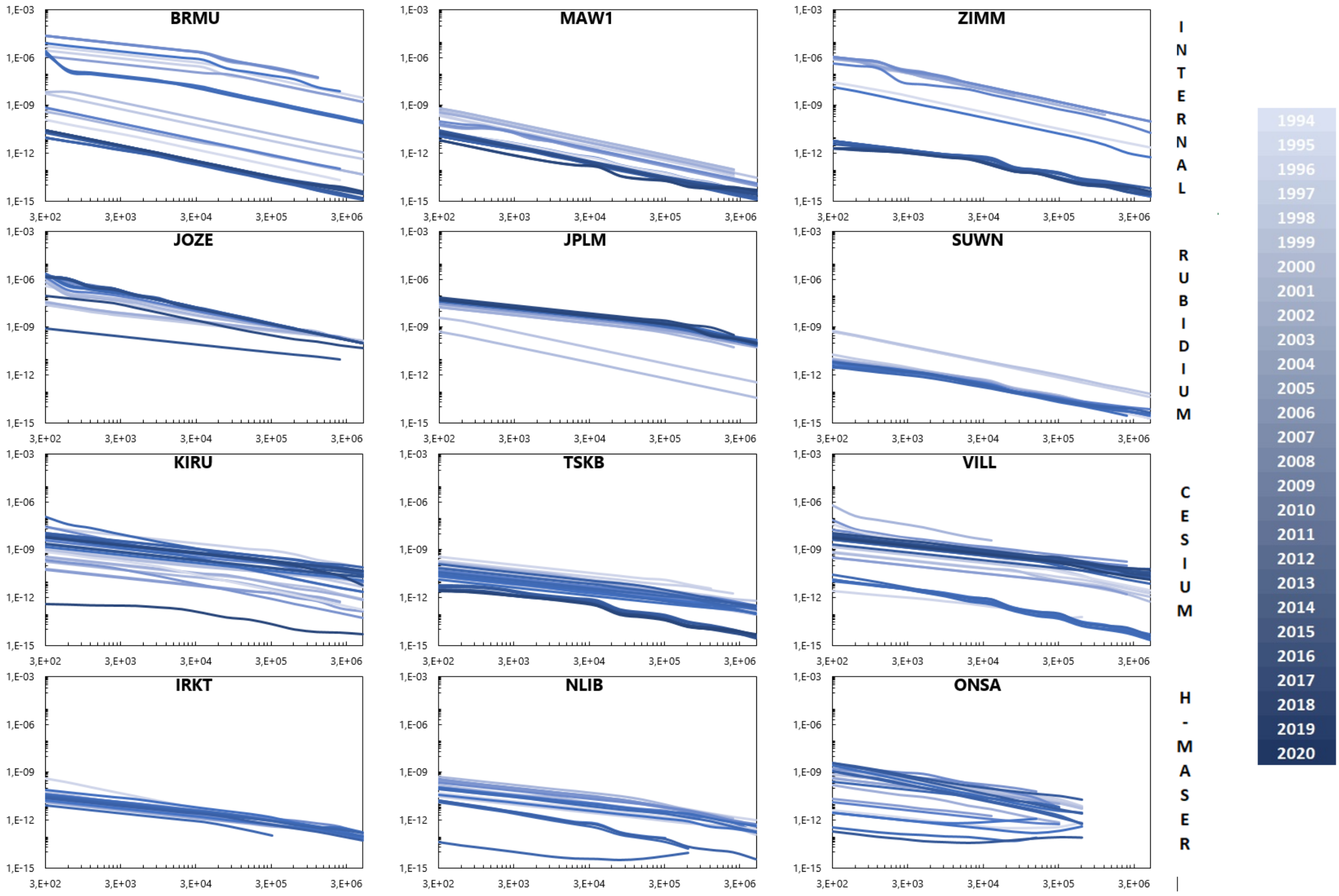


*Fig. 4. Comparison of the year-to-year ground clocks stabilities for period 1994 (light blue) to 2020 (dark navy). Each Y-axis - ADEV [s], each X-axis - averaging time τ [s]; $1^{st}$ row – internal oscillators, $2^{nd}$ – rubidium, $3^{rd}$ – caesium and $4^{th}$ – H-Maser*

of the results comparing individual years occurred at stations MAW1 (internal), SUWN (rubidium), and IRKT (h-maser). On the contrary, a comparative analysis of individual years among themselves for one station did not show significant changes. Only for 2 stations with an embedded clock (MAW1 and ZIMM) is a clear increase in stability over time evident. At the station ZIMM clocks for 1994-2008 years are at 1e-6 s to 1e-11 s stability. For years 2009-2020 at 1e-11 to 1e-15 s. Similar for a MAW1 station.

## 4. Conclusions

GNSS clocks are crucial in navigation and positioning. Thus, its continuous, uninterrupted, and stable operation is the basis for satellite navigation systems. In this paper, the author wanted to provide a brief analysis of the change in the stability of the GNSS reference station clocks over time. For this purpose, all reference stations available in the clock files since the beginning of the IGS network were analyzed. The results obtained were divided into 4 types of clocks that are available. Then, 3 randomly selected reference clocks were selected from this set for each of the 4 clock types (embedded, rubidium, cesium, and hydrogen masers) that were selected from this set. The results showed that there are no clock-type-specific variations in timing; the variations are stochastic in nature. Furthermore, only an increase in stability on 2 of the 3 embedded clocks analyzed was correlated with a change in time. The other 3 types of external clocks are stable over time and show no change.

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