A Novel Integrated Time Scale Method for Timekeeping Atomic Clocks (Postprint)

Authors: Jiang Meng(1, In recent years, deep learning has achieved breakthrough progress in image classification, natural language processing, and other fields. However, deep neural networks (DNN) typically require large amounts of labeled data to achieve ideal performance, which is a significant challenge in many practical applications. To address this issue, researchers have proposed methods such as transfer learning and meta-learning. Among them, transfer learning transfers knowledge from source domains to target domains, significantly reducing the need for labeled data. Specifically, transfer learning can be divided into several categories, including feature-based transfer, instance-based transfer, and model-based transfer. In deep learning, feature-based transfer methods are the most common, typically achieved by pre-training models on large-scale datasets (such as ImageNet) and then fine-tuning on specific tasks. This approach has achieved great success in computer vision and is widely applied in various practical tasks.

Although transfer learning performs well in many tasks, it still has some limitations. First, transfer learning assumes that source and target domains have similar feature distributions. When this assumption does not hold, transfer effectiveness significantly decreases, even causing negative transfer phenomena. Second, transfer learning typically requires designing and training separate models for each new task, which is inefficient when there are numerous tasks or tasks change dynamically. Additionally, traditional transfer learning methods struggle to effectively utilize structured information between different tasks, such as hierarchical relationships or semantic similarity between tasks. To overcome these limitations, meta-learning has attracted widespread attention as an emerging learning paradigm. Meta-learning aims to learn a "learning algorithm" that enables models to quickly adapt to new tasks. Unlike transfer learning, meta-learning not only transfers knowledge but also transfers the learning strategy itself. Typical meta-learning methods include Model-Agnostic Meta-Learning (MAML), Prototypical Networks, and Relation Networks, etc. These methods have achieved remarkable results in few-shot learning tasks.

However, existing meta-learning methods still face many challenges. On one hand, many meta-learning methods require sampling a large number of tasks during training, which may be difficult to achieve in certain domains (such as medical diagnosis). On the other hand, the generalization ability of meta-learning models is often limited by the distribution of training tasks, and performance drops sharply when test tasks differ significantly from training tasks. Additionally, meta-learning typically assumes all tasks are equally important, ignoring differences and correlations between tasks. To address these issues, this paper proposes a Task-Similarity-based Adaptive Meta-Learning framework (TSAML). This framework dynamically evaluates similarity between tasks and adaptively adjusts knowledge transfer strategies in the meta-learning process. Specifically, TSAML contains two core modules: a task similarity assessment module and an adaptive knowledge transfer module. The task similarity assessment module learns task representations through a contrastive learning mechanism and calculates similarity between tasks; the adaptive knowledge transfer module dynamically adjusts the parameter update strategy of the meta-learner based on task similarity, enabling rapid transfer for similar tasks and cautious handling for dissimilar tasks.

The main contributions of this paper can be summarized as follows:

- We propose a novel task similarity assessment method that learns distributed representations of tasks through contrastive learning, capable of accurately capturing semantic similarity between tasks.
- We design an adaptive meta-learning framework that can dynamically adjust knowledge transfer strategies based on task similarity, effectively alleviating the negative transfer problem.
- We conduct extensive experiments on multiple benchmark datasets, including Omniglot, miniImageNet, and CIFAR-FS, validating the superior performance of TSAML on standard few-shot classification tasks and cross-domain few-shot learning tasks. Experimental results show that TSAML improves classification accuracy by 2-5% compared to existing methods, and exhibits stronger robustness when task distribution differences are large.

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Abstract

This article proposes a hydrogen-cesium composite time scale generation method based on improved exponential smoothing and Vondrak_{Cepek} joint smoothing. Grounded in the minimum error method as the theoretical foundation, it dynamically estimates the frequency drift parameters of hydrogen masers to enhance the prediction accuracy of hydrogen maser clock differences; it generates the hydrogen maser ensemble time scale using improved quadratic exponential smoothing and the cesium clock time scale using a weighted average method, while simultaneously designing a Vondrak_{Cepek} filter to combine the long-term and short-term stability advantages of the two types of time scales, thereby improving composite time scale performance. Experimental results demonstrate that the hydrogen-cesium composite time scale generated by the proposed method achieves a time stability of 1.60×10^{-15} and a day stability of 3×10^{-15}, outperforming the time scale performance produced by three classical methods: ALGOS, AT1, and Kalman filtering.

Full Text

A New Method for Generating a Comprehensive Time Scale for Time-keeping Atomic Clocks

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Abstract

This paper proposes a comprehensive time scale calculation method for hydrogen maser and cesium atomic clock based on improved exponential filtering and Vondrak-Cepek joint smoothing. Grounded in minimum error theory, this method dynamically estimates the frequency drift parameters of hydrogen masers to improve the accuracy of hydrogen atomic clock bias prediction. It generates a hydrogen maser time scale using an improved quadratic exponential smoothing method and a cesium atomic clock time scale using a weighted average method. Simultaneously, a Vondrak-Cepek filter is designed to combine the long-term and short-term stability advantages of the two types of time scales, thereby enhancing comprehensive time scale performance. Experimental results demonstrate that the proposed method achieves a comprehensive hydrogen-cesium time scale stability of 1.60 × 10−15 at 1 hour and 3 × 10−15 at 1 day, outperforming the time scale performance generated by three classical methods: ALGOS, AT1, and Kalman filtering.

Keywords: time scale, clock difference prediction, dynamic estimation, stability

High-precision time represents one of the manifestations of a nation's comprehensive strength and finds widespread application in social life, economy, military affairs, and other domains[1-2]. Currently, International Atomic Time is generated through the weighted average of over 600 time-keeping atomic clocks from more than 70 time laboratories worldwide[3]. Time-keeping atomic clocks are primarily divided into two types: hydrogen masers and cesium atomic clocks[4]. Hydrogen masers exhibit excellent short-term characteristics but poor long-term performance, whereas cesium clocks demonstrate good long-term stability but significant short-term fluctuations[5-6]. The key to improving comprehensive time scale performance lies in the rational utilization of the advantages of these two types of atomic clocks.

Current hydrogen-cesium composite time scale models primarily employ weighted averaging methods, with weights assigned based on atomic clock historical data, placing greater emphasis on the long-term stability of the comprehensive time scale[7]. In reference[8], to fully leverage the short-term advantages of hydrogen masers, hydrogen masers were used as a reference time scale to calculate cesium atomic clock noise, followed by filtering the cesium clocks and removing their frequency rates. Subsequently, the frequency and frequency drift parameters of hydrogen masers were estimated, and the hydrogen maser data with drift and rate removed were used for comprehensive time scale calculation. In reference[9], a time scale generated by all cesium clocks served as a reference to estimate the frequency and frequency drift parameters of each hydrogen maser, followed by wavelet filtering to reduce hydrogen maser noise, ultimately producing a comprehensive time scale. The above research results indicate that when using hydrogen masers as a measurement reference for cesium atomic clocks, the primary noise is Gaussian white noise. Even after filtering to remove noise, short-term performance remains subject to interference from cesium clock noise. Although wavelet transform can effectively reduce cesium atomic clock noise, it requires careful consideration of decomposition levels, wavelet function selection, and other issues. These subjective factors directly determine the effectiveness of wavelet filtering and may consequently impact comprehensive time scale performance.

This paper further explores methods for generating comprehensive time scales for time-keeping atomic clocks and conducts in-depth research on joint techniques for different types of time scales. By generating a hydrogen maser time scale through an improved quadratic exponential smoothing method, producing a cesium clock time scale using a weighted average algorithm, and effectively combining the two types of time scales through Vondrak-Cepek (V-C) smoothing, the accuracy and stability metrics of the comprehensive time scale for time-keeping atomic clocks are improved. First, based on minimum error theory, a mathematical model for hydrogen maser frequency drift parameter prediction is established to estimate this parameter more accurately. Then, a full hydrogen maser time scale is generated using the quadratic exponential smoothing method. Finally, the V-C smoothing method is employed to combine the two types of atomic clock group time scales, thereby improving the performance of the comprehensive time scale for time-keeping atomic clocks.

The main innovations of the proposed method are as follows. First, guided by minimum error theory, a prediction model for hydrogen atomic clock frequency drift parameters is established to improve the accuracy of hydrogen atomic clock bias prediction. Second, the concept of fusing different types of atomic clock data at the time scale level is proposed, with a V-C filtering method designed and parameters optimized. By utilizing the first derivative of the full hydrogen maser time scale to improve the performance of the full cesium clock time scale, the long-term and short-term stability performance of the hydrogen-cesium comprehensive time scale is ultimately enhanced.

2 Theoretical Foundation

2.1 Quadratic Exponential Smoothing Clock Bias Prediction Method

The main steps of the traditional quadratic exponential smoothing method are clock bias prediction, clock rate prediction, and determination of weights for each atomic clock. Based on the clock bias measurement data at the current time t, the clock bias at the next moment is estimated:

$$\hat{X}_i(t+\tau) = X_i(t) + Y_i(t)\tau + d\tau^2,$$

where $X_i(t)$ and $Y_i(t)$ are the clock bias and rate of clock i at time t, respectively, τ is the measurement time interval, d is the atomic clock frequency drift parameter, and $\hat{X}_i(t+\tau)$ is the estimated clock bias of atomic clock i at time $(t+\tau)$. Simultaneously, according to the characteristics of atomic clock bias data, n differences between the master clock and ‘paper time’ can be obtained corresponding to n atomic clocks. Finally, reasonable weighting of these n differences between the master clock and ‘paper time’ yields the optimal time:

$$X_j(t+\tau) = \text{(cid:88)} w_i(\tau)\hat{X}_i(t+\tau) - X_{ij}(t+\tau) = \Delta(\tau_1)\{x(t+\tau_1)\} - \Delta(\tau_2)\{x(t)\},$$

where $\Delta(\tau_1)$ represents the clock bias value and predicted value at measurement interval τ_1.

2.2 Optimized Quadratic Exponential Smoothing Method Model

This method utilizes prediction error to dynamically estimate hydrogen atomic clock frequency drift parameters. Compared with traditional quadratic exponential smoothing clock bias estimation, it adds a prediction interval parameter. Within this time period, optimal estimation of d and averaging time is performed based on the minimum Root Mean Square (RMS) prediction error principle, thereby improving the accuracy of clock bias estimation.

The prediction operator expression is as follows:

$$\hat{x}(t+\tau_1) = x(t) + \tau_1 y(t,\tau_2) +,$$

where $\hat{x}(t+\tau_1)$ is the atomic clock bias prediction operator at time $(t+\tau_1)$, τ_1 is the prediction interval, τ_2 is the averaging time, $x(t)$ represents the atomic clock bias at time t, and $y(t,\tau_2)$ is the causal moving average operator of the atomic clock rate at time t with averaging time τ_2.

The prediction error is defined as:

$$\varepsilon(t,\tau_1,\tau_2) = x(t+\tau_1) - \hat{x}(t+\tau_1).$$

The prediction error RMS is:

$$\mathrm{RMS}\{\varepsilon(t,\tau_1,\tau_2)\} = (\text{cid:90})_{\infty} s_{xx}(f) \times |H(j2\pi f)|^2 df,$$

where f is the atomic clock frequency and s_{xx} represents the sum of squared deviations of the atomic clock bias.

The transfer function $|H(j2\pi f)|^2$ is defined as follows:

$$|H(j2\pi f)|^2 = 4\sin^2(\pi f\tau_2) + (\text{cid:16})\frac{\tau_1}{(\text{cid:17})}(\text{cid:16})(\text{cid:17})(\text{cid:16})(\text{cid:17})(\text{cid:16})\frac{\tau_1}{(\text{cid:17})}\sin^2(\pi f\tau_1) - \sin^2(\pi f$$

2.3 Vondrak-Cepek Smoothing Modeling

The optimized quadratic exponential smoothing method generates a hydrogen maser time scale, the improved weighted average method obtains a full cesium clock time scale, and finally the two different types of time scales are organically combined. Here, the full cesium clock time scale (TA-Cs) is denoted by $m(t)$, a function of time t, with its first derivative at time t defined as:

$$m'(t) = [m(t+\tau_{Cs}) - m(t)]/\tau_{Cs},$$

where τ_{Cs} represents the clock bias measurement interval of cesium atomic clocks. $M(t)$ denotes the full hydrogen maser time scale (TA-H), with its first derivative defined as:

$$M'(t) = [M(t+\tau_H) - M(t)]/\tau_H,$$

where τ_H represents the clock bias measurement interval of hydrogen masers. $m'(t)$ and $M'(t)$ represent the rates of the two types of clock group time scales. If the measurement intervals of cesium and hydrogen atomic clocks are identical, then $m'(t) = M'(t)$. Consequently:

$$\int_{\mathrm{MJD1}}^{\mathrm{MJD}_2} m'(\text{TA-Cs})dt = \int_{\mathrm{MJD1}}^{\mathrm{MJD}_2} M'(\text{TA-H})dt,$$

where MJD (Modified Julian Day) is the modified Julian date. The estimation of the cesium clock group time scale is calculated as follows:

$$m(\mathrm{MJD}_2) = m(\mathrm{MJD}_1) + M'(t)\Delta t,$$

where Δt represents the time interval.

In the calculations presented herein, the selected atomic clock data measurement interval is 1 hour, making the measurement intervals of the two types of atomic clocks identical. Therefore, the clock bias estimate of the full cesium clock time scale at the next moment can be generated using the sum of the current full cesium clock time scale bias value and the product of the full hydrogen maser time scale rate and time interval. The selection of atomic clock data measurement intervals also significantly impacts time scale performance. Excessively large measurement intervals cause the frequency drift of hydrogen masers to increase within the measurement period, affecting comprehensive time scale accuracy. Conversely, excessively high measurement frequencies may cause the atomic clock' s inherent noise to be masked by measurement noise, making accurate atomic clock modeling more difficult and ultimately affecting time scale performance.

2.4 Algorithm Advantages

The method for generating hydrogen-cesium comprehensive time scales in reference[8] uses a high-performance hydrogen maser as the measurement reference to obtain the clock bias of each cesium atomic clock relative to this high-performance hydrogen maser. Mathematical filtering methods are then applied to each cesium clock' s bias data to remove noise, followed by least squares fitting of the cesium clock bias data to estimate each cesium atomic clock' s rate, which is subsequently removed for later use. Simultaneously, the frequency and frequency drift parameters of hydrogen masers are predicted using quadratic fitting methods. Finally, cesium clocks with rates removed and hydrogen masers with rates and drift removed constitute the time-keeping clock group, and a weighted average method is used to generate the comprehensive time scale.

In contrast, the proposed method avoids using hydrogen masers as a measurement reference. It employs improved quadratic smoothing to dynamically estimate hydrogen maser parameters for generating a hydrogen maser group time scale, utilizes a weighted average algorithm to generate a cesium clock time scale, and finally adopts V-C smoothing to combine the long-term and short-term advantages of the two clock group time scales. This method uses optimal estimation to dynamically predict hydrogen maser frequency drift parameters, providing more accurate and reasonable drift parameter estimation than quadratic fitting methods. Additionally, the weighted average method is used to generate the cesium clock time scale, while quadratic smoothing generates the hydrogen maser time scale. The algorithm selection considers that the weighted average method allocates weights based on all historical information of atomic clocks, emphasizing long-term time scale performance and being suitable for cesium atomic clock groups with better long-term performance. The quadratic exponential smoothing method, conversely, focuses more on time scale real-time performance and is better suited for hydrogen maser groups with good short-term performance. Ultimately, the V-C joint smoothing method integrates the advantages of both time scales to enhance comprehensive time scale performance.

3.1 Algorithm Design

Based on the Fortran language, this paper develops a software system in the Visual Studio compilation environment to implement the improved quadratic exponential smoothing (OX) and V-C smoothing (OX+V-C) hydrogen-cesium comprehensive time scale algorithm. Figure 1 [Figure 1: see original paper] illustrates the design process of the OX+V-C method. OX+V-C implementation mainly includes the following components: estimation of d, clock difference prediction between n atomic clocks and ‘paper time’ , weight assignment for each atomic clock, clock difference and rate prediction between the master clock and ‘paper time’ , improved quadratic exponential smoothing time scale for hydrogen maser groups, weighted average time scale for cesium clock groups, generation of full hydrogen maser time scale rates, V-C filter design, and···

3.2 Experimental Process and Results Analysis

This experiment takes hydrogen masers and cesium atomic clocks as research subjects, with three hydrogen masers and three cesium atomic clocks constituting the time-keeping clock group. Atomic clock data from MJD 59945–59975 (January 1 to January 31, 2023) is selected to validate the effectiveness of the proposed method. First, the frequency drift parameters of each hydrogen maser are estimated based on minimum error theory, an exponential filter is designed, and the improved quadratic exponential smoothing time scale TA-DH is calculated.

To analyze the improvement of this method on time scale performance, a comparison is made with the traditional quadratic exponential smoothing full hydrogen maser time scale. Frequency drift parameters are estimated based on quadratic fitting of the last 5 days of hydrogen maser clock bias data, and the quadratic exponential smoothing time scale TA-H is calculated, with results shown in Figure 2 [Figure 2: see original paper]. Simultaneously, the Allan deviation (ADEV) of both time scales is calculated, with results presented in Table 1 .

As shown in Figure 2, the time scale obtained by the improved quadratic exponential smoothing has a deviation within 4 ns over a 31-day interval, whereas the time scale produced by the fixed frequency drift method has a deviation within 8 ns during the same period. Therefore, the proposed improved quadratic exponential smoothing method can effectively improve the accuracy of the full hydrogen maser time scale. According to Table 1, TA-DH exhibits smaller Allan deviation values than TA-H at different averaging times, indicating that the improved quadratic exponential smoothing time scale has slightly better long-term and short-term stability than the time scale calculated using traditional methods for the same clock group. TA-DH achieves a stability of 1.29 × 10−14 at 1 hour and 7.0 × 10−15 at 1 day. In summary, the improved quadratic exponential smoothing method can effectively enhance time scale accuracy while also improving stability metrics.

Next, the cesium clock group time scale TA-Cs is generated through a weighted average algorithm. The full cesium clock time scale exhibits large short-term fluctuations but small long-term variations, whereas the full hydrogen maser time scale shows the opposite pattern—this situation aligns perfectly with the V-C smoothing theoretical model. Finally, by calculating the first-order difference of the full hydrogen maser time scale, the hydrogen-cesium comprehensive time scale is computed according to the V-C smoothing algorithm, with the time scale curve shown in Figure 3 [Figure 3: see original paper]. Figure 4 [Figure 4: see original paper] displays the residual distribution between the time scale generated by weighted averaging of three cesium clocks and the OX+V-C time scale. As seen in Figure 3, the two curves follow the same trend, but the OX+V-C curve is much smoother than TA-Cs, proving that the method effectively improves short-term time scale fluctuations while preserving the long-term performance of the full cesium clock time scale. Additionally, the experimental results are evaluated using the Root Mean Square Error (RMSE) between the full cesium clock time scale and the OX+V-C time scale, yielding RMSE = 0.02. This indicates that the time scale obtained by the V-C smoothing method can follow the trend of TA-Cs, retain most of its information, and effectively utilize the long-term advantages of the full cesium clock time scale. Figure 4 shows that the residuals of the two time scales fluctuate around zero, and the residuals follow a normal temporal distribution pattern, which is consistent with white noise characteristics.

To verify whether the OX+V-C hydrogen-cesium comprehensive time scale method improves long-term and short-term stability, this paper also compares the corresponding metrics of comprehensive time scales generated by three classical algorithms: AT1, ALGOS, and Kalman filtering. First, the influence of frequency drift on the clock bias is removed from the three hydrogen masers, which then participate in the calculation along with the three cesium clocks. Comprehensive time scales are generated using the traditional AT1, ALGOS, and Kalman filtering algorithms. The time scale results are shown in Figure 5. The red curve represents the hydrogen-cesium comprehensive time scale produced by the ALGOS method, the blue curve represents that produced by the AT1 method, the green curve indicates the hydrogen-cesium comprehensive time scale generated by the proposed OX+V-C method, and the black curve shows the hydrogen-cesium comprehensive time scale from the Kalman filtering algorithm. As seen in Figure 5 [Figure 5: see original paper], the OX+V-C time scale curve is smoother than the other three, and exhibits the smallest time deviation over a one-month interval. Simultaneously, the Allan deviation of the four comprehensive time scales is calculated, with data metrics and distribution presented in Table 2 and Figure 6 [Figure 6: see original paper]. According to Table 2 and Figure 6, the OX+V-C time scale achieves a stability of 1.60 × 10−15 at 1 hour and 3.0 × 10−15 at 1 day, which is superior to the corresponding metrics of time scales produced by the AT1, ALGOS, and Kalman filtering methods. Therefore, this further demonstrates that the long-term and short-term stability of the proposed method exceeds that of time scales obtained by the three classical methods, while also proving that the method can effectively utilize the advantages of both atomic clock group time scales to further enhance comprehensive time scale performance.

Additionally, this paper uses the same time-keeping clock group atomic clock data to generate two fusion time scales, TA1 and TA2, based on the hydrogen-cesium comprehensive time scale calculation methods adopted in references[8] and[9]. It also uses the optimized quadratic smoothing method to generate hydrogen maser group and cesium clock group time scales separately, then produces the comprehensive time scale TA-EF-VC through V-C smoothing. The stability metrics of the three types of time scales are calculated and compared with the proposed method, with results presented in Table 3 . As shown in Table 3, the time stability and day stability of the comprehensive time scale generated by the proposed OX+V-C method are superior to the corresponding metrics of the other three time scales, further proving that the OX+V-C algorithm achieves optimal performance in the calculations using the six atomic clocks selected for this paper. Moreover, the time scale stability metrics produced by the proposed method are also better than those of the TA-EF-VC method. The reason is analyzed to be that since cesium clocks have no frequency drift term, the optimized quadratic smoothing method primarily focuses on optimal estimation of hydrogen maser drift, emphasizing short-term time scale stability and being more suitable for hydrogen maser groups with better short-term performance.

Based on optimized quadratic exponential smoothing and V-C smoothing methods, this paper establishes a new time scale generation model for time-keeping atomic clocks. By utilizing derivative information from the hydrogen maser group time scale to address the problem of large short-term noise in the cesium clock group time scale, it achieves the integration of full hydrogen maser and full cesium clock at the time scale level. Experimental results demonstrate that the comprehensive time scale generated by the proposed method achieves a stability of 1.60 × 10−15 at 1 hour and 3.0 × 10−15 at 1 day, representing significant improvements in long-term and short-term performance compared to comprehensive time scales calculated by three traditional methods: ALGOS, AT1, and Kalman filtering. The method achieves the expected results, proving the effectiveness of the proposed approach.

References

[1] 董绍武, 王燕平, 武文俊, 等. 时间频率学报, 2018, 41: 73
[2] 张继海, 武文俊, 广伟, 等. 仪器仪表学报, 2018, 39: 96
[3] Sruthikeerthi N R, Maharana S, Rajathilagam B, et al. MAPAN, 2020, 35: 547
[4] Petit G, Arias F, Panfilo G. Comptes Rendus Physique, 2015, 16: 480
[5] Panfilo G and Arias F. Metrologia, 2019, 56: 042001
[6] Levine J. Review of Scientific Instruments, 2012, 83:
[7] Arias F, Panfilo G, Petit G. Metrologia, 2011, 48: S145
[8] Suman S, Pascale D. Proceedings of Conference on Precision Electromagnetic Measurements. South Korea: IEEE Xplore, 2010, 1: 454
[9] 宋会杰, 董绍武, 姜萌, 等. 天文学报, 2018, 59: 5

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