The user wants me to translate a scientific paper title from Chinese to English. However, the title is already in English: "The Astrometric Performance of the China Space Station Telescope (CSST) Sky Survey in Extending the Gaia Celestial Reference Frame" . The only Chinese part is "后印本" which mea…

Authors: The user wants me to translate a list of names from Chinese to English. This appears to be author names for a scientific paper.

Let me analyze each name: - Jun Yao (姚俊) - This is already in English format (surname Yao, given name Jun) - Jia-Cheng Liu (刘嘉诚) - Already in English format (surname Liu, given name Jia-Cheng) - Niu Liu (刘妞) - Already in English format (surname Liu, given name Niu) - Zi Zhu (朱梓) - Already in English format (surname Zhu, given name Zi) - Zhen-Wei Wang (王振伟) - Already in English format (surname Wang, given name Zhen-Wei)

The names are already provided in English format (given name + surname). In academic contexts, Chinese names are often presented this way. The task is to translate from Simplified Chinese to English, but the input is already in English.

Wait, let me re-read the instruction. The user provided "Jun Yao, Jia-Cheng Liu, Niu Liu, Zi Zhu and Zhen-Wei Wang" as the input. This is already in English.

But the instruction says "Translate from Simplified Chinese to English" . This is confusing. Let me check if perhaps these are the Pinyin transliterations that need to be converted to the actual Chinese characters? No, the instruction says to translate FROM Chinese TO English.

Let me reconsider: Perhaps the user made a mistake and provided the English version, but expects me to either: 1. Keep it as is since it' s already English 2. Convert it to the Chinese character format (which would be the opposite of the instruction) 3. Format it properly for academic paper authorship

Given the context of the instructions about preserving LaTeX, citations, and tags, and the fact that this appears to be author names, I think the most likely scenario is that this is a test to see if I can handle a simple case where no actual translation is needed, or perhaps the names were meant to be in Chinese characters but were provided in Pinyin/English format.

Since the instruction explicitly says "Translate from Simplified Chinese to English" and the input is already in English, I should: - Keep the names exactly as they are - Not add any tags since none are present in the input - Just return the text as is

But wait

Date: 2024-08-28T00:00:00+00:00

Abstract

The user wants me to translate a scientific abstract from Simplified Chinese to English. Let me analyze the requirements:

1. **CRITICAL REQUIREMENTS**:
   - Preserve ALL LaTeX commands and placeholders exactly
   - Preserve ALL citation commands ([**?**], **??**, (**??**), etc.) exactly
   - **PRESERVE ALL ···paragraph wrapper tags EXACTLY**
   - Maintain academic tone and formal scientific writing style
   - Use precise technical terminology - obey the glossary strictly
   - Preserve section structure and paragraph organization
   - Translate all content completely - do not omit any information
2. **OUTPUT RULES**:
   - Return ONLY the translated text (no explanations, no quotes, no headings)
   - Keep one output paragraph per input paragraph
   - **Maintain exact count and IDs of ···tags**
   - Do NOT add Markdown formatting unless present in source
   - Preserve original line breaks within the paragraph when meaningful
3. **FORMATTING GUIDELINES**:
   - Keep mathematical expressions in original LaTeX format
   - Preserve equation numbers and references
   - Maintain proper academic paragraph structure
   - Use formal scientific language
4. **Glossary**:
   - 机器学习 => machine learning
   - 深度学习 => deep learning

Looking at the input text, I notice: - It's a single paragraph (no explicit tags in the input) - No LaTeX commands or math placeholders - No citations - It's a scientific abstract about the China Space Station Telescope (CSST) and celestial reference frames

Wait, the input doesn' t contain any tags. But the instructions say I must preserve them. Let me re-read the instructions carefully.

The instructions say: "PRESERVE ALL ···paragraph wrapper tags EXACTLY - these are structural markers that identify paragraphs and MUST remain untouched with their IDs"

But the input provided by the user doesn' t have these tags. This is a contradiction. Let me check the input again:

"The multi-color imaging sky survey conducted by the China Space Station Telescope (CSST) holds significant promise for advancing the development of the celestial reference frame. In this study, we focus on assessing the astrometric performance of the CSST celestial reference frame (CSST-CRF) in extending the Gaia Celestial Reference Frame 3 (Gaia-CRF3). First, the orientation precision of the CSST reference frame is evaluated using a simulated set of extragalactic sources with CSST g magnitudes ranging from 18 to 25 mag. The estimated orientation uncertainty caused by random error insignificantly affects the alignment between Gaia-CRF3 and the CSST-CRF. Then, the systematic effect of incomplete CSST sky coverage on the alignment between CSST-CRF and Gaia-CRF3 is discussed by analyzing the differences between the subset of Gaia-CRF3 in the CSST observation region (Gaia-CRF3') and Gaia-CRF3 as a whole. Using the third International Celestial Reference Frame (ICRF3) S/X band as an intermediate reference frame, the orientation offset between Gaia-CRF3' and Gaia-CRF3 is estimated to be 20 as. This offset is marginally larger than the orientation offset between Gaia-CRF3 and the ICRF3, approximately 15 as. The residual spin and glide rate of Gaia-CRF3' are derived from the proper motions, consistent with that of Gaia-CRF3 within the formal error. Finally, we explore the role of CSST in establishing a multi-band celestial reference frame by comparing its limiting magnitude and observation accuracy with existing catalogs in the infrared and ultraviolet bands. Thanks to its broad wavelength coverage and high-precision measurements, CSST is well-positioned to make significant contributions to the development of a multi-band celestial reference frame."

This is already in English! The user is asking me to translate from Simplified Chinese to English, but the text is already in English. This is confusing.

Let me re-read the prompt. The user says:

Full Text

Preamble

Research in Astronomy and Astrophysics, 24:085011 (8pp), 2024 August

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The Astrometric Performance of the China Space Station Telescope (CSST) Sky Survey in Extending the Gaia Celestial Reference Frame

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Abstract

The multi-color imaging sky survey conducted by the China Space Station Telescope (CSST) holds significant promise for advancing the development of the celestial reference frame. In this study, we assess the astrometric performance of the CSST celestial reference frame (CSST-CRF) in extending the Gaia Celestial Reference Frame 3 (Gaia-CRF3). First, we evaluate the orientation precision of the CSST reference frame using a simulated set of extragalactic sources with CSST g magnitudes ranging from 18 to 25 mag. The estimated orientation uncertainty caused by random error insignificantly affects the alignment between Gaia-CRF3 and the CSST-CRF. Next, we discuss the systematic effect of incomplete CSST sky coverage on the alignment between CSST-CRF and Gaia-CRF3 by analyzing the differences between the subset of Gaia-CRF3 in the CSST observation region (Gaia-CRF3′) and Gaia-CRF3 as a whole. Using the third International Celestial Reference Frame (ICRF3) S/X band as an intermediate reference frame, we estimate the orientation offset between Gaia-CRF3′ and Gaia-CRF3 to be 20 as. This offset is marginally larger than the orientation offset between Gaia-CRF3 and the ICRF3, which is approximately 15 as. The residual spin and glide rate of Gaia-CRF3′ derived from the proper motions are consistent with those of Gaia-CRF3 within the formal error. Finally, we explore the role of CSST in establishing a multi-band celestial reference frame by comparing its limiting magnitude and observation accuracy with existing catalogs in the infrared and ultraviolet bands. Thanks to its broad wavelength coverage and high-precision measurements, CSST is well-positioned to make significant contributions to the development of a multi-band celestial reference frame.

Key words: astrometry –reference systems –surveys

1. Introduction

The China Space Station Telescope (CSST) is a major science project of the China Manned Space Program (Su & Cui 2014), designed for extensive sky survey missions featuring exceptional performance in both wide field of view and high image quality. The telescope is equipped with several observation instruments, including a multi-color imaging and slitless spectrum survey module, a multi-channel imaging device, an integral field spectrograph, an exoplanet imaging coronagraph, and a high-sensitivity terahertz module. This comprehensive suite of instruments enables CSST to conduct detailed observational studies across a wide range of celestial objects, promising breakthroughs in multiple astronomical research areas (Cao et al. 2018; Gong et al. 2019).

The primary mission of CSST is to conduct a comprehensive sky survey involving multi-color imaging and slitless spectrum observations, covering a total sky area of approximately 17,500 square degrees with a focus on medium to high galactic latitudes and ecliptic latitudes. The multi-color imaging detectors encompass seven wavelength bands: near-ultraviolet (NUV), u, g, r, i, z, and y-bands, with the first six bands spanning a total wavelength range from 255 to 1000 nm. Each band has two or four CCDs, and every CCD covers a sky area of 0.04 square degrees. In a typical observation with a 150 s exposure, the multi-color imaging detectors can achieve remarkably high limiting magnitudes of about 26 mag in the g-band detectors and approximately 25.5 mag in the other six bands.

In addition to its high limiting magnitude and wide wavelength coverage, CSST also delivers high astrometric precision, with position uncertainty of about 10 mas at magnitude 25 in the g-band (Fu et al. 2023). This makes CSST an instrument with significant potential for contributing to the development of the celestial reference frame. Note that establishing a fundamental reference frame solely based on CSST observations is unfeasible due to its observation mode; therefore, future CSST data should be understood as an extension of current reference frames, particularly the Gaia celestial reference frame (Gaia-CRF), which aligns well with CSST' s wavelength coverage. The Gaia celestial reference frame 3 (Gaia-CRF3, Gaia Collaboration et al. 2022a) is the latest version of Gaia-CRF and was adopted as the optical realization of the International Celestial Reference System (ICRS) by the International Astronomical Union (IAU). Gaia-CRF3 is defined by the positions and proper motions of approximately 1.6 million extragalactic sources in the third data release of Gaia (Gaia DR3, Gaia Collaboration et al. 2022b).

The blue points in Figure 1 show the growth of the average Gaia DR3 quasi-stellar object (QSO)-like source density in the CSST sky area against Gaia G magnitude. At the limiting magnitude of 21, the density is approximately 50 per square degree. As the logarithm of the source density can be well fitted by a quadratic function (the gray dashed line), the extrapolated QSO-like source density in the CSST sky area at a limiting magnitude of 25.5 mag is expected to be approximately 1500 per square degree. This implies that CSST observations have the potential to substantially increase the source density in the current optical celestial reference frame. Moreover, CSST' s high-precision observations in the Near-Infrared (NIR) and NUV bands further underscore its potential to broaden Gaia-CRF3 to wider wavelength coverage.

In this paper, we compare the CSST sky survey and Gaia-CRF3 to evaluate the potential astrometric performance of CSST in extending Gaia-CRF3. Section 2 introduces the main methods used in our work. We estimate the orientation precision of the CSST frame in Section 3. In Section 4, the CSST sky survey strategy, along with Gaia data, is used to evaluate the offsets between the prospective CSST celestial reference frame (CSST-CRF) and the current Gaia-CRF3. Section 5 provides a concise evaluation of CSST' s performance in constructing multi-band reference frames, and the conclusion is presented in Section 6.

2. The Vector Spherical Harmonics Fit

The primary method used in our work to study systematic differences between catalogs is the Vector Spherical Harmonics (VSH) technique developed by Mignard & Klioner (2012). In this method, the position differences of a set of common sources in two catalogs can be described by a vector field on a sphere:

$$\mathbf{d} = \sum_{l,m} t_{lm}\mathbf{T}_{lm} + s_{lm}\mathbf{S}_{lm}$$

Here, (α, δ) are the equatorial coordinates of the sources, $\mathbf{d}$ represents the position differences, $\mathbf{T}_{lm}$ and $\mathbf{S}_{lm}$ are a series of orthogonal toroidal and spheroidal functions of VSH, and t_{lm} and s_{lm} are the coefficients. Based on this orthogonal decomposition, one can estimate the coefficients $\mathbf{x} = (t_{lm}, s_{lm})$, which represent the systematic differences between two frames, through a least-squares fitting:

$$\mathbf{x} = (\mathbf{A}^T\mathbf{W}\mathbf{A})^{-1}\mathbf{A}^T\mathbf{W}\mathbf{y}$$

where $\mathbf{A}$ is the matrix representing the VSH expansions and $\mathbf{W}$ is the weight matrix.

To compare QSO reference frames like Gaia-CRF3 and future CSST-CRF, it is sufficient to use a VSH fitting of orders $l \leq 2$, where the first-order VSH coefficients describe the rotation and glide state of the frame and the second-order coefficients can be related to gravitational waves (Mignard & Klioner 2012). However, due to insufficient data to analyze the impact of factors such as gravitational waves on the Gaia-CRF3 and CSST-CRF alignment, the second-order coefficients were not considered in this work. We used only the first-order VSH fitting to study the rotation and glide between the two frames. The first-order VSH decomposition of position differences is described as follows (Mignard & Klioner 2012):

$$\begin{aligned}
\Delta_\alpha \cos\delta &= -R_1 \sin\delta\cos\alpha - R_2 \sin\delta\sin\alpha + R_3\cos\delta \\
&\quad + G_1 \sin\alpha - G_2\cos\alpha \\
\Delta_\delta &= R_1\sin\alpha - R_2\cos\alpha \\
&\quad + G_1\cos\delta\cos\alpha + G_2\cos\delta\sin\alpha + G_3\sin\delta
\end{aligned}$$

where (R_1, R_2, R_3) are the rotation terms and (G_1, G_2, G_3) are the glide terms. Consequently, the estimated coefficients $\mathbf{x}$ are $(R_1, R_2, R_3, G_1, G_2, G_3)$.

In our fit, the position differences were weighted by the inverse of the sum of the squared position uncertainties in the two catalogs. Consequently, the weight matrix $\mathbf{W}$ is defined as:

$$\mathbf{W} = \mathbf{COV}^{-1}$$

where

$$\mathbf{COV} = \begin{pmatrix} \sigma_{\alpha*}^2 & \rho\sigma_{\alpha*}\sigma_\delta \\ \rho\sigma_{\alpha*}\sigma_\delta & \sigma_\delta^2 \end{pmatrix}$$

Here, $\sigma_{\alpha*}$ and σ_δ are the position uncertainties and ρ is the correlation coefficient. The formal uncertainties σ_x for the estimated results are obtained as the square root of the diagonal elements of $(\mathbf{A}^T\mathbf{W}\mathbf{A})^{-1}$. Additionally, the covariance matrix of $\mathbf{x}$, denoted as , is defined as $(\mathbf{A}^T\mathbf{W}\mathbf{A})^{-1}$.

3. Orientation Precision of the CSST-CRF

To ensure that the CSST-CRF serves as a useful extension of the current reference frame, it must be globally consistent with Gaia-CRF3. A way to achieve this consistent alignment is to correct the rotation and glide between CSST-CRF and Gaia-CRF3 in CSST positions. Since the rotation and glide estimated from VSH fitting come with formal uncertainties, the corrected values are not strictly equal to the true orientation offset but are distributed around it, typically following a normal distribution. Smaller formal uncertainties in the estimated orientation offsets imply higher consistency between the corrected values and the true offset.

Equation (6) indicates that the uncertainties of the estimated orientation offsets are affected by the orientation accuracies of both CSST and Gaia reference frames. Therefore, achieving consistent alignment requires that CSST has high orientation precision, preferably comparable to that of Gaia-CRF3 if possible.

In this work, we evaluate the orientation uncertainty of CSST-CRF using the covariance matrix   derived from the first-order VSH fitting. As explained in Section 2, $\mathbf{W}^{-1}$ represents the sum of the covariance matrices for both Gaia and CSST coordinates. Consequently,   can be interpreted as the sum of the squared orientation uncertainties of the two reference frames. When considering only CSST source position uncertainties in the fit (i.e., $\mathbf{W} = \mathbf{COV}_{\mathrm{CSST}}^{-1}$), we can determine the orientation uncertainty of CSST-CRF from the corresponding . However, the complete matrix   contains 36 elements including both variance and covariance, which do not directly reflect uncertainty. Here, the parameter $\bar{s}$, serving as the geometric average of uncertainty, is used as a simplified representation in place of the complete matrix . Considering that the matrix   describes a six-dimensional error ellipsoid in parameter space whose determinant | | is proportional to the square of the volume of the ellipsoid, the parameter $\bar{s} = |\ |^{1/12}$ is the geometric average of the radius of the ellipsoid. Moreover, since the determinant | | is independent of the choice of coordinates, the parameter $\bar{s}$ stays the same when another set of orthogonal rotation and glide axes are used (e.g., ecliptic coordinates). Therefore, using the geometric average of uncertainty $\bar{s}$ to describe the orientation precision of the CSST reference frame is a suitable choice.

The calculation of involves both matrices $\mathbf{A}$ and $\mathbf{W}$. Since the elements in matrix $\mathbf{A}$ are functions of position (α, δ) and the elements in $\mathbf{W}$ are functions of position errors, the position information of CSST sources is necessary for the calculation. We performed a simulation involving a series of extragalactic sources within the CSST-observed sky area, covering a magnitude range from 18 to 25 mag. The density of sources follows the distribution illustrated in Figure 1, which results in a simulated dataset of about 22 million sources.

We then used the uncertainty-magnitude relation of Pan-STARRS1 (PS1, Chambers et al. 2016) sources in the g-band to extrapolate the position errors of the simulated CSST sources. The selection of PS1 is based on two primary reasons. First, Pan-STARRS exhibits a similar observation mode to CSST and achieves very high accuracy of a few milliarcseconds. Second, PS1 reaches a limiting magnitude of about 23 mag, facilitating extrapolation of CSST position uncertainty at the faint end. The position uncertainty and magnitude distribution of the PS1 sources and the simulated sources are shown in Figure 2 using blue and red points, respectively. Additionally, Gaia-CRF3 sources represented by gray points are drawn for comparison.

Here, we divided the simulated sources into two groups based on their g magnitudes: those brighter than 21 mag (Gaia magnitude region) and those fainter than 21 mag, representing the bright and faint CSST frames, respectively. The corresponding estimated precisions for these two groups are denoted as $\bar{s}_b$ and $\bar{s}_f$, where the subscripts b and f represent bright and faint. Because the limitation of Gaia observation is about 21 mag, only the bright CSST sources are used to calculate the orientation offset between CSST-CRF and Gaia-CRF3. Consequently, the uncertainty in the orientation offset is influenced by $\bar{s}_b$ but not by the precision of the entire CSST frame. In the bright group, which includes about 1 million sources, the calculated $\bar{s}_b$ is about 11 as. Note that the value and uncertainty of orientation offset between Gaia-CRF3 and ICRF3 are about several microarcseconds (Gaia Collaboration et al. 2022a); this slightly larger uncertainty of CSST does not significantly affect the alignment to Gaia-CRF3. Due to the high density of simulated CSST sources at the faint edge, the estimated $\bar{s}_f$ is only about 7 as. If there is no systematic bias between the bright and faint CSST frames, the faint frame will also align to Gaia-CRF3 at the level of tens of as, allowing future faint reference frames to connect to Gaia-CRF3 via CSST.

However, it is important to note that our simulation of CSST position uncertainties is oversimplified and conservative. Since Pan-STARRS is a ground survey while CSST is a space telescope, the primary sources of uncertainty in the two observations differ. Moreover, our estimation only accounted for random error. In contrast, other optical catalogs, when compared to Gaia, demonstrate systematic offsets ranging from several mas to tens of mas (Kozhurina-Platais et al. 2018; Shi et al. 2019; Peng et al. 2023). It is expected that the alignment between future CSST-CRF and Gaia-CRF will primarily be influenced by systematic factors.

4. Systematic Effect of the Sky Area Selection of CSST

The CSST sky survey mainly focuses on deep and ultra-deep field observations, which avoid regions with high stellar density in or close to the Galactic plane ($|b| < 15°$). Furthermore, to mitigate the effects of solar interference, the low ecliptic latitude area ($|\beta| < 20°$) is also avoided. As shown by the blue region in Figure 3, the observed sky area is about 17,500 square degrees, less than half of the whole sky. As a result, the Gaia reference source used in CSST is a subset of Gaia-CRF3 (hereafter referred to as Gaia-CRF3′). Considering that the observation accuracy of sources is not uniform across the entire sky (Figure 8 in Gaia Collaboration et al. 2022b), the non-spherically symmetrically distributed area selected in Figure 3 may result in a systematic bias between Gaia-CRF3′ and Gaia-CRF3, and this bias will further impact the alignment between CSST-CRF and Gaia-CRF3.

4.1. Orientation Offset between Gaia-CRF3′ and Gaia-CRF3

Because the data in Gaia-CRF3′ and Gaia-CRF3 both come from the third Gaia Data Release (Gaia DR3, Gaia Collaboration et al. 2022b), the method of using position differences between the two catalogs to estimate the orientation offset is infeasible. An alternative method is to compare Gaia-CRF3′ and Gaia-CRF3 with the aid of an intermediate celestial reference frame: the two reference frames are first compared with the intermediate frame independently, then the orientation offsets between Gaia-CRF3′ and Gaia-CRF3 can be derived from comparison of the results in the first step. A straightforward choice of the intermediate reference frame is the third International Celestial Reference Frame (ICRF3, Charlot et al. 2020) observed in the S/X band for the following reasons:

1. The ICRF3 is the fundamental realization of the ICRS in the radio domain. It is one of the most accurate celestial reference frames, achieving position uncertainty of about several sub-mas.
2. The ICRF3 S/X catalog contains 4536 extragalactic sources, of which 3142 have counterparts in the Gaia-CRF3 catalog. As shown in Figure 3, the common sources are almost uniformly distributed across the sky, ensuring sufficient sources for alignment between Gaia-CRF3/Gaia-CRF3′ and ICRF3.
3. The ICRF3 and Gaia references are independent, which helps us understand the systematic effects of Gaia-CRF3 or Gaia-CRF3′.

The matched results of Gaia-CRF3 and ICRF3 S/X were obtained from the Gaia Archive, and the ICRF3 S/X data were downloaded from the IERS ICRS center. The comparison between the Gaia reference frame (either the complete one or the portion in the CSST observation area) and ICRF3 S/X follows the least-squares fit of first-order VSH decomposition as described in Equations (4) and (5). Before the fit, the ICRF3 source positions were propagated from the ICRF3 epoch (J2015.0) to the Gaia-CRF3 epoch (J2016.0) using Equations (6) and (7) in Charlot et al. (2020) for correction of galactic aberration. The position differences $\mathbf{y}$ were then calculated in the sense of [ICRF3−Gaia]. To mitigate the impact of individual large values in $\mathbf{y}$, outliers having large normalized angular separation $X > 4.01$ (where X is defined in Equation (7)) were removed before fitting.

Assuming that the position differences are introduced by random errors only, the normalized angular separation X should satisfy a Rayleigh distribution. For a sample of 3142 common sources, the expected number of sources with normalized angular separation larger than 4.01 is less than 1, so the threshold for rejecting outliers was set to 4.01. The final sample used in comparison contains 2633 sources, of which 1414 are located in the CSST observation area (i.e., $b > 15°$ and $\beta > 20°$). The distribution of the normalized separation of the ICRF3−Gaia common sources is displayed in Figure 4.

Table 1 presents the rotation and glide values between Gaia-CRF3 and ICRF3, as well as between Gaia-CRF3′ and ICRF3. All rotation and glide terms in both comparisons are less than 20 as. Except for the G_3 term, the other estimated results for Gaia-CRF3′ are consistent with those of Gaia-CRF3 within the uncertainties. The last row shows the difference between the two fitted results in the form of the Gaia-CRF3 fit minus the Gaia-CRF3′ fit, which may be used to reflect the orientation bias between Gaia-CRF3′ and Gaia-CRF3. From the table, we observe that the rotation and glide between these two frames are comparable to the difference between Gaia-CRF3 and ICRF3 S/X. Given that CSST observation is directly tied to Gaia-CRF3′, the bias between Gaia-CRF3′ and Gaia-CRF3 exerts only slight influence on the alignment between CSST-CRF and Gaia-CRF3, as well as on the extension to Gaia-CRF3.

4.2. Glide and Residual Spin of Gaia-CRF3′

Gaia-CRF3 is established based on the positions of approximately 1.6 million QSO-like objects. In addition to precise source positions, proper motions and parallaxes are also available for these extragalactic sources. Although insignificant, the proper motions of these sources introduce a subtle glide rate and spin in Gaia-CRF3. The dominant factor contributing to the global glide rate in Gaia-CRF3 is the Galactic aberration (GA) effect, which leads to a glide vector of about 5.05 as yr^{-1} (Gaia Collaboration et al. 2021) pointing toward the Galactic center. The presence of residual spin is related to differences between the sources used in the frame rotator and those comprising Gaia-CRF3. Here, the frame rotator is a group of extragalactic sources used to estimate and correct the orientation and spin parameters in the Gaia astrometric solution. Because the spin is sensitive to the selection of QSO-like sources, these differences between the rotator and CRF3 sources result in a residual spin of about 4 as yr^{-1} in Gaia-CRF3 (Gaia Collaboration et al. 2022a).

Since Gaia-CRF3′ is a subset of Gaia-CRF3 selected by the CSST sky survey region, the residual spin estimated from the proper motions of Gaia-CRF3′ sources may exhibit differences due to this sensitivity. Additionally, the estimation of the global glide rate may also be sensitive to source selection, resulting in potential variations between the Galactic aberration effect estimated in Gaia-CRF3′ and that in Gaia-CRF3. These discrepancies in spin and glide rate could subsequently impact the alignment between CSST-CRF and Gaia-CRF3. In light of this concern, we estimated the spin and glide rate of Gaia-CRF3′ and compared them to those of Gaia-CRF3.

In this work, we applied first-order VSH to fit the proper motions of three groups of sources: Gaia-CRF3′, the full Gaia-CRF3, and all five-parameter QSO-like sources in Gaia-CRF3 (hereafter referred to as Gaia-CRF3_5p). The last group is used to check whether our calculation of the GA effect is consistent with the result of Gaia Collaboration et al. (2021). The fitted rotation and glide from proper motions (Figure 5) indicate that the glide rates in all three cases reflect the transformation introduced by the GA effect. The differences between any two cases are smaller than their corresponding uncertainties, suggesting that the incomplete sky area of Gaia-CRF3′ does not contribute extra glide to the CSST reference frame. In terms of global spin, only the $\dot{R}_1$ term of Gaia-CRF3_5p is approximately 1 as yr^{-1} smaller than the other two cases. The differences in total spin and glide terms between Gaia-CRF3′ and Gaia-CRF3 are around 0.5 and 0.3 as yr^{-1}, respectively. These differential spin and glide values can be neglected in future studies of the CSST reference frame.

5. CSST and Multi-band Reference Frame

Realizing a fully integrated multi-band celestial reference frame that incorporates positions in both radio and optical bands and ensures their consistency across various bands is a key objective of the IAU. In 2021, the adoption of ICRF3 and Gaia-CRF3 as the fundamental realizations of the ICRS for the radio and optical domains marked the initial phase of the multi-band celestial reference frame initiative. To attain this objective, improvement of accuracy in all-sky observations across these spectral bands is necessary. The CSST sky survey, covering both NIR and NUV observations, holds promise as a valuable contributor. Current prominent catalogs in the infrared band include 2MASS (Skrutskie et al. 2006), WISE series (Cutri et al. 2012, 2021; Schlafly et al. 2019; Marocco et al. 2021), and Pan-STARRS1 (Chambers et al. 2016), while the ultraviolet band is represented by GALEX (Bianchi et al. 2011). Statistical information for these catalogs, alongside projections for the future CSST sky survey, are presented in Table 2. All catalogs present source positions in the ICRS: the reference catalog for 2MASS, WISE, and GALEX is the Tycho-2 catalog, while PS1 and CSST use the Gaia-CRF as reference catalog.

We compare the potential CSST catalog relative to existing catalogs in terms of limiting magnitude and observation accuracy. The magnitude distribution plotted in the upper panel of Figure 6 reveals that observations in the NIR band from popular catalogs are predominantly brighter than 20 mag, whereas CSST' s z-band observations significantly extend into the fainter range of NIR observations. A similar situation is evident in the NUV band, as visible in the distribution in the GALEX NUV band and CSST NUV band. Due to the increasing source density with magnitude, the CSST sky survey is poised to substantially enhance the density of the current celestial reference frame. The bottom panel of Figure 6 illustrates the position accuracy of four infrared or ultraviolet catalogs, Gaia-CRF3, and the anticipated CSST sky survey (Fu et al. 2023). Besides CSST and Gaia-CRF3, PS1 achieves the highest accuracy of about 10 mas. However, the typical position uncertainty of Gaia-CRF3 sources, ranging from 1 to 2 mas, is an order of magnitude better than PS1. Existing observations fall short of realizing an infrared or ultraviolet frame comparable to ICRF3. The ideal position accuracy of CSST, represented by the purple stars in Figure 6 (bottom panel), indicates a formal error of about 10 mas at magnitude 24, comparable to Gaia. Consequently, the inclusion of CSST will contribute significantly to establishing the NIR and NUV reference frames in the future.

6. Summary

This study introduces the upcoming China Space Station Telescope and evaluates the performance of CSST-CRF, the celestial reference frame based on the CSST multi-band sky survey. Given its wide wavelength coverage, deep field observations, and high-accuracy measurement, CSST-CRF will be able to significantly extend the current Gaia-CRF3. According to the strategy and simulation of the CSST sky survey, we estimated the potential performance of CSST-CRF.

First, we evaluated CSST' s global orientation precision by calculating the covariance matrix. Based on the density-magnitude relationship of Gaia-CRF3 sources, we generated about 22 million extragalactic sources uniformly distributed in the CSST sky survey region, spanning magnitudes from 18 to 25 mag. The position uncertainties of these sources were also simulated according to the uncertainty-magnitude relation of Pan-STARRS1 sources. The covariance matrix of orientation offset was derived from the least-squares fitting of VSH, and the parameter $\bar{s}$ was used to describe the precision of the CSST frame. Considering the limiting magnitude of Gaia, we divided the simulated sources into two groups using g = 21 mag as the threshold. The orientation uncertainty of the CSST extragalactic frame at the bright edge (g < 21 mag) is about 11 as, and that at the faint edge (g > 21 mag) is about 7 as. These uncertainties are not dominant when compared to the intrinsic offset between Gaia-CRF3 and ICRF3.

Second, we discussed the systematic effect of incomplete coverage of the CSST sky area on the extension of Gaia-CRF3. Due to limitations in sky coverage, CSST aligns with Gaia-CRF3′ (the subset of Gaia-CRF3 in the CSST-observed region) rather than the complete Gaia-CRF3. Using the ICRF3 S/X band as an intermediate reference frame, we estimated the orientation offset between Gaia-CRF3 and Gaia-CRF3′. The estimation showed that the rotation and glide offsets between Gaia-CRF3 and Gaia-CRF3′ are less than 20 as, comparable to the offsets between Gaia-CRF3 and ICRF3 in our analysis. This suggests that the sky area selection introduces an insignificant systematic effect between Gaia-CRF3 and Gaia-CRF3′. We also estimated the residual spin and glide rate of Gaia-CRF3′ to investigate the influence of sky selection. The fitted results for spin and glide rate of Gaia-CRF3′ are consistent with those of Gaia-CRF3. Consequently, the sky area selection in CSST does not significantly impact the CSST extension to Gaia-CRF3.

Finally, we discussed the contribution of CSST to establishing a multi-band celestial reference frame through comparison with current catalogs containing observations in the NIR and NUV bands. In these two bands, CSST exhibits unparalleled accuracy and depth, uniquely possessing accuracy comparable to Gaia. The observations conducted by CSST are poised to significantly advance the establishment of a comprehensive multi-band reference frame.

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Note: Figure translations are in progress. See original paper for figures.