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Full Text

Preamble

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The Velocity Aberration Effect of the CSST Main Survey Camera*

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Abstract

In this study, we conducted simulations to quantify the geometric aberrations expected for images taken by the Main Survey Camera of the Chinese Space Station Telescope (CSST) due to its motion. As anticipated by previous work, our findings indicate that the geometric distortion of light impacts the focal plane's apparent scale, with a more pronounced influence as the size of the focal plane increases. Our models suggest that the effect consistently influences the pixel scale in both the vertical and parallel directions. The apparent scale variation follows a sinusoidal distribution throughout one orbital period. Simulations reveal that the effect is particularly pronounced toward the Galactic Center and gradually diminishes along the direction of ecliptic latitude. At low ecliptic latitudes, the total aberration leads to about a 0.94 pixel offset (for a 20 minute exposure) and a 0.26 pixel offset (for a 300 s exposure) at the edge of the field of view. Appropriate processing strategies for this geometric effect during the CSST pre- and post-observation phases are presented.

Key words: astrometry – telescopes – Astronomical Instrumentation – Methods and Techniques

1. Introduction

High-resolution observations from space have opened a crucial window for studying celestial objects in astrophysics, astrometry, and dynamic astronomy. Compared to ground-based observations, the velocity aberration effect is more significant for high-resolution observations in space. The combined velocities of the space telescope and Earth's orbital motions can lead to a deviation in the observed direction of celestial objects compared to the actual arrival direction of photons, and this effect is defined as the total velocity aberration. The total velocity aberration is a combination of diurnal and annual velocity aberrations. The diurnal velocity aberration results from the Chinese Space Station Telescope (CSST)'s orbital motion (about 8 km s^{-1}), and the annual velocity aberration is caused by the Earth's orbital speed (about 30 km s^{-1}) around the Sun.

In a simple observational system equipped with a single sensor oriented orthogonally to the optical axis, the velocity aberration effect becomes apparent as a change in the pixel-to-angle ratio, known as the apparent pixel scale, within the field of view (FOV) captured by the observation image. The term “apparent pixel scale” (unit: arcsec pixel^{-1}) serves as a substitute for the terms “apparent plate scale” or “apparent focal panel scale” (unit: arcsec mm^{-1}), clearly and accurately describing the projection from the observed image to the celestial sphere. In our study, we define the “pixel” as a unit of length in the focal panel, allowing us to apply this definition consistently, even in the theoretical focal plane without a sensor. The effect of velocity aberration becomes more pronounced as the focal plane size increases. This phenomenon could lead to more noticeable elongation of a star’s point-spread function (PSF) and displacement of the star’s position, particularly when observing stars closer to the focal plane periphery.

In the case of a sophisticated observational system with multiple sensors deployed on a sizable focal plane, where the center of the focal plane aligns orthogonally to the optical axis, the velocity aberration effect becomes more severe and intricate. However, the optical axis within the focal plane may or may not be centered, as seen in systems like the Hubble Space Telescope (HST) or the CSST. The focal plane’s substantial size amplifies the velocity aberration effect’s impact, especially at its edges. Furthermore, the velocity aberration effect becomes intertwined with other factors, including the complex distortion inherent to the large focal plane, variations in the wave front induced by changes in temperature, Adaptive Optics or Precision Image Stabilization System, and the intra-pixel effect (P.-P. Wang et al. 2024, in preparation).

Moreover, this effect varies across different positions in the sizable focal plane, and coupled with alterations during the exposure, it can introduce a differential component of the velocity aberration. These factors pose significant challenges in accurately measuring celestial objects’ shapes and positions.

To ensure both high image quality and a large FOV, the Chinese two-meter space telescope CSST adopts the Cook-type off-axis three-mirror anastigmat optical design, which does not have any obstructions in the optical path to guarantee high light transmission efficiency and eliminate diffraction patterns caused by mirror supports. CSST also employs active optical technology to enhance image quality further. Combined with these advantages, within its 1.1 square degree FOV, the PSF 80% Encircled Energy Radius (REE80) is expected to be lower than 0.15. The PSF ellipticity is expected not to exceed 0.15, which can be compared to the HST (Finner et al. 2023).

The Main Survey Camera (MSC) is the primary observation instrument of CSST, accounting for over 70% of on-orbit observation time. This instrument comprises 30 detectors, with 18 dedicated to multi-band imaging observations and 12 for spectroscopic observations (Zhan 2021).

This study aims to investigate the velocity aberration effect on CSST MSC observations through simulations. The findings from this research will have implications for the planning of CSST sky surveys and observation strategies. Additionally, it will contribute to enhancing the data processing pipeline for CSST MSC multiband imaging in astrometry and photometry, as well as improving spectral processing for slitless spectroscopy. The paper is organized as follows. Section 2 presents the theoretical explanations of velocity aberration. Section 3 introduces the simulation data and simulation method. Section 4 presents the apparent pixel scale change of the MSC on orbit due to position variations of stars according to the simulation methods. Finally, Section 5 summarizes our findings and suggests various mitigation methods to reduce this effect.

2. Theoretical Explanations of Velocity Aberration Effects

It is well-established that the speed of light remains constant, with changes in the gravitational field being the only factor capable of modifying it. In the theoretical framework, HST first introduced the concept of velocity aberration within space observation (Cox & Gilliland 2003). Building upon several foundations (Pirzkal et al. 2001; Anderson & King 2003; Cox & Gilliland 2003; Griggio et al. 2023), we have derived the velocity aberration effect from a macroscopic perspective with relativity theory applied to CSST. Specifically, we have investigated the influence of aberration on the apparent pixel scale of CSST MSC. The derivation is presented as follows.

[Figure 1: see original paper] Relativistic interpretation of velocity aberration when α is an acute angle.

In Figure 1, $\vec{v_0}$, $\vec{r}$, and $\vec{r'}$ represent the synthesis of the combined speed of the orbital velocity of CSST and the speed of the Earth revolving around the Sun. $\vec{r}$ indicates the direction from which photons emitted by celestial bodies arrive, while $\vec{r'}$ signifies the direction in which these photons are observed. The three vectors $\vec{v_0}$, $\vec{r}$, and $\vec{r'}$ are coplanar. Suppose there is a scenario where a telescope records a star at point O (disregarding the internal light path of the telescope) and establishes a stationary coordinate system Σ with O as the origin. The x-axis aligns with the CSST moving direction of $\vec{v_0}$, and the y-axis is perpendicular to the x-axis with the right-handed system. Both the x-axis and y-axis lie within the Σ plane. In parallel, another coordinate system S' is established. It shares its coordinate axes' orientation with those of Σ but has a relative motion.

Utilizing the Lorentz transformation, the change in the pixel scale of the focal plane caused by velocity aberration is inferred where α or α' is the angular distance between the direction of photon arrival or observation from celestial bodies relative to the motion direction of the CSST. The symbol d represents a differential operator. $d\alpha$ is the radial change in pixel scale, $d\alpha'$ is the tangential change in pixel scale. Remarkably, while these two values are identical, indicating that the pixel scale alteration in the focal plane within the FOV is isotropic and centrally symmetric.

The proof presented above pertains to the case when α is an acute angle. It can be readily demonstrated that even when α is an obtuse angle (i.e., the supplement angle of α), the change in pixel scale of the focal plane caused by velocity aberration remains governed by formula (1). In essence, whether the telescope is oriented toward or moving away from the star, the pixel scale alterations in the focal plane induced by velocity aberration remain consistent. It depends solely on the angle (α) between the telescope's motion direction and the line of sight when it maintains a constant speed.

3.1. CSST Orbit Simulation

Based on theoretical analysis, we calculated the velocity aberration effect, accounting for the orbital motion of CSST within one orbital period and the Earth's annual revolution. Our study employed astrometry-related processing utilizing the Standards Of Fundamental Astronomy library, adhering to the IAU official specifications (IERS 2021). The model's precision is capable of reaching a level of ten milliarcseconds. We utilized simulated orbital data for CSST to facilitate this analysis. Initially, we obtained concise orbital data covering a relatively extended period. For the one-orbit total velocity aberration effect analysis, we specifically selected orbital data (approximately 90 minutes), ranging from "2022 July 6 01:33:40" to "2022 July 6 03:03:40" in UTC. The orbital data within this duration have about a 2 minute interval between consecutive data points.

Figure 2 illustrates the orbital position (left) and velocity (right) during this period. The color gradient represents progression in time, and the black arrow indicates the direction of CSST motion along the orbit. For the annual velocity aberration effect analysis, we set the orbital position and velocity to zero, with a time interval of one hour between data points.

3.2. Simulation of the Velocity Aberration for the CSST MSC

This study assumes that variations in pixel scale can adequately represent the velocity aberration effect on CSST MSC. With this assumption as the foundation, our objective is to obtain the distribution of pixel scale changes across CSST MSC as it observes specific sky regions from different orbital positions and with varying speed vectors based on simulation.

Assume that the optical axis is perpendicular to the center of the focal plane. We have selected seven pairs of sampling points based on the arrangement of sensors along the symmetric axis of MSC. We have subsequently established seven measurement baselines, denoted as AB, EE', FF', GG', CD, HH', and II', to represent the pixel scales in general. As illustrated in [Figure 3: see original paper], a standard coordinate system (,) has been established on the MSC, and these sampling points have been marked. lists these points with their corresponding standard coordinates. The simulation methods are described in detail as follows:

1. We initiate the calculation of equatorial coordinates for these reference points based on their standard coordinates in the following steps. Given that the CSST sky survey operates in the ecliptic coordinate system, we select a specific pointing (λ, β) in the ecliptic coordinate as the center of the FOV. We then establish standard coordinates (,) with the following orientation: the X-axis parallels the ecliptic latitude and follows the direction of increasing longitude, while the Y-axis is perpendicular to the X-axis and follows the direction of increasing latitude.

2. We compute the equatorial coordinates for the reference points, accounting for both the presence and absence of velocity aberration effects. These reference points, represented by their equatorial coordinates, can be regarded as celestial objects. Several astrometric effects should be involved when considering the light path from these celestial objects in the CSST focal plane. Our analysis concentrates solely on the velocity aberration effects while disregarding other factors, such as projection effects, coordinate transformation errors, etc. Utilizing the simulated orbital data as input, we employ the Control Variable Method to quantify the distinctions between scenarios with and without these velocity aberrations.

3. We determine the spherical arc length of the equatorial coordinate system for the pairs AB, EE', FF', GG', CD, HH', and II', by employing a spherical arc length calculation formula, as expressed in Equation (4):

   $$\mathrm{R\ arccos\ cos}$$

   where R represents the radius of the celestial sphere, which we have normalized to a unit value. The pairs of coordinates (λ_1, β_1) and (λ_2, β_2), exemplified here with the arc length AB, correspond to the equatorial coordinates of the reference points A and B.

4. We deduce the pixel scale change induced by the total or annual velocity aberration. The ratio of arc length with or without velocity aberration indicates the pixel scale change, as defined by Equation (5):

   $$\mathrm{Ratio} = \frac{\text{arc length with aberration} - \text{arc length without aberration}}{\text{arc length without aberration}}$$

4. Results

We initiated total velocity aberration simulations during one orbit of CSST when the CSST was directed toward the Galactic Center to investigate the pixel scale variations. The results of this simulation are illustrated in [Figure 4: see original paper]. The left subgraph of Figure 4 illustrates the simulated variation in the scale of the MSC caused by the total velocity aberration during one orbit of the CSST, which lasts approximately 90 minutes when observed in the direction of the Galactic Center. In the figure, we have represented the maximum and minimum gradients with black crosses and blue points, respectively. To estimate the maximum total velocity aberration, we have highlighted the CSST typical long exposure (20 minutes) with light green as the black cross in the center. Similarly, we have used light blue to emphasize the typical 300 s exposure for CSST ordinary sky surveys. The maximum values for scale change are 3.184 $\times$ 10^{-5} arcsec pixel^{-1} and 0.849 $\times$ 10^{-5} arcsec pixel^{-1} for velocity aberration in 20 minutes and 300 s, respectively. Assuming an FOV of 1°.2, this pixel scale change amounts to 0.069 for the long exposure. Consequently, during approximately 20 minutes of exposure, a star image located at the edge of the focal plane undergoes an approximate shift of 0.929 pixels as the plate scale value of the MSC is 0.074 pixel^{-1}.

Additionally, we conducted annual velocity aberration simulations for one year in the same sky area. As the right subgraph of Figure 4 shows, the changes of different measurement baselines on MSC coincide, indicating these pixel scale change rates and trends are the same.

We conducted similar simulations to assess both the total velocity aberration effect over a single CSST orbit and the annual velocity aberration effect over one year when CSST observed at different ecliptic latitudes (20°, 60°, 89°). The outcomes of these simulations are presented in [Figure 5: see original paper]. In the left column of the subgraphs, we observe the variations in the total velocity aberration effects on the MSC during one CSST orbit, showcasing different trends. Notably, the discrepancy between the maximum and minimum values of pixel scale changes decreases as the ecliptic latitude rises. Meanwhile, the right column of the subgraphs illustrates the impact of annual velocity aberration. Remarkably, the trends across different measurement baselines within the MSC align, indicating that these rates of scale change remain consistent. Furthermore, we observe that akin to the total velocity aberration, the difference between the maximum and minimum values of scale changes diminishes with higher ecliptic latitudes.

As presented in , we have compiled the maximum variations in focal plane scale for 20 minute and 300 s exposures in the context of the three selected sky regions also presented in Figure 5. The second and third columns provide the FOV centers in ecliptic coordinates (λ, β). The fourth column lists the maximum pixel scale change caused by total velocity aberration, corresponding to the positions marked by black crosses in the left sub-graph of Figure 5. The fifth column presents the positional change for the edge of FOV, measured in arcseconds. The last column displays the corresponding maximum offset in pixels, offering a more intuitive and direct representation.

Furthermore, we conducted tests to assess the changes in pixel scale under varying longitudes while maintaining the same latitudes. The results, as depicted in [Figure 6: see original paper], reveal a sinusoidal distribution trend akin to that seen in Figure 5. However, unlike the trend observed with increasing ecliptic latitudes, the difference between the maximum and minimum values of the pixel scale change remains consistent. Therefore, it becomes apparent that the effect of velocity aberration on the focal plane scale is more pronounced when the observed object is in proximity to the orbital plane of the telescope. In contrast, the impact is independent of changes in ecliptic longitudes.

The Galactic Bulge is a crucial component that preserves the Milky Way galaxy's early evolutionary trajectory (Barbuy et al. 2018), but more observational evidence is needed. The insufficient observational data are primarily due to the high extinction and stellar density in the Milky Way's central region, making it difficult to achieve the required observational depth and precise positional measurements of individual stars. The high image quality and resolution of CSST could provide an opportunity to obtain sufficient observations in different epochs. As mentioned above, we should estimate the velocity aberration effect following the galactic coordinate system.

[Figure 7: see original paper] and [Figure 8: see original paper] visually depict the disparity between the maximum and minimum values of the MSC scale change caused by total and annual velocity aberration, respectively, as functions of Galactic coordinates. The Galactic Center is centrally positioned within both images. These figures exhibit strikingly similar patterns. It is worth noting that the velocity aberration effect presents a pronounced variation within the nuclear bulge region near the Galactic Center, as evidenced by the deep red coloring. Additionally, the effect appears minimal at the north and south ecliptic poles, as indicated by the deep blue coloring. A more pronounced gradient in the distribution of the velocity aberration effect is observed along the direction of ecliptic latitude compared to the longitude direction.

5. Conclusions

The characteristics of the CSST MSC velocity aberration effect, obtained from the theoretical analysis and simulation results of this study, can be summarized as follows:

1. The velocity aberration effect occurs due to the motion of a space telescope and the limited speed of light. This effect impacts the pixel scale of the focal plane, with a more pronounced impact on space observation platforms equipped with larger focal panels.
2. The velocity aberration effect affects the pixel scale consistently within the MSC across different measurement baselines and in both the vertical and parallel directions.
3. The pixel scale variation follows a sinusoidal distribution throughout a single orbit, leading to distinct minimum and maximum points for the velocity aberration effect.
4. It is observed that the influence of velocity aberration on the pixel scale is more pronounced for targets located at lower ecliptic latitudes. In the cen-

tral region of the Galaxy, the velocity aberration has a significant impact on the focal plane scale.

5. At low ecliptic latitudes, the total velocity aberration causes a pixel scale change of approximately 3×10^{-5} for a 20 minute exposure and 0.9×10^{-5} for a 300 s exposure. This results in a position offset at the edge of the FOV of about 0.94 pixel for the 20 minute exposure and 0.26 pixel for the 300 s exposure.

In conclusion, the velocity aberration effect substantially influences the precision of celestial object measurements acquired through CSST MSC observations, which represents significant additional data processing for the CSST high-resolution observations. As a result, meticulous consideration and processing of the velocity aberration effect are necessary for the pre- and post-observation phases.

Since the magnitude of the velocity aberration effect varies according to its inherent characteristics, it becomes feasible to mitigate the effect by strategically utilizing forecasted orbital parameters and the orientation of the observation target. Careful selection of specific start exposure times is essential when planning CSST observation strategies, particularly in the low ecliptic latitude observation areas.

Further refinement of post-processing techniques can enhance the accuracy of PSF reconstruction and object positioning. These techniques encompass the compilation of correction tables for ePSF data, and PSF reconstruction through multi-Gaussian (J.-L. Nie et al. 2024, in preparation) fitting with additional velocity aberration effect parameters.

Lastly, the influence of the velocity aberration effect on the MSC Fine Guidance Sensors is relevant, and proper consideration should be given to uploading guide star positions and developing on-orbit guiding programs.

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