Astrometric Observations of NEA 1998 HH49 Using the Daocheng 50 cm Telescope Postprint

Authors: Huan Xu, Xiang-Ming Cheng, Yi-Gong Zhang, Teng-Fei Song, Zhen-Jun Zhang and Qing-Yu Peng

Date: 2024-08-14T00:00:00+00:00

Abstract

This study details an astrometric observation campaign of the Near-Earth Asteroid 1998 HH49, conducted with the aim of refining our understanding of its physical characteristics. Utilizing the 50 cm telescope located at the Wumingshan Mountain in Daocheng, Sichuan, images were obtained over four nights, from 2023 October 19 to October 22. These observations were processed using Astrometrica software, facilitating the precise determination of the asteroid's position. The observational results were compared with the ephemerides from three distinct sources to verify accuracy: the Jet Propulsion Laboratory (JPL) Horizons System, the Institut de Mécanique Céleste et de Calcul des Éphémérides (IMCCE) Miriade, and the Near-Earth Objects Dynamic Site (NEODyS-2).

Full Text

Preamble

Astrometric Observations of NEA 1998 HH49 Using the Daocheng 50 cm Telescope

Huan Xu[12], Xiang-Ming Cheng[1234], Yi-Gong Zhang[5], Teng-Fei Song[1], Zhen-Jun Zhang[6], and Qing-Yu Peng[78]

[1]Yunnan Observatories, Chinese Academy of Sciences, Kunming 650216, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China
[3]Key Laboratory of the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, Kunming 650216, China
[4]School of Information Engineering, Kunming University, Kunming 650214, China
[5]School of Computer Science and Information Engineering, Anyang Institute of Technology, Anyang 455000, China
[6]Department of Computer Science, Jinan University, Guangzhou 510632, China

[7]Sino-French Joint Laboratory for Astrometry, Dynamics and Space Science, Jinan University, Guangzhou 510632, China

Received 2024 March 6; revised 2024 May 13; accepted 2024 May 13; published 2024 July 8

Abstract

This study details an astrometric observation campaign of the Near-Earth Asteroid 1998 HH49, conducted with the aim of refining our understanding of its physical characteristics. Utilizing the 50 cm telescope located at Wumingshan Mountain in Daocheng, Sichuan, images were obtained over four nights from 2023 October 19 to October 22. These observations were processed using Astrometrica software, facilitating the precise determination of the asteroid's position. The observational results were compared with ephemerides from three distinct sources to verify accuracy: the Jet Propulsion Laboratory (JPL) Horizons System, the Institut de Mécanique Céleste et de Calcul des Éphémérides (IMCCE) Miriade, and the Near-Earth Objects Dynamic Site (NEODyS-2).

When compared with the JPL ephemeris, the observations yielded a mean observed-minus-calculated (O-C) result of 0.07 in the R.A. direction and −0.35 in the decl. direction. Comparison with the IMCCE ephemeris produced mean O-C results of 0.08 in R.A. and −0.06 in decl., while comparison with NEODyS-2 yielded mean O-C values of 0.06 in R.A. and −0.49 in decl. The findings demonstrate general consistency between the observed data and ephemeris predictions, with minor discrepancies observed across datasets. Notably, both the JPL and NEODyS-2 ephemerides show larger residuals in the decl. direction than in R.A. These disparities may result from atmospheric differential color refraction, ephemeris uncertainties, observational errors, and other factors. Further investigation is required to fully understand the influence of these additional factors. Overall, the Daocheng 50 cm Telescope demonstrates the capability to conduct high-precision positional measurements.

Key words: astrometry – ephemerides – time

1. Introduction

High-precision astrometry of Near-Earth Objects (NEOs) substantially contributes to pivotal scientific inquiries regarding the solar system's genesis and evolution while fortifying global preparedness against potential NEO impacts. NEO mitigation is integral to strategic advancements within China's scientific endeavors, representing a significant directive in the "14th Five-Year Plan." Since 2021, China has been formulating a long-term strategy for NEO impact risk management, with ambitions to conduct kinetic impact deflection trials on selected near-Earth asteroids within this timeframe. Accurate orbital determination of NEOs fundamentally depends on the acquisition of precise epochal positions.

The measurement and tracking of near-Earth asteroids (NEAs) utilizes diverse space-based and ground-based technologies, each with distinct capabilities and limitations. Space-based technologies, exemplified by missions such as the Near-Earth Object Wide-field Infrared Survey Explorer (NEOWISE) [?], employ infrared sensors to detect thermal emissions from asteroids. This method is less affected by daylight and atmospheric conditions, facilitating continuous monitoring. The recently launched Near-Earth Object Surveillance Mission (NEOSM, later renamed NEO Surveyor) extends these capabilities by providing more comprehensive coverage and enhanced detection sensitivity. However, space missions are considerably more expensive and involve complex logistics and extended preparation times.

Ground-based techniques play a pivotal role in comprehensive NEA observation, predominantly involving radar measurements and optical telescopes. Radar technology, such as that used by NASA's Goldstone Solar System Radar, provides precise determinations of an asteroid's location, shape, and velocity, and even facilitates surface imaging. However, radar effectiveness is limited by range capabilities and requires asteroids to be relatively close to Earth for optimal functionality. Ground-based optical telescopes are instrumental in discovering new asteroids. Systems like the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) [?], which employs wide-field cameras to detect and track asteroids against stellar backgrounds, significantly contribute to celestial measurement and monitoring. Although large ground-based telescopes offer superior observational capabilities, their numbers are limited and available observing time is heavily subscribed. Additionally, the vast quantity of NEAs means that relying solely on large telescopes is insufficient for comprehensive observation. These targets typically require extensive follow-up observation histories to derive precise astrometric coordinates, and a critical bottleneck is the constraint of appropriate observational windows, which demands coordinated effort across a global network.

The dynamic nature of these objects, influenced by gravitational interactions with planets and the Sun as well as non-gravitational forces such as the Yarkovsky effect, makes predicting their long-term trajectories complex [?, ?]. Consequently, smaller-aperture telescopes become essential tools for such observations. Maximizing the astrometric observational utility of China's existing and forthcoming observatory infrastructures is therefore paramount for enhancing NEO research and defense mechanisms.

Considerable scholarly attention has been allocated to studying Potentially Hazardous Asteroids (PHAs), with research dedicated to conducting astrometric observations of NEOs including PHAs to obtain high-precision epoch positions [?, ?, ?, ?]. This paper focuses on the astrometric study of 1998 HH49, a PHA discovered on 1998 April 20 by the Lincoln Near-Earth Asteroid Research (LINEAR) [?]. According to the Minor Planet Center (MPC) database, this NEA was discovered on 1998 April 24 by the Spacewatch survey (MPC code 691). Minor Planet Electronic Circulars (MPECs) made dual announcements about this target [?, ?]. The asteroid is classified as a PHA because its orbit allows close approaches to Earth, with an estimated size of 650 m by 190 m. 1998 HH49 orbits the Sun with a semimajor axis of 1.22 astronomical units (au), an orbital period of approximately 2.8 yr, an absolute magnitude of 21.4, and a rotational period of about 2.7 hr. Close approaches of this asteroid could pose a significant regional threat, with its substantial mass estimated at 50 million tons and specific orbital characteristics that include approaches to Earth within 60–78 times the planet's diameter. These attributes, coupled with its potential energy release equivalent to multiple hydrogen bombs, have led to its consideration as a possible "Asteroid Weapon" in strategic defense scenarios [?]. These characteristics highlight the necessity of precise astrometric monitoring to refine our understanding of its trajectory and physical properties, thereby assessing potential impact risk.

The Wumingshan Mountain site in Daocheng, Sichuan, located at coordinates 100.06° E, 29.06° N and an altitude of 4700–4800 m, is recognized by Yunnan Observatories for its favorable astronomical observation conditions [?, ?]. The site features average annual cloud cover below 50%, up to 270 clear nights per year by astronomical standards, median night seeing of 0.9 , integrated water vapor content of 2.5 mm, relative humidity below 60%, and average wind speed below 5 m s^{-1} [?]. The Daocheng 50 cm Telescope is accompanied by a 6.3 m spherical dome with a 1.2 m wide skylight enabling 360° rotation. See Figure 1 [Figure 1: see original paper] for an image of the telescope and observation room. To address challenges of high-altitude observations and enable remote, automated operation, Zhang et al. implemented significant modifications using the Modbus/TCP protocol to integrate a Programmable Logic Controller (PLC), achieving automated dome control [?]. This strategic implementation is pivotal for remote observations, substantially enhancing the telescope's operational capabilities and providing a reference model for automation in mid-size astronomical systems.

This paper is structured as follows: Section 2 provides a detailed account of our four-night observational campaign at Wumingshan Mountain using the 50 cm telescope to acquire images of the moving target. Section 3 describes data processing, wherein observed asteroid positions are meticulously compared with ephemerides from JPL, IMCCE, and NEODyS-2. Section 4 analyzes the astrometric measurements, Section 5 discusses factors potentially influencing these measurements, and the final section provides a summary.

2. Observations

We conducted astrometric observations of 1998 HH49 using a 50 cm telescope equipped with a 2048 × 2048 pixel CCD camera at a focal length of 3454 mm at Wumingshan Mountain in Daocheng, Sichuan. These observations were carried out over four nights from 2023 October 19 to October 22. The target exhibits an approximate signal-to-noise ratio (S/N) of 30 in the images. Partial information about the targets observed during these four nights is listed in Table 1 , while telescope and CCD detector specifications are presented in Table 2 . A typical image of the observational target is shown in Figure 2 [Figure 2: see original paper].

The astrometric observations employed the J2000.0 epoch as the reference time, aligning with standard astronomical practice for ensuring consistency in celestial coordinates across datasets. The coordinate system used was the International Celestial Reference System (ICRS), an ideal framework that uses distant extragalactic sources for its practical realization in the International Celestial Reference Frame (ICRF), providing a stable framework for reporting celestial positions. Flat-field images were acquired during twilight to mitigate brightness discrepancies caused by pixel sensitivity variations and optical system flaws, with approximately ten flat-field frames captured each evening. Dark-frame images were acquired using identical exposure times as those for the target object to correct thermal noise from extended exposures. We obtained images of the asteroid in the Clear filter with exposure times varying each night depending on the asteroid's apparent motion: 2, 4, 6, and 8 s per frame. Up to 100 frames were captured on some nights, with each image having dimensions of 2048 × 2048 pixels. We processed the images using standard astrometric techniques to determine the asteroid's precise position relative to nearby stars. These measurements may be used for orbital calculations, with specific observation details provided in Table 3 .

3. Data Processing

3.1 Target Position

To ensure astrometric quality, images with poor fits affected by cloud cover were excluded. Valid images were processed using the astrometric software Astrometrica [?] for flat-field and dark-frame corrections, as well as for determining the topocentric astrometric position in equatorial coordinates. After selecting the Gaia Data Release 2 (DR2) star catalog [?] and a quadratic fit model for plate solution, the target was manually identified and marked to generate an output text file with the asteroid's measured position.

3.2 O-C Results

Ephemerides for the target asteroid were obtained from the JPL, IMCCE, and NEODyS-2 databases. Due to the asteroid's rapid motion, the JPL ephemeris precisely matched our observation timings, while those from IMCCE and NEODyS-2 utilized one-minute time intervals. These one-minute intervals were subsequently interpolated using quadratic interpolation to obtain values at exact observation moments. Tests across intervals from 0.01 s to 1 minute confirmed that interpolation errors remained below 1 milliarcsecond, validating the use of one-minute intervals. NEODyS-2 data with their fixed one-minute interval were used directly without additional interpolation.

Variations in target positions among different ephemerides primarily stem from differing orbital theories underlying each ephemeris and distinct datasets used for orbital fitting. The JPL case primarily utilizes its Development Ephemeris (DE) series, such as DE440 and DE441, which are sophisticated models based on general relativity for high-precision ephemerides. In contrast, IMCCE uses planetary theories like INPOP19a, integrating both Newtonian dynamics and relativistic corrections. NEODyS-2, focusing on NEOs, employs numerical integration methods to track and predict asteroid trajectories, catering specifically to the dynamic nature of these bodies. Each model is continuously refined and updated to incorporate the latest observational data, ensuring accuracy in their respective domains. Table 4 summarizes the orbital parameters and epochs used by these ephemeris services.

Quadratic interpolation was applied to ephemerides to derive astrometric positions at precise observation moments, simplifying comparison of observed (O) and calculated (C) positions and leading to observed-minus-calculated (O-C) discrepancies. All calculations are based on topocentric celestial positions. To enhance accuracy, outlier points were efficiently removed using the 3σ rule, producing more reliable O-C values unaffected by outliers. Daily O-C results are shown in Table 5 , while Figure 3 [Figure 3: see original paper] presents O-C results in R.A. and decl. directions over four days, comparing JPL, IMCCE, and NEODyS-2 ephemerides. The dispersion changes in O-C values are significantly related to the target's motion speed, as evident when comparing residual plots with motion speeds listed in Table 1 .

4. Results Analysis

Calculations based on O-C results reveal that the NEODyS-2 ephemeris shows mean O-C values of 0.06 in R.A. and -0.49 in decl., the JPL ephemeris presents O-C values of 0.07 in R.A. and -0.35 in decl., and the IMCCE ephemeris yields mean O-C values of 0.08 in R.A. and -0.06 in decl. The O-C residuals are generally consistent across the three sources, though both JPL and NEODyS-2 ephemerides show significantly larger residuals in decl. than in R.A. While the IMCCE ephemeris does not exhibit this discrepancy, the O-C values on the first day are noticeably larger, possibly attributable to higher target speed on that day. Although the asteroid's speed is slightly higher in the decl. direction compared to R.A., the small difference suggests that motion's impact on O-C inconsistency between directions is negligible. Further investigation is required to understand the underlying causes of observed variations in O-C residuals between the two directions.

5. Discussion

Analysis of the target's O-C results identifies two main discrepancies: differences in O-C values arising from various ephemerides, and variations in O-C values between R.A. and decl. directions as observed in JPL and NEODyS-2 ephemerides. Referencing Brumberg (2017), we conduct a brief analysis:

(1) Observational Errors: These can arise from several sources including instrument calibration, data processing, and human error. The 50 cm telescope's optical and tracking systems were meticulously calibrated, and exposure times were under 10 s, producing no significant defects in observed images. Data processing employed Astrometrica software, significantly reducing handling and human error. Analysis of multiple background stars at different reference times using two-dimensional Gaussian centroiding methods yielded average standard deviations of approximately 0.064 for R.A. and 0.067 for decl., consistently showing low error and high stability, with slightly more pronounced impact on decl. though the overall effect remains minor.

(2) Geometric Distortions in CCD Imaging: CCD cameras are widely used in astrometry but can introduce geometric distortions from pixel irregularities, optical misalignments, and thermal effects. Research [?, ?] discusses correction methods crucial for reducing astrometric errors. In all images presented here, asteroid 1998 HH49 is positioned near the field-of-view center to minimize field distortion impact. Detailed correction of field astrometric distortion will further enhance accuracy, particularly in the R.A. direction, highlighting a critical area for future research: developing and applying distortion models to reduce celestial measurement errors.

(3) Deviation of Photocenter: An asteroid's non-uniform geometry can influence light reflection, impacting its perceived location. Understanding and modeling the object's shape can lead to more accurate motion and position predictions. Given 1998 HH49's size of approximately 650 m, and using the brightness center deviation calculation method from Lindegren (1977), with Earth-target distance of approximately 0.03 au and Earth-Sun-target angle of approximately 19.43°, the calculated brightness center offset is 47.84 m, causing an astrometric position deviation of approximately 0.002 . Therefore, photocenter deviation's impact on astrometric processing is negligible.

(4) Atmospheric Refraction: This phenomenon bends light from celestial objects passing through Earth's atmosphere, altering apparent sky position depending on elevation. The high-order constant model includes atmospheric refraction effects, so this factor need not be separately considered.

(5) Differential Color Refraction: Dispersion and Color Refraction (DCR) occurs when light of varying wavelengths undergoes differential atmospheric refraction due to wavelength-dependent refractive indices, with shorter wavelengths experiencing greater refraction than longer wavelengths [?]. Research by Guo et al. and Lin et al. has advanced DCR understanding [?, ?]. A fundamental DCR model is:

$$\mathrm{DCR} = k \cdot \tan(Z) \cdot \mathrm{CI}$$

where k is a coefficient reflecting refraction degree per unit color index at 45°

zenith distance, empirically determined from observations or theory. We utilize $k = 0.1$ from Guo et al. (2023), Z is zenith distance, and CI is the color index quantifying magnitude difference between two photometric filters. Following Zhai et al. (2024), we set CI = 0.85. Calculations based on this model range from 0.06 to 0.13 . However, accurate DCR values are influenced by various factors including climate conditions, humidity, observation site elevation, and atmospheric composition, necessitating more complex models for future research.

6. Conclusions

This paper presents an astrometric analysis of NEA 1998 HH49 conducted using the 50 cm telescope at Wumingshan Mountain in Daocheng, Sichuan. The O-C results show discrepancies from JPL ephemeris of about 0.07 in R.A. and −0.35 in decl., from IMCCE ephemeris of 0.08 in R.A. and −0.06 in decl., and from NEODyS-2 ephemeris of 0.06 in R.A. and −0.49 in decl. This analysis highlights variance in accuracy between different ephemeris sources for NEA astrometric observations. Overall, results show observational data are consistent with all three ephemerides used. The IMCCE ephemeris provides the closest match to observed positions in both coordinates. The other two ephemerides exhibit disparities that could potentially be attributed to DCR influence, minor observational inaccuracies, or variations in orbital models, necessitating further comprehensive investigation. Future work should consider target velocity, atmospheric refraction, observational errors, object shape, DCR, and CCD geometric distortions to enhance astrometric precision. Based on these findings, the 50 cm telescope at the Daocheng Wumingshan Mountain site, with its favorable astronomical conditions, is capable of supporting high-precision astrometric measurement requirements for NEOs, providing important support for China's NEO defense and kinetic impact experiments.

Acknowledgments

We acknowledge support from staff at the 50 cm telescope administered by Daocheng Observatory. This study benefited from precise ephemeris data provided by JPL and IMCCE, enhancing our astrometric analysis accuracy. We are deeply thankful for Astrometrica software's contribution to our observations and data analysis. Additionally, this research utilized data from the NEODyS-2 service, whose contribution we gratefully acknowledge.

This work was funded by the National Key R&D Program of China (grant No. 2022YFE0116800), the National Natural Science Foundation of China (NSFC, grant No. 12173085), the West Light Foundation of the Chinese Academy of Sciences, and Key scientific research projects of colleges and universities in Henan Province (grant No. 23B16001).

ORCID iDs:
Xiang-Ming Cheng: https://orcid.org/0000-0002-0282-528X

References

Bottke, W. F., Vokrouhlický, D., Rubincam, D. P., & Nesvorný, D. 2006, *AREPS*, 34, 157

Brumberg, V. 2017, *Essential Relativistic Celestial Mechanics* (Boca Raton, FL: CRC Press)

Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018, *A&A*, 616, A1

Gehrels, T., Scotti, J. V., & Williams, G. V. 1998, *MPEC*, 1998–J08

Guo, B. F., Peng, Q. Y., Fang, X. Q., & Lin, F. R. 2023, *MNRAS*, 525, 4999

Ivezić, Ž., Tyson, J. A., Jurić, M., et al. 2007, in *Near Earth Objects, our Celestial Neighbors: Opportunity and Risk*, ed. G. B. Valsecchi, D. Vokrouhlický, & A. Milani, Vol. 236 (Cambridge: Cambridge Univ. Press), 353

Kaiser, N., Aussel, H., Burke, B. E., et al. 2002, *Proc. SPIE*, 4836, 154

Lin, F. R., Peng, Q. Y., & Zheng, Z. J. 2020, *MNRAS*, 498, 258

Lindegren, L. 1977, *A&A*, 57, 55

Liu, Y., Li, X. B., Zhang, X. F., et al. 2018, *Proc. SPIE*, 10704, 784

Lunan, D. 2014, *Incoming Asteroid!: What Could We Do About It?* (New York: Springer), 109

Mainzer, A., Bauer, J., Grav, T., et al. 2011, *ApJ*, 731, 53

Peng, Q. Y., & Tu, B. 2011, *SSPMA*, 41, 1126

Peng, Q. Y., Vienne, A., Zhang, Q. F., et al. 2012, *AJ*, 144, 170

Perna, D., Dotto, E., Ieva, S., et al. 2016, *AJ*, 151, 11

Raab, H. 2012, *Astrometrica* software

Song, T.-F., Liu, Y., Wang, J.-X., et al. 2020, *RAA*, 20, 85

Song, T. F., Liu, Y., Cai, Z. C., et al. 2021, *MNRAS*, 505, 3070

Stokes, G. H., Evans, J. B., Viggh, H. E. M., Shelly, F. C., & Pearce, E. C. 2000, *Icarus*, 148, 21

Stone, R. C. 2002, *PASP*, 114, 1070

Veillet, C., Shapiro, A., & Williams, G. V. 2000, *MPEC*, 2000–Y39

Wang, X. W., Cao, J., & Peng, Q. Y. 2014, *AR&T*, 11, 34

Zhai, C. X., Shao, M., Saini, N., et al. 2024, *PASP*, 136, 034401

Zhang, G. J., Song, T. F., Cheng, X. M., Wang, J. X., & Zhang, Y. G. 2020, *AR&T*, 17, 548

Zhang, X.-L., Yu, Y., Wang, X.-L., et al. 2015, *RAA*, 15, 435

Zhang, Z.-J., Zhang, Y.-G., Cheng, X.-M., Wang, J.-C., & Su, J. 2019, *RAA*, 19, 071

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