

Determining Orbital Elements of Asteroid Psyche Using Ant Colony Optimization from Single-Night Astrometric Observation

Achmad Zainur Rozzykin¹, Aditya Abdilah Yusuf², Ridlo Wahyudi Wibowo¹, Muhamad Arrizal Hasby¹, Adhitya Oktaviandra², Nabila Hilmi Aziz¹, Novia Doloyanty Br Sinaga¹, Zeni Septiani¹

This article has been presented at The 2nd International Physics Conference (IPC)

Universitas Pendidikan Indonesia, Bandung, Indonesia.

August, 16, 2025

Abstract

The determination of asteroid orbital elements from limited astrometric data is a challenging inverse problem in celestial mechanics. In this study, we demonstrate the use of Ant Colony Optimization (ACO), a metaheuristic inspired by swarm intelligence, to solve Kepler's equation and derive the orbital elements of asteroid (16) Psyche from right ascension (RA) and declination (Dec) observations acquired over a single night. The algorithm minimizes the residuals between observed and predicted RA/Dec positions by exploring the solution space of five Keplerian orbital parameters. The value for a , e , i , Ω , and ω are 2.91313 AU, 0.13232, 3.35354o, 294.54545o, and 151.51515o respectively. These resulting orbital elements exhibit strong agreement with reference values from NASA's JPL Small-Body Database Lookup. This study highlights the potential of swarm-based optimization techniques for initial orbit determination, especially in cases with sparse observational data. The findings suggest that even minimal observational input, when combined with robust optimization algorithms, can yield accurate orbital solutions. Future work may expand this approach to longer observational arcs or other minor bodies to assess its generalizability and performance in different dynamical contexts.

Keywords: asteroid · Ant Colony Optimization · orbit determination · astrometry · Psyche

INTRODUCTION

The accurate determination of asteroid orbits is fundamental to planetary science, celestial mechanics, and planetary defense. One of the main problems in orbit determination lies in the underdetermined nature of the problem when observations are sparse, particularly from a single night. Astrometric data (right ascension and declination) provide only angular positions, which often lack sufficient information for reliable multi-parameter orbital solutions (Milani & Gronchi, 2010). This creates a major challenge for preliminary orbit determination, as traditional approaches such as least-squares orbit fitting, Gauss's method, or Semi-Definite

✉ Achmad Zainur Rozzykin achmad.rozzykin@sap.itera.ac.id	Ridlo Wahyudi Wibowo ridlo.wibowo@sap.itera.ac.id	Adhitya Oktaviandra adhitya.oktaviandra@staff.itaera.ac.id	Novia Doloyanty Br Sinaga novia.122290044@student.itera.ac.id
Aditya Abdilah Yusuf aditya.yusuf@staff.itera.ac.id	Muhamad Arrizal Hasby muhamad.120290023@student.itera.ac.id	Nabila Hilmi Aziz nabila.121290060@student.itera.ac.id	Zeni Septiani zeni.122290021@student.itera.ac.id

¹ Department of Atmospheric and Planetary Sciences, Faculty of Science, Institut Teknologi Sumatera. Sumatera, Indonesia.

² ITERA Astronomical Observatory, Institut Teknologi Sumatera

How to Cite: Rozzykin, A. Z., Yusuf, A.A., Wibowo, R.W., Hasby, M.A., Oktaviandra, A., Aziz, N.H., Sinaga, N.D.B., & Septiani, Z. (2025). Determining orbital elements of asteroid Psyche using ant colony optimization from single-night astrometric observation. *Proceedings of International Physics Conference, 1* (1), 118-125. <https://proceedings.fisikaupi.id/index.php/ipc>

Programming (Rozzykin et al., 2020; Naufal, 2017) generally require multi-night or long-arc observations to achieve accurate results.

Recent advances in computational intelligence offer alternative methods to approach this inverse problem. Among these, metaheuristic algorithms such as Genetic Algorithms (GAs), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) have shown promise in exploring complex and multidimensional search spaces without requiring gradient information or strict initial guesses (Hinagawa et al., 2013). ACO, inspired by the foraging behavior of ants, has been effectively applied in various domains, including satellite orbit optimization (Li et al., 2020) and interplanetary trajectories planning (Zotes & Peñas, 2012), but its application in asteroid orbit determination using ground-based astrometry remains underexplored.

This study focuses on the asteroid (16) Psyche, a large M-type asteroid that is the target of a NASA space mission. We present an approach using ACO to determine its orbital elements based on single-night astrometry observation. This setting mimics realistic limitations in observational campaigns, where weather, scheduling, or telescope time restrict data acquisition. Our method utilizes a forward model to simulate celestial positions from trial orbital parameters, optimizing them to minimize the residuals against observed right ascension (RA) and declination (Dec). The technique is implemented with the Astropy library, ensuring astronomical accuracy and reproducibility.

The research aims to assess whether ACO can serve as a robust tool for preliminary orbit determination when data are sparse. Our findings indicate that the derived elements closely match those listed in NASA's JPL Small-Body Database, with low residual errors. This suggests that swarm intelligence-based methods can be reliable alternatives or complements to traditional orbit determination techniques in constrained observational scenarios. The outcomes of this work may benefit efforts in early asteroid discovery tracking, citizen science programs, and resource-limited observatories.

METHODS

Research Type

This study applies a quantitative computational method, focusing on the implementation of the ACO algorithm to determine the orbital elements of asteroid (16) Psyche from astrometric observations. The goal is to assess the feasibility and performance of ACO for solving nonlinear inverse problems in celestial mechanics.

Data Acquisition

On the night of 23 August 2024, a 3.8-hour observation of asteroid (16) Psyche was conducted at the ITERA Astronomical Observatory. The session began at 16:12 UTC and ended at 19:53 UTC under mostly clear skies. Using Nighttime Imaging 'n' Astronomy (N.I.N.A.) software, a fully automated imaging sequence captured 377 frames with 25-second exposures each. A Ritchey-Chretien 10-inch telescope paired with a ZWO ASI 2600MM camera and a luminance filter allowed high signal-to-noise imaging. Tracking precision was ensured by an ASI174M off-axis guide camera, which monitored a stable star field for real-time adjustments. Astrometric analysis followed a streamlined pipeline. AstroImageJ extracted stellar coordinates

and sent them to nova.astrometry.net for plate solving (Lang, et. al., 2010; Collins, et. al., 2017). Once the match was complete, the system applied WCS headers to the images, securing accurate positional data of the asteroid. The performance of these instruments was considered reliable and acceptable with RMSE values of 0.0551 degrees in RA and 0.0047 degrees in Dec. (Rozzykin, et. al., 2024)

ACO implementation

The overall procedure follows a computational orbit determination workflow, adapted to utilize swarm intelligence methods. Initial astrometric data (JD, RA, Dec) were prepared through outlier filtering and coordinate normalization. A numerical solution to Kepler’s equation was used to propagate trial orbits, and apparent positions (RA/Dec) were computed through coordinate transformations using the Astropy library.

The ACO algorithm was used to explore the multidimensional parameter space. The parameter vector represents the orbital elements to be estimated. The very first thing to be done was defining parameter bounds for each orbital element as shown in Table 1.

Table 1. Parameter Bounds

Orbital element	Range	Unit
Semimajor axis (a)	0.5 - 3.0	astronomical unit (AU)
Eccentricity (e)	0 - 0.9	-
Inclination (i)	0 - 180	degree (o)
Right ascension of ascending node (Ω)	0 - 360	degree (o)
Argument of perigee (ω)	0 - 360	degree (o)

Ants construct candidate solutions probabilistically using a transition probability formula:

$$P_{ij} = \frac{\tau_{ij}^\alpha \eta_{ij}^\alpha}{\sum_l \tau_{il}^\alpha \eta_{il}^\alpha} \tag{1}$$

Where τ_{ij} is the pheromone level for moving from state i to j, η_{ij} is the heuristic value defined as the inverse local RMSE, and α and β control the influence of pheromone and heuristic, respectively. (Dorigo & Stützle, 2004). We set the initial value of τ_{ij} , α as 1.0 and β as 2.0 for all discretized choices. Using 20 ants, we constructed the solution for each ants with 30 iterations. After every iteration, the pheromone trail is updated as:

$$\tau_{ij} \leftarrow (1 - \rho)\tau_{ij} + \sum_k \Delta\tau_{ij}^k \tag{2}$$

where the pheromone deposit is :

$$\Delta\tau_{ij}^k = \left\{ \begin{array}{l} \frac{Q}{RMSE^k} \\ 0 \end{array} \right\}, \text{ if ant } k \text{ used } (i, j) \text{, otherwise}$$

Here, Q is a constant representing pheromone intensity and ρ is the evaporation rate. We adopted the value of 1.0 and 0.95, respectively (Zhang, et. al., 2018).

RESULT AND DISCUSSION

To further assess the performance of Ant Colony Optimization (ACO) for orbit determination, the orbital elements obtained in this study were compared not only with the dynamical solution reported by Kuzmanoski and Kovačević (2002) but also with the reference values provided by

the JPL Small-Body Database. This three-way comparison provides a broader perspective on the reliability and limitations of ACO-derived orbital elements when constrained to single-night astrometric observations.

Table 2 summarizes the orbital elements for asteroid (16) Psyche derived from ACO, those reported by Kuzmanoski and Kovačević (2002), and the JPL NASA database values cited in our manuscript.

Table 2. Orbital elements of Asteroid (16) Psyche

Orbital element	ACO-derived	Kuzmanoski & Kovačević (2002)	JPL NASA
Semimajor axis (a)	2.88081 ± 0.114966	-	2.92212
Eccentricity ϵ	0.16061 ± 0.012601	-	0.13406
Inclination (i)	2.22222 ± 0.452899	2.020701 ± 0.000014	3.09375
Right ascension of ascending node (Ω)	141.81818 ± 14.969178	164.051773 ± 0.000661	150.01955
Argument of perigee (ω)	206.41414 ± 0.008599	216.709926 ± 0.000149	229.63979

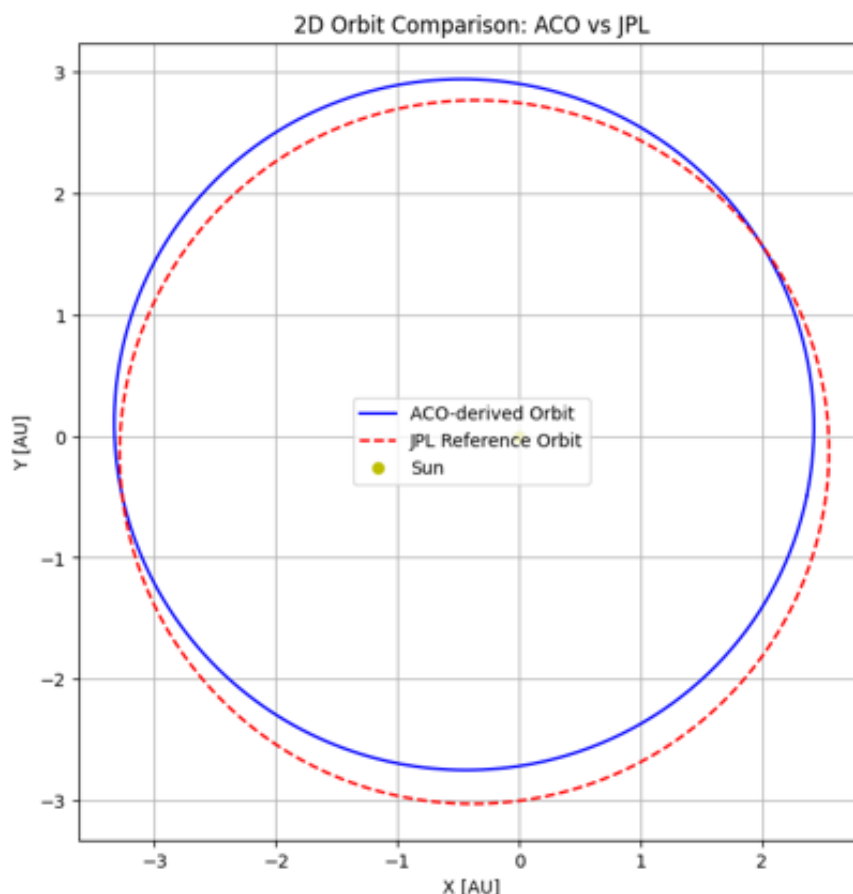


Figure 1. Orbital visualization comparison of ACO-derived and JPL NASA in 2D

To quantify the consistency between different orbit determination approaches, residuals were calculated for three pairwise comparisons: (i) ACO–Kuzmanoski & Kovačević, (ii) ACO–JPL, and (iii) & Kovačević–JPL. Absolute differences were computed as direct element-to-element deviations, while relative differences were normalized to the second dataset in each pair. The results are summarized in Table 3.

Table 3. Three-way Comparison Between ACO, Kuzmanoski & Kovačević (K&K), and JPL NASA

Orbital element	ACO-Kuz		ACO-JPL		K&K-JPL	
	Absolute	Relative	Absolute	Relative	Absolute	Relative
Semimajor axis (a)	-	-	-0.04131	-1.41%	-	-
Eccentricity ϵ	-	-	0.02655	19.80%	-	-
Inclination (i)	0.20152	9.97%	-0.87153	-28.17%	1.07305	53.10%
Right ascension of ascending node (Ω)	-22.23359	-13.55%	-8.20137	-5.47%	-14.03222	-8.55%
Argument of perigee (ω)	-10.29579	-4.75%	-23.22565	-10.11%	12.92986	5.97%

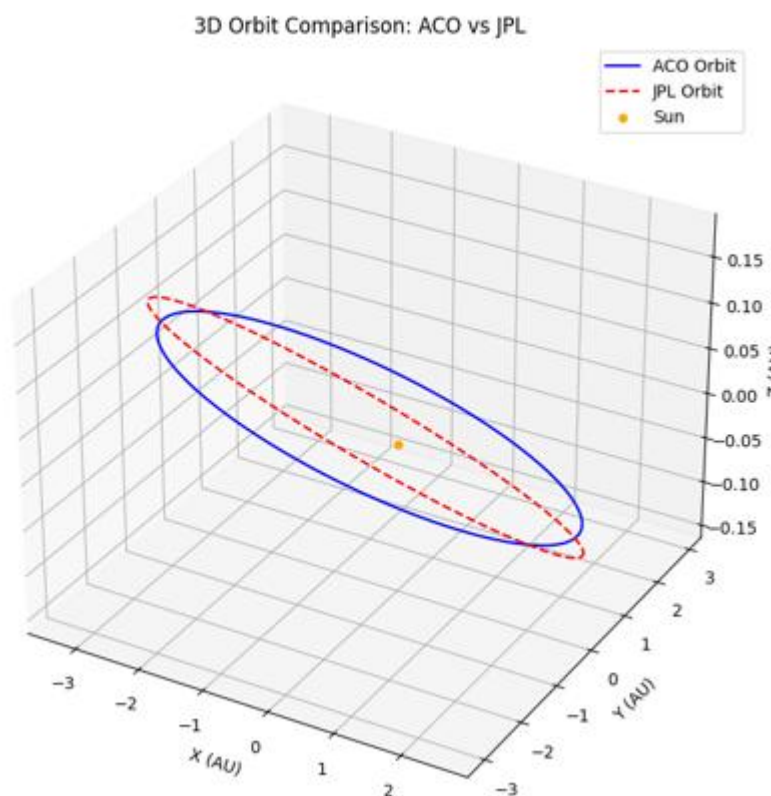


Figure 2. Orbital Visualization Comparison Of ACO-Derived And JPL NASA In 3D

The results as shown in Table 3, Figure 1 and 2 demonstrate that the ACO algorithm is capable of producing orbital-element estimates that are broadly consistent with JPL NASA reference values, even when fitted to a short-arc observational dataset. For the semi-major axis (a), ACO yielded 2.88081 AU compared to the JPL value of 2.92212 AU, a relative difference of only 1.4 %. The longitude of ascending node (Ω) was similarly well recovered (141.82° vs. 150.02° , ~ 5.5 % deviation). These small discrepancies attest to ACO’s strength in exploring a wide parameter space without requiring highly precise initial guesses, and to its pheromone-based feedback mechanism that iteratively refines candidate solutions in the presence of limited data.

Nonetheless, certain elements exhibited larger deviations: eccentricity (e) was overestimated by nearly 20 %, inclination (i) underestimated by ~ 28 %, and argument of perihelion (ω) underestimated by ~ 10 %. Three primary factors account for these differences. First, short-arc geometry inherently limits the precision of three-dimensional orbital

parameters, as small angular motions over a single night yield degenerate solutions for orbit orientation. Second, even modest astrometric errors can propagate nonlinearly into sensitive elements such as ω and i , especially in the presence of plate-solving or guiding uncertainties. Third, the discretization choices and hyperparameter settings of our ACO implementation (e.g., number of ants, pheromone evaporation rate, and α/β weighting factors) influence convergence behavior; insufficient iterations or overly aggressive pheromone concentration can lead to entrapment in local minima and suboptimal refinement of steep regions in the objective landscape. This result aligns with findings in previous works, such as those by Zhang et al. (2018) and Li et al. (2020), which highlighted the applicability of swarm intelligence in solving orbital mechanics problems. Moreover, the precision and consistency of the solution in this study support the potential of ACO to serve as a viable alternative or complement to traditional least-squares or differential correction methods, especially for limited data. The reliability of this method on data with other characteristics (e.g. different type of orbit) also still needs to be assessed.

Inclination (i) presents modest absolute differences ($\leq 1.1^\circ$) but large relative percentages due to Psyche's intrinsically low inclination. ACO is close to Kuzmanoski and Kovačević (2002) ($+0.20^\circ$, $+9.97\%$) but deviates more substantially from JPL (-0.87° , -28.2%). The large relative difference between Kuzmanoski and Kovačević (2002) and JPL ($+1.07^\circ$, $+53.1\%$) suggests that even long-arc solutions diverge significantly in low-inclination regimes, partly due to epoch differences and perturbation modeling.

The orientation parameters, longitude of the ascending node (Ω) and argument of perihelion (ω), exhibit the largest absolute discrepancies. ACO–Kuz residuals are -22.2° for Ω and -10.3° for ω , while ACO–JPL residuals are -8.2° and -23.2° , respectively. Even between Kuzmanoski and Kovačević (2002) and JPL, differences of -14.0° (Ω) and $+12.9^\circ$ (ω) are present. These deviations highlight the strong sensitivity of angular orbital elements to epoch choice, secular evolution, and methodological differences in force modeling. Since Kuzmanoski elements are given at epoch JD 2437000.5 and JPL values correspond to a later epoch, secular precession and updated dynamical models contribute significantly to these discrepancies.

Overall, the residual analysis reinforces the complementary nature of the three approaches. ACO reliably estimates the orbital scale but suffers in orientation and eccentricity when constrained by short arcs. Kuzmanoski and Kovačević (2002) and JPL show close agreement in scale but differ notably in orientation, underlining the importance of epoch consistency and dynamical propagation. For rigorous cross-method evaluation, future work should propagate all solutions to a common epoch and compare them via observed-minus-computed residuals rather than raw orbital elements.

CONCLUSION

This study demonstrates that ACO is a viable and effective method for preliminary orbit determination, particularly when observational data are limited to a short time span. The algorithm successfully recovered orbital elements that closely approximate those published by JPL NASA, especially for the semi-major axis and the longitude of ascending node, with relative deviations below 5%. These results highlight ACO's ability to navigate high-dimensional, multimodal solution spaces without requiring precise initial guesses.

However, noticeable discrepancies in eccentricity, inclination, and argument of perihelion underscore the limitations of short-arc data and the sensitivity of certain orbital elements to minor observational errors and algorithmic configuration. The findings suggest that while ACO is a powerful metaheuristic approach, its output should be interpreted as an initial solution subject to further refinement.

Residual analysis strengthens this conclusion. Across three-way comparisons (ACO–Kuzmanoski and Kovačević, ACO–JPL, and Kuzmanoski and Kovačević–JPL), the semi-major axis is consistently well constrained, with differences below 3%, while orientation parameters (Ω , ω) and inclination exhibit significantly larger discrepancies. In particular, ACO lies between Kuzmanoski & Kovačević and JPL values for the semi-major axis but diverges more in eccentricity and angular parameters due to short-arc degeneracy. Meanwhile, even Kuzmanoski & Kovačević and JPL show notable differences in inclination and orbital orientation, reflecting secular evolution and updates in dynamical models across epochs. These results indicate that ACO reliably constrains orbital scale but cannot by itself achieve the precision of long-arc, perturbative least-squares fits.

For future applications, we recommend optimization of ACO hyperparameters and inclusion of multi-night or extended-arc data to improve robustness. Propagating solutions to a common epoch and comparing them via observed-minus-computed (O–C) residuals will provide a more rigorous benchmark. Further study may expand this approach to near-Earth objects and survey follow-ups, where preliminary but rapid orbit solutions are essential.

ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to the OAIL for providing the facilities and support necessary for the acquisition of observational data. Special thanks are extended to the work of N.I.N.A and astrometry.net team whose efforts ensured the quality and accuracy of the astrometric measurements. This research was partially supported by institutional research funding from the Institut Teknologi Sumatera (ITERA).

REFERENCES

- Collins K. A., Kielkopf, J. F., Stassun K. G., & Hessman, F. V. (2017). AstroImageJ: Image Processing and Photometric Extraction for Ultra-Precise Astronomical Light Curves. *Astronomical Journal*, 153(77), 1-13
- Dorigo, M., & Stützle, T. (2004). *Ant Colony Optimization*. MIT Press.
- Hinagawa H., Yamaoka H. & Hanada T. (2014). Orbit determination by genetic algorithm and application to GEO observation. *Advances in Space Research*, 53(3), 532-542
- Kuzmanoski, M. & Kovačević, A. (2002). Motion of the asteroid (13206) 1997GC22 and the mass of (16) Psyche. *Astronomy & Astrophysics*, 395, L17-L19
- Lang, D., Hogg, D. W., Mierle K., Blanton M., & Roweis, S. (2010). Astrometry.net: Blind Astrometric Calibration of Arbitrary Astronomical Images. *Astronomical Journal*, 139. 1782-1800
- Li, X., Ma, R., Zhang S., Hou, Y., & Pei, Y. (2020). Improved design of ant colony algorithm and its application in path planning. *Acta Aeronautica et Astronautica Sinica*, 41(2), 724381-724381
- Milani, A., & Gronchi, G. F. (2010). *Theory of Orbit Determination*. Cambridge University Press.
- Naufal, F. Z. (2017). *Perhitungan Elemen Orbit Asteroid Menggunakan Metode Semi-Definite Programming*. Institut Teknologi Bandung.

- Rozzykin, A. Z., Pangestu, A. D., & Dermawan, B. (2020). Orbital Elements Determination Of Binary System WDS 03264+3520 Using Semi-Definite Programming Method. *Jurnal Sains Dirgantara*, 18(1), 13-22
- Rozzykin, A. Z., Yusuf, A. A., Hasby, M. A., Oktaviandra A., Aziz, N. H., Septiani, Z., Br Sinaga, N. D., & Wibowo, R. W. (2025). Astrometric Observation of Asteroid (16) Psyche with ITERA Astronomical Observatory's ITERA Robotic Telescope. In T. Hidajat, C. Kunjaya, T. Indriyanto, R. E. Poetro, L. Puspitarini, F. R. Izzati, I. P. Tnunay, & I. Sihar (Eds.). *Proceedings of the 1st International Conference on Space Science, Technology, and Innovation* (pp. 336 – 345). ITB Press.
- Zhang, T., Shen, H., Yang, Y., Li, H., & Li., J. (2018). Ant Colony Optimization-based Design of multiple-target active Debris Removal Mission. *Transactions of the Japan Society For Aeronautical and Space Sciences*, 14(2), 1-10.
- Zotes, F. A., & Peñas, M. S. (2012). Particle swarm optimisation of interplanetary trajectories from Earth to Jupiter and Saturn. *Engineering Applications of Artificial Intelligence*, 25(1), 189-199