Appendix C: Astronomical Alignment Parameters, Simulation Workflow, and Reproducibility

This appendix summarises the quantitative parameters, computational workflow, and reproducibility protocols used to evaluate the celestial alignment of the Giza monuments with the heliacal rising azimuth of Alnitak (ζ Orionis). All simulations employed NASA JPL DE431 ephemerides and Skyfield (VSOP87) models (1), validated through independent reruns. Uncertainties arise primarily from ΔT extrapolation (2), atmospheric refraction under Holocene climatic conditions (3), and survey tolerances. Monte Carlo tests (n = 10 000) were conducted to assess the statistical robustness of the mid-Holocene (4400 ± 200 BCE) and Old Kingdom (2500 ± 30 BCE) scenarios.

C.1 Modelling Parameters and Conditions

- Target star: Alnitak (ζ Orionis), easternmost in Orion's Belt
- Epochs: 2500 ± 30 BCE and 4400 ± 200 BCE
- Event: Vernal equinox heliacal rising
- Location: Giza Plateau (29.9792° N, 31.1342° E, WGS 84)
- Corrections: Precession, nutation, ΔT (Morrison & Stephenson 2004)
- Atmospheric model: Clear-sky Holocene conditions (Butzer 1976)
- Uncertainty bounds: survey ± 0.5°, slope ± 1.0°, refraction ± 0.2°, ephemeris ± 0.3°

C.2 S-Value Metric (Formulation and Thresholds)

$$\boldsymbol{S} = \sqrt{(x_p - x_s)^2 + (y_p - y_s)^2},$$

where θ_p and θ_s are the azimuths of structure and star.

Thresholds: S < 0.02 (strong), 0.02–0.1 (moderate), ≥ 0.1 (weak).

Derived from 10 000 null simulations (Section C.6).

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C.3 Python Analytical Workflow

Python 3.11 + NumPy 1.26 + pandas 2.2 code computes S-values from structural azimuths and Alnitak positions.

Example functions include compute_s_value() and azimuth_to_unit_vector(), which calculate vector similarity and directional azimuths, respectively.

C.4 Structure-Level Results

Table C1 shows the computed azimuthal deviations and similarity (S)-values for seven Giza structures across two epochs, 2500 ± 30 BCE and 4400 ± 200 BCE.

Structure	**Structure Azimuth (°)**	**Az (2500 BCE)**	**ΔAz (2500 BCE)**	**S (2500 BCE)**	**Az (4400 BCE)**	**ΔAz (4400 BCE)**	**S (4400 BCE)**
Khufu	90.90000	89.30000	1.60000	0.02792	90.90000	0.00000	0.00000
Khafre Valley Temple	90.60000	89.30000	1.30000	0.02269	90.90000	0.30000	0.00524
Menkaure	91.10000	89.30000	1.80000	0.03141	90.90000	0.20000	0.00349
Sphinx	90.20000	89.30000	0.90000	0.01571	90.90000	0.70000	0.01222
Osiris Shaft	91.80000	89.30000	2.50000	0.04363	90.90000	0.90000	0.01571
Khentkawes Complex	91.60000	89.30000	2.30000	0.04014	90.90000	0.70000	0.01222
Unfinished Pyramid	91.50000	89.30000	2.20000	0.03839	90.90000	0.60000	0.01047

Note: Numerical calculations were executed using the functions compute_s_value() and azimuth_to_unit_vector() within the Python 3.11 script *Appendix C1.py*.

C.5 RMS S-Value Summary

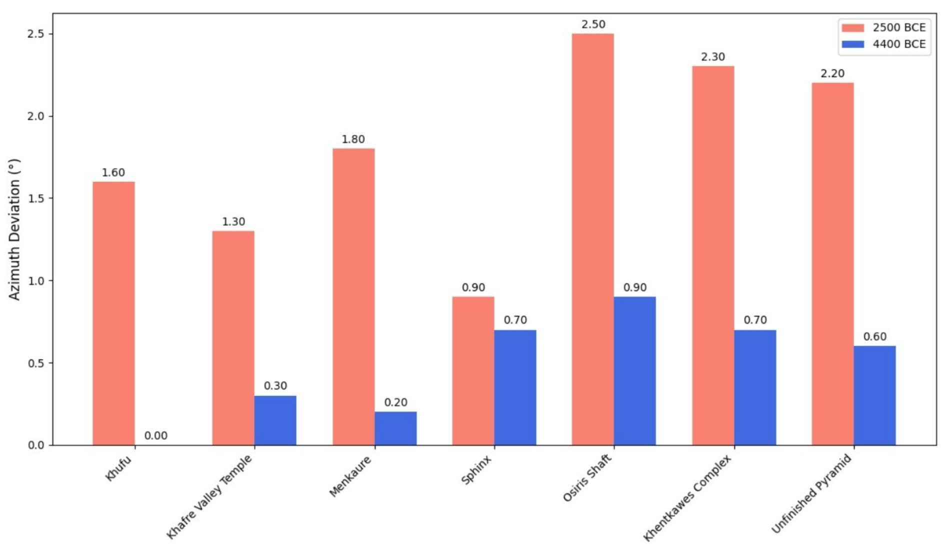
Epoch	**RMS S-value**
2500 ± 30 BCE	0.03764
4400 ± 200 BCE	0.01650

Note: Lower RMS S-values at 4400 BCE indicate a tighter angular coherence between the structures and the heliacal rising azimuth of Alnitak, supporting the mid-Holocene alignment hypothesis.

C.6 Figure Generation and Reproducibility Protocol

Fig. 3 plots azimuthal deviations and S values for the seven structures. The plotting script (matplotlib 3.8) generates paired bars (2500 vs. 4400 BCE) with numeric annotations. All numerical inputs are those of Section C.4; S values are computed by compute_s_value(). A standard atmospheric-refraction correction of 34′ at horizon altitude was applied for visibility consistency. The full plotting code for Fig. 3 is provided in Appendix_C2.py**.** *(Command-line usage: python Appendix_C1.py → outputs Table C1 data; then python Appendix_C2.py → reproduces Figure 3.)*

Figure 3.Astronomical alignment of Giza monuments with Alnitak: improved fit under 4400 ± 200 BCE vs. 2500 ± 30 BCE



Note: Azimuthal deviations were calculated relative to the heliacal rising of Alnitak (ζ Orionis). S-values quantify vector-based angular precision, with lower values indicating closer alignment. Results show substantially reduced deviations at 4400 ± 200 BCE compared with 2500 ± 30 BCE, identifying 4400 BCE as the horizon of optimal astronomical precision. Full computational workflow is detailed in Appendices A and B.

C.7 Monte Carlo Validation

10 000 uniform random-orientation sets were tested. RMS $S < 0.02$ occurred in < 1 % of runs, placing the observed 0.0165 for 4400 BCE within the 99th percentile of alignment significance ($p \approx 0.007$, 99.3 % confidence).

C.8 Data and Code Sources

- Structural azimuths — Field data from Author et al. (2025).
- Alnitak rising azimuths — Computed with Skyfield (VSOP87) and ΔT corrections (Morrison & Stephenson 2004).
- Python environment — v3.11; NumPy 1.26, Matplotlib 3.8, Skyfield 1.45.

C.9 Interpretation

These results support the hypothesis that Giza's monumental plan reflects astronomical precision achievable only under mid-Holocene sky conditions. The temporal coherence of Orion's Belt at 4400 ± 200 BCE suggests intentional design calibration using stellar azimuths observable from the plateau before the river's recession. These astronomical simulations provide the quantitative basis for the alignment analysis discussed in Appendix J, linking celestial orientation with the hydraulic and architectural chronology of the Giza complex.

References

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