Field Validation of a Copernicus GLO-30 Horizon Model for Archaeoastronomical Analysis: The Case of Zorats Karer, Armenia

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Abstract

Testing whether a monument's orientation corresponds to an astronomical target, and evaluating that correspondence statistically, requires an accurate numerical horizon profile as input — traditionally often obtained through a dedicated field campaign. This note validates an open, globally available alternative for producing that input dataset: the Copernicus GLO-30 digital elevation model (DEM), tested against 34 independent field zenith-distance measurements taken at 10° azimuthal intervals around the horizon of the Zorats Karer megalithic complex in Syunik Province, Armenia. The DEM-derived horizon profile matched the field survey with a mean deviation of +0.031°, a root-mean-square error of 0.128°, and 94.1% of points agreeing within ±0.25°. This level of agreement supports the use of the validated DEM profile as the numerical horizon dataset underlying the astronomical analysis and Monte Carlo statistical evaluation of Zorats Karer's structural orientations. More broadly, Copernicus GLO-30 can also be applied for generating such datasets at other Armenian monuments where field measurements are unavailable, although it should be borne in mind that its accuracy may differ from site to site.

Keywords: *archaeoastronomy; digital elevation model; horizon reconstruction; Copernicus GLO-30; field validation; Zorats Karer*

1. Introduction

Archaeoastronomical analysis of a monument's orientation depends on an accurate numerical model of the altitude of the local horizon as seen from the monument. Moreover, the rising and setting azimuths of the luminaries depend strongly on the actual altitude of the horizon (Ruggles, 2015c, p. 465; Ruggles, 2015a, p. 376): at the latitude of Zorats Karer ($\varphi \approx 39.55°$), a 1° rise in horizon altitude shifts the azimuth of sunrise by about 0.8–1.0°, and at a horizon altitude of 7° by about 6–7°. This horizon profile is usually obtained by a field survey, measuring horizon altitude at regular azimuthal intervals with a theodolite or total station. This is slow, weather-dependent, and rarely repeated by later researchers, which limits both the reproducibility and the geographic reach of such studies, particularly in regions such as the Armenian Highlands where systematic archaeoastronomical surveys remain comparatively limited.

The real altitude of the horizon also matters for statistical evaluation. Uncertainties in determining an orientation are naturally described by a distribution in azimuth rather than in declination, and because horizon altitude varies from point to point, a normal distribution in azimuth is generally transformed into a more complex distribution in declination space (Ruggles, 2015b, p. 418). The same applies to the null hypothesis: even for a single site, randomly oriented structures do not produce a uniform distribution of declinations but a bimodal one, with the probability concentrated at the extremes of the range (corresponding to the northern and southern directions) and with sharp limits (Ruggles, 2015b, p. 420). In mountainous terrain, where horizon altitude varies considerably with azimuth, the declination distribution is distorted still further, and modelling it analytically is problematic. In the case of Zorats Karer this is clearly visible: with the horizon profile derived from the Copernicus GLO-30 DEM, the declination distribution for uniformly random azimuths is likewise bimodal with sharp limits, as described by Ruggles (2015b), but the limits shift to about +57.4° and −47.8° (instead of the ±50.45° of a flat horizon) and the distribution becomes asymmetric (Figure 1). For Zorats Karer, therefore, the accuracy of the astronomical and landscape

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correspondence and of its statistical analysis depends directly on the accuracy of the horizon profile, which makes validation of the DEM important. A real, digitised horizon profile solves this problem: the declination corresponding to each azimuth is computed directly from the real horizon altitude, so the null distribution can be obtained by numerical (Monte Carlo) simulation without the assumption of a flat horizon.

A practical alternative is to derive this horizon dataset from a freely available global digital elevation model (DEM; Patat, 2011). For testing astronomical targets, however, this is useful only if it can be shown that the resulting numerical profile reproduces field-survey accuracy closely enough for the declination precision that such statistical evaluation requires — typically a few tenths of a degree. At the same time, the accuracy of the horizon altitude must be comparable to the accuracy of azimuth measurement, which can become a problem when the altitude of a relatively near horizon is estimated from numerical data of insufficient resolution (Ruggles, 2015a, p. 376). This note presents just such a validation, carried out specifically to create a reliable numerical horizon dataset for the astronomical analysis and statistical evaluation of the Zorats Karer megalithic complex (Malkhasyan, in press), and discusses its implications both for that analysis and, more generally, for creating comparable horizon datasets at other sites in Armenia.

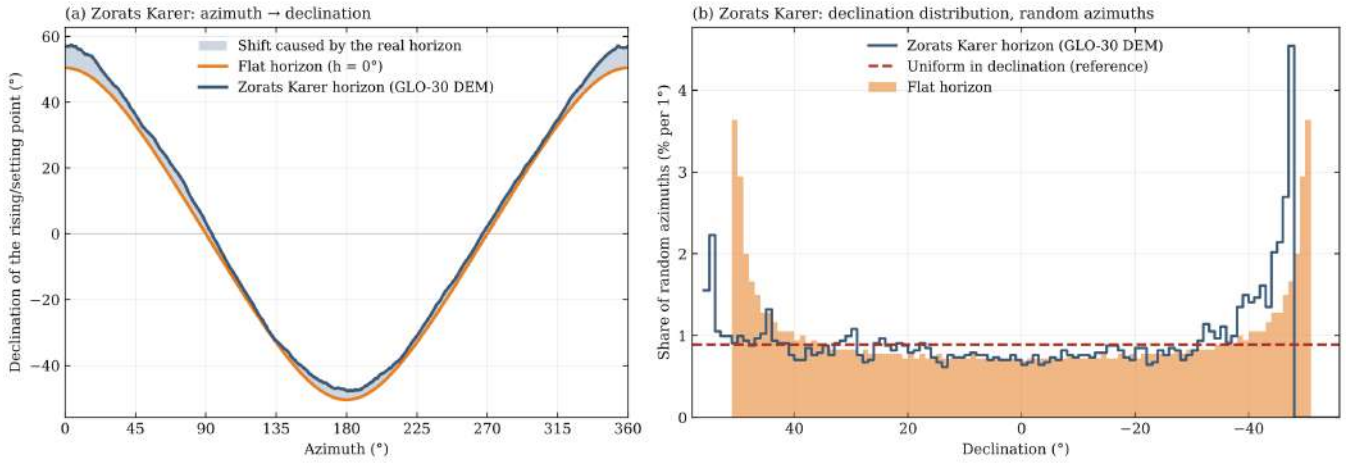

Figure 1. Declination distribution calculated for Zorats Karer for uniformly random azimuths, for a flat horizon ($h = 0°$) and for the real Zorats Karer horizon (Copernicus GLO-30 DEM, 0.1° step; $\varphi = 39.5514592°$ N). (a) Declination as a function of azimuth. (b) Declination distribution (1° bins, share of azimuths in %): orange bars, flat horizon; blue step line, DEM horizon; dark red dashed line, level of a distribution uniform in declination (the declination axis runs from + to −). The 1° binning is used only for the graphical representation of the distribution. The calculation is simplified: the radius of the luminary's disc and parallax are not included.

2. Constructing and Validating the Horizon Model

The local horizon-altitude profile for Zorats Karer was derived from the Copernicus GLO-30 global DEM (30 m resolution, open access; European Space Agency, 2024), sampled at 0.1° azimuthal steps around the full 360° circle, with the standard (Gaussian) terrestrial refraction coefficient $k = 0.13$ applied throughout (Brunner, 1984). This 0.1° interval is the angular sampling step used to construct the profile and should not be read as the spatial resolution of the underlying 30 m DEM. Horizon altitudes were computed from the observer's eye-level position ($\varphi = 39.5514592°$ N, $\lambda = 46.0289140°$ E, elevation 1770.6 m — the ArmRef002 ground point at $Z = 1769.128$ m plus a 1.5 m eye height), accounting for Earth's curvature.

The DEM-derived profile was validated against field-survey measurements taken during the 2020 survey, from the same observer position, using a Trimble C5 total station independently of the DEM construction: zenith-distance observations of the horizon at 10° azimuthal intervals around the monument. The angular accuracy of the instrument is 1″. One measurement was taken in each direction, at the point as close as possible to the skyline. The overall uncertainty of the field measurements includes, in addition to the angular accuracy of the instrument, the uncertainty in identifying the horizon point, particularly for distant peaks. Of 36 candidate directions, 34 yielded valid measurements; two (at azimuths 70° and 240°) were excluded due to cloud cover over distant mountain peaks at the time of the survey.

Table 1. Comparison of field-survey and DEM-derived horizon altitudes at 10° azimuthal intervals (observer position: $\varphi = 39.5514592°$ N, $\lambda = 46.0289140°$ E, $H = 1770.6$ m; $k = 0.13$). $\Delta h = h_{\text{field}} - h_{\text{DEM}}$. Azimuths 70° and 240° were excluded from the validation statistics due to cloud cover over distant peaks at the time of survey. Distance denotes the horizontal distance from the observation point to the terrain feature defining the DEM-derived horizon altitude along each azimuth.

Azimuth (°)	Field h (°)	DEM h (°)	Δh (°)	Distance (km)
0.0	6.555	6.528	+0.027	14.4
10.0	6.667	6.743	−0.076	12.4
20.0	6.135	6.250	−0.115	14.1
30.0	4.636	4.667	−0.031	14.8
40.0	4.783	4.880	−0.096	12.3
50.0	3.989	3.737	+0.252	13.9
60.0	5.453	5.423	+0.029	14.1
70.0	— (cloud)	6.590	—	13.4
80.0	5.894	6.026	−0.132	13.6
90.0	5.169	5.359	−0.190	14.1
100.0	3.358	3.365	−0.007	14.3
110.0	2.809	2.582	+0.228	1.6
120.0	2.124	1.938	+0.186	1.7
130.0	0.596	0.563	+0.034	3.1
140.0	1.952	1.672	+0.280	9.4
150.0	2.663	2.490	+0.174	9.6
160.0	2.871	2.905	−0.034	13.7
170.0	2.884	2.987	−0.103	17.3
180.0	2.707	2.773	−0.066	25.9
190.0	2.560	2.477	+0.083	16.4
200.0	3.131	2.911	+0.220	19.7
210.0	2.257	2.368	−0.110	26.1
220.0	2.380	2.331	+0.049	17.7
230.0	3.043	3.014	+0.029	17.2
240.0	— (cloud)	3.541	—	3.6
250.0	3.000	3.030	−0.030	6.8
260.0	3.086	2.947	+0.139	1.2
270.0	3.472	3.505	−0.033	1.2
280.0	3.325	3.347	−0.022	21.5
290.0	2.400	2.595	−0.195	17.8
300.0	1.670	1.609	+0.062	17.2
310.0	1.939	1.802	+0.137	6.6
320.0	3.019	2.845	+0.174	9.1
330.0	3.567	3.532	+0.034	8.6
340.0	5.359	5.252	+0.107	11.6
350.0	6.486	6.431	+0.055	11.4

3. Results

The comparison (Figure 2) yielded a mean deviation (field − DEM) of +0.031°, a standard deviation of 0.124°, a root-mean-square error of 0.128°, and a maximum absolute deviation of 0.280° (at azimuth 140°). The standard deviation was calculated using the population formula (division by n). Of the 34 field-survey measurements, 94.1% fell within ±0.25° of the DEM-derived value. The small mean deviation indicates little overall systematic offset between the two methods, while the standard deviation and RMS quantify the dispersion of the individual differences.

The terrain features defining the horizon lie 1.2–26.1 km from the observation point (Table 1), i.e. at least 40 DEM cells away. The resulting RMS deviation of approximately 0.13° indicates that the DEM-derived horizon altitudes reproduce the field measurements within a range generally sufficient for archaeoastronomical applications requiring angular precision of a few tenths of a degree. The corresponding uncertainty in derived declinations, however, also depends on the accuracy of the azimuth. On this basis, the validated DEM profile was adopted as the primary horizon model for the subsequent orientation analysis of Zorats Karer, in place of a purely field-measured profile.



Figure 2. Comparison of the DEM-derived horizon model (Copernicus GLO-30, $k = 0.13$) with 34 independent field-survey zenith-distance measurements at Zorats Karer. Upper panel: horizon profile (shaded) and field measurements (points). Lower panel: azimuthal distribution of the differences (Δh), colour-coded by magnitude ($|\Delta h| \leq 0.05°$, $0.05°$–$0.15°$, $> 0.15°$), with the $\pm 0.25°$ tolerance band shown as dashed lines. Mean deviation = $+0.031°$, RMS = $0.128°$.

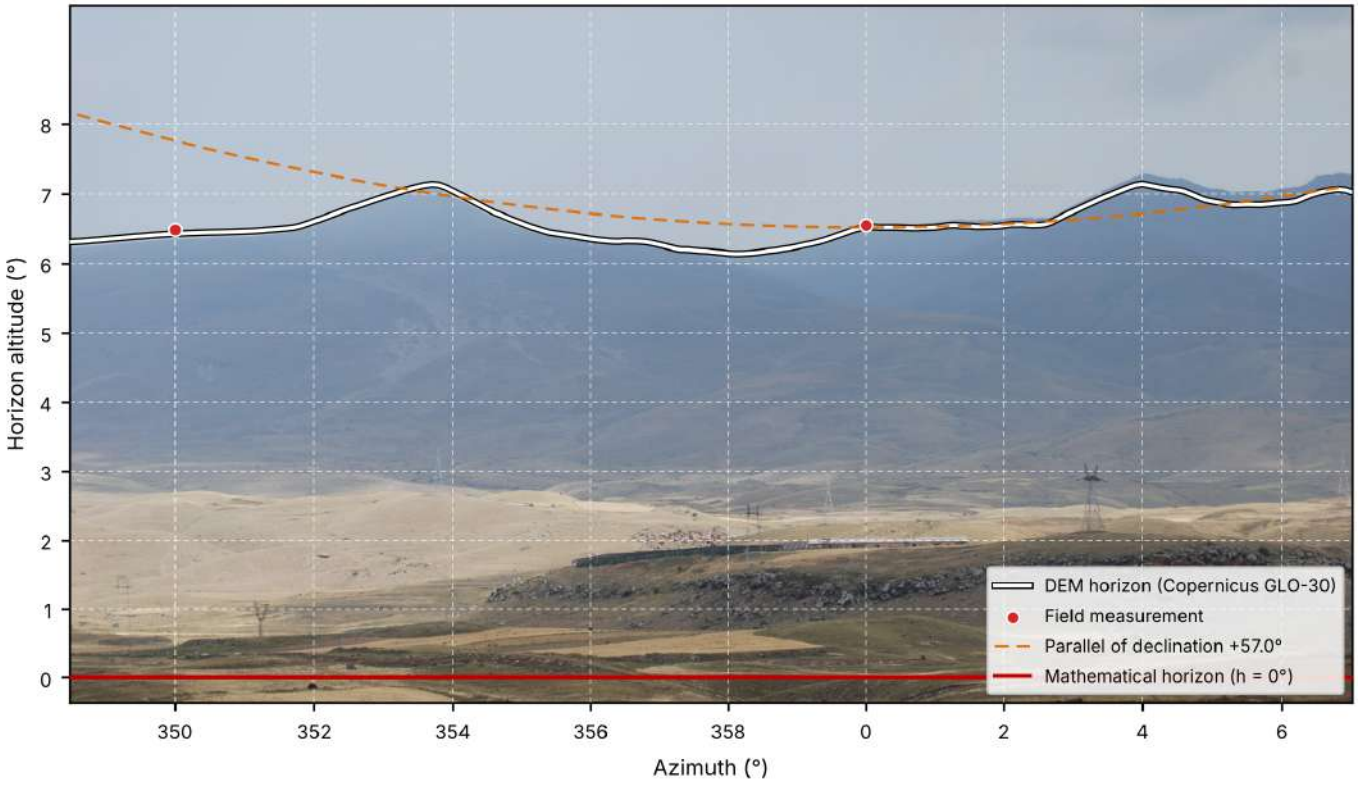

Figure 3. Northern horizon at Zorats Karer: open, sparsely vegetated highland terrain and the mountain ridges that define the skyline, with the Copernicus GLO-30 DEM horizon (white line), the mathematical horizon (red line), the field measurements (red points) and the parallel of declination $+57.0°$ (dashed; the diurnal circle of a star of that declination, meeting the DEM horizon at azimuth $0°$; atmospheric refraction is not included) superimposed. The photograph was registered to the DEM profile by fitting its field of view, central azimuth and vertical position to the skyline. Photo: G. Stepanyan.

4. Discussion: Implications for Future Work

Two implications follow from this result, one specific to Zorats Karer and one more general.

First, for Zorats Karer itself, the DEM profile provides the horizon (Figure 3) against which the monument's structural orientations are tested for correspondence with candidate astronomical targets, and that correspondence is evaluated statistically through Monte Carlo null-hypothesis testing. That analysis is the subject of a separate, full-length treatment (Malkhasyan, in press) and is not repeated here; the present note is concerned only with establishing that this underlying dataset is accurate enough to support that astronomical and statistical use.

Second, and more broadly, the result bears on horizon reconstruction at other Armenian megalithic and archaeological sites. Because Copernicus GLO-30 provides global, freely accessible 30 m-resolution coverage, research groups working at other sites in Armenia can, in principle, construct a horizon profile without a dedicated theodolite campaign. On the basis of the agreement demonstrated here, Copernicus GLO-30 may also be applicable at other Armenian archaeoastronomical sites. This is a possibility, not a general guarantee: terrain roughness, vegetation cover, and satellite-derived elevation artifacts can vary by location, and the DEM's performance at Zorats Karer — an open, sparsely vegetated highland setting (Figure 3) — may not hold to the same degree at a more topographically complex or more heavily vegetated site.

A further practical point concerns reproducibility. Because the DEM and the sampling procedure are both openly available, the horizon model constructed here can be exactly regenerated by another researcher, which is not generally true of a field-measured profile unless the original survey data are published. We would encourage future horizon-based studies in the region to report their validation statistics in the same form used here — mean deviation, standard deviation, and the proportion of points within a stated tolerance — so that the reliability of DEM-based horizon models can be compared across sites and over time.

5. Conclusion

Over the 34 directions measured at Zorats Karer, the open, 30 m-resolution Copernicus GLO-30 DEM reproduced the field-surveyed horizon to within $\pm 0.25^\circ$ in 94.1% of cases (mean deviation $+0.031^\circ$). The DEM horizon therefore serves as the primary horizon model for the ongoing archaeoastronomical analysis at the site, including the statistical testing of structural orientations reported elsewhere. The same approach may also be applicable for horizon reconstruction at other Armenian sites, with the site-specific accuracy of the DEM kept in mind.

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