

The Viking sun-compass could function before and after sunset

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Vikings routinely crossed the North Atlantic without having the magnetic compass and left marks even on Greenland, Newfoundland and Baffin Island. Based on an artefact dial fragment found at Uunartoq in Greenland under the ruins of an 11th century Benedictine convent it is widely accepted that they sailed along chosen latitudes using primitive sun-compasses. Such instruments were tested on sea and proved to be efficient handheld navigation tools, but dimensions and incisions of the Uunartoq find are far from optimal in this role. On the base of written sources and speculations on primitive skylight polarimetry incompatible hypotheses were formed on the presumed Viking navigation procedures. We reinterpret here the Uunartoq artefact as a ‘twilight board’ that is a combination of a horizon board and a sun-compass optimised for using when the sun is close to the horizon. We deducted an appropriate solar navigation procedure that synthesises earlier suggested methods in harmony. It could have allowed Vikings to navigate around the clock, use the artefact dial as a sun-compass during long parts of the day and utilise skylight polarization patterns in the twilight period. In field tests we found that true north could be appointed with such a medieval twilight compass with an error of about 4° when the artificially occluded sun had elevation angles between 10° and -8° relative to the horizon. Our interpretation also allows us to assign exact dates to

the gnomonic lines on the artefact and outline the schedule of the merchant-ships that sustained the Viking colony in Greenland a millennium ago.

Viking navigation discipline covered more than knowledge on currents, characteristic landmarks, bright stars and trails of birds and sea animals (Thirslund, 2001; Karlsen, 2003). Vikings divided the horizon to eight named sections forming the ‘attir’ system, a primitive analogue of modern compass points, which served as an independent directional and temporal reference. Beside the widely accepted hypothesis of Viking sun-compasses (Sølver, 1953; Thirslund, 2001) written sources attest the distinguished role of solar azimuth angles and inspired the idea of the horizon board, which is a primitive tool appointing true directions in the moment of sunset and sunrise (Karlsen, 2003). A calcite crystal recently found in an Elizabethan shipwreck (Le Floch *et al.*, 2013) seems to support another popular hypothesis that birefringent crystals called sunstones were used for skylight polarimetry in order to locate the occluded sun (Ramskou, 1969; Roslund and Beckman, 1994; Hegedüs *et al.*, 2007a,b; Horváth *et al.*, 2011; Ropars *et al.*, 2012).

The half disc of the Uunartoq dial wears two deliberately incised lines which were earlier interpreted as truncated gnomonic lines to be used with a 4.3 mm high central gnomon on the days of Equinox and summer solstice at the 61st latitude (Fig 1A). The dial has a diameter of mere 70 mm and a large central hole with a diameter of 17 mm. Large sections of the supposed gnomonic lines are missing constraining operation to solar elevation angles between 7° and 27°. Understandably scholars studying this artefact hypothesized a lost central part with a pin-like gnomon and a complement of the gnomonic lines (Thirslund, 2001).

We suggest that the dial should be rotated 8.7° counter-clockwise to be interpreted appropriately (Fig. 1B). The large central hole might have a key role. It could house a broad and short central conical gnomon with a diameter of 15.7 mm, the base of which was tangential to the asymptotes of the incised gnomonic lines. The edge of the gnomon shadow fitted to the asymptotes when the sun was close to the horizon (Fig. 2). The dial of this reconstructed instrument that we call ‘twilight board’ may be small and may wear only those inner sections of the gnomonic lines that significantly deviate from their asymptote. Yet the navigator can derive true directions from the metre-long gnomon shadow by rotating the levelled dial until the shadow edge aligns to the outmost shown point of the valid gnomonic line. Although the conical gnomon unavoidably covers the central sections of gnomonic lines a twilight board can function as a sun-compass at medium solar elevations. Since the asymptotes appoint the bearings of the setting and rising sun it can double also as a horizon board (Fig. 2A). No circle is tangential to asymptotes of all gnomonic lines, thus applying a

single gnomon with a given base diameter results in a navigation error that limits the period in which that gnomon could effectively be used (Fig. 3A).

The instrument would be useless when fogbanks or distant clouds occlude the sun unless its position could be estimated using sunstones or sighting instructive atmospheric optical phenomena (Können, 1985; Horváth and Varjú, 2004; Suhai and Horváth, 2004; Barta *et al.*, 2005). Then an acute object of a characteristic arrow-head shape can be used to replace the shadow (Fig. 1C). This ‘shadow stick’ wears a series of sockets located at distances from its tip equalling with the distances between the gnomon tip and the shadow tip at selected solar elevations. In case of sockets corresponding to low solar elevations the width of the stick should represent the shadow width at the edge of the dial at a distance from the socket equalling with that between the gnomon tip and the dial edge (Fig. 1C).

For symmetry reasons the twilight board can function a fully functional medieval twilight compass if aided by sunstones and a shadow stick; it can be used even after sunset until the end of civil twilight (Figs. 1C, 2) (Ramskou, 1969). The tip of the shadow of an imaginary conical gnomon pointing downward in the northern focus of the hyperbola of the gnomonic line and ‘illuminated’ by the set sun from below the horizon would follow the same gnomonic line (Fig. 2). The place of this imaginary gnomon changes day by day along the north-south line (Fig 3A). But if the other branch of the hyperbola of the gnomonic line is marked on the dial, one can rotate the dial by 180° to swap the real and imaginary gnomons. The northern branch of the hyperbola will move to right position and the shadow stick will function like before sunset (Fig. 2C). Both branches of the hyperbola may be drawn by tracking the gnomon shadow on days when the sun is seen to set 180° away from the rising sun on the matching date. Such dates can be appointed by counting matching numbers of days ahead and back from the day of Equinox and can be verified with the aid of the attir system. In our field tests, a counterpart twilight board aided by a shadow stick and a pair of sunstones was found to appoint true north with a wide interval of 95% confidence: $\delta = 356.1^\circ \pm 2.2^\circ$ (Fig. 3B). Our best performing observer reached an average bearing error of mere 1.5°, and all test people remained within a 95% confidence interval of about 11°.

The Gregorian dates March 10 and 31 can be assigned to the gnomonic lines incised in the artefact dial and outline the schedule of Norse merchant-ships crossing the North Atlantic Ocean. A departure on the first days of March would predict landing in Greenland around Equinox. The compass is quite accurate until the middle of April at the 61st latitude (Fig. 3A) allowing a safe return by the end of March. Risks of such an early crossing would be unacceptable in our time, but could have been admissible during the Medieval Climate

Optimum characterised by relatively calm oceanic conditions and less dense sea ice (Severin, 1978; Miller *et al.*, 2010; Ribeiro *et al.*, 2012). The artefact dial is equally functional on September 1 and 30, but an autumnal North Atlantic crossing is less justified by mercantile considerations. Some written sources contradict the above equinoctial schedule, which might be a result of their late origin and possible revisions influenced by the cooling climate and decaying mercantile activities (Arneborg, 2000). Discrepancies may origin also from the asynchronous calendar systems (primarily Julian and old Nordic) referred in the original narratives. The weak point of our interpretation is the unfitting outer section of the southern incised line on the artefact. Since its inner section is sufficient for using the twilight board, we have to assume that it was imperfectly formed.

The potential of the twilight board is remarkable for its simplicity. In the season of the equinox the Uunartoq artefact could operate as a twilight board for about 5 hours after sunrise and before sunset. If used with birefringent crystals and a shadow stick, this solar navigation instrument could operate for about 50 minutes before sunrise and after sunset (Können, 1985; Karlsen, 2003; Ropars *et al.*, 2012). It could be reliable as aligning to the Pole star, which itself could cause a bias of 12°28' in the Viking era. One should consider that no artefact shadow sticks were identified until now. However, some genuine examples may easily lay in collections without recognising their true purpose and registered as pendants or clasps.

Methods:

A digital model of the Uunartoq artefact was created using high-resolution photographs kindly provided by the Danish Maritime Museum and published by Thirslund (2001). We considered a series of notches to mark true north. The calculated position of unmarked equinoctial line implies a 4.3 mm high central gnomon. Gregorian date were assigned to the northern incised line by selecting the gnomonic line with asymptote parallel to it, while to the southern one by the selecting the gnomonic line fitting best to its inner section (Fig. 1B). Parameters of gnomonic lines and asymptotes were calculated by our self-written computer program without considering atmospheric refraction.

Base diameter of conical gnomons casting 7.9 mm long equinoctial noon shadow tangential to the asymptotes of gnomonic lines were calculated for every day between winter and summer solstices for the latitudes of 46°, 51°, 56°, 61° and 66° N (Fig. 3A). Length of the period coverable by a single optimal gnomon was defined by a range of the base diameter not wider than 1.1 mm and causing an orientation error smaller than 1°.

Field trials were performed with a pendulum-levelled counterpart twilight compass integrated with a coverable magnetic compass during the autumn equinoctial period (24

August – 19 October 2012) in Budapest, Hungary (47° 28'N; 19° 4'E). Positions of the occluded sun situated between 10° and -8° according to the horizon were estimated in clear weather using only a pair of non-optical quality but polished rhombohedra Icelandic spar sunstones sized 5×5×2.5 cm. Data on real position of the sun was obtained from the USNO Naval Oceanography Portal. To orient the twilight board we used a shadow stick that represented the shadow of a conical gnomon with optimal base diameter (22 mm at the latitude of Budapest and a gnomon height of 9.8 mm) at solar elevations of 1.4°, 3.7°, 5.7°, 9°, 13.5° and 18°. These angles correspond to the average arcs subtended by the fingers and fists on the extended arm of the observers (six city-dwelling white males). The error of considered north was defined as the deviation of the magnetic needle from the local magnetic north measured to one tenth of a degree. The mean vector and the angular scatter were calculated to determine the deviation from true north (Zar, 2010).

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Figure legends

Figure 1: (A) Figure and engraved markings of the artefact dial fragment (grey shades) with a hypothesized central gnomon. Deliberately incised lines are shown as thick solid lines. A depression (shown as grey oval) is a hypothesized marking of East (after Thirslund, 2001). Thirslund interpreted the straight incised line as the equinoctial line. The series of notches were supposed to be an approximate marking of North. Dash-dot lines show the appropriate gnomonic lines at the 61st latitude at Equinox and on 8th of April. On the later date the shadow tip would follow the inner section of the curved incised line. Thin solid lines in the left side represent the asymptotes of the gnomonic lines. **(B)** We consider the short notches in the northern part to be the marking of the north-south line and the dial is rotated by 8.7° CCW. Incised lines fit to the path of the shadow on 10th and 31st of March. These gnomonic lines are the northern and southern branches of a hyperbola with asymptotes nearly tangential to a central conical gnomon with a base diameter of 15.7 mm. The dial can be used either as a twilight board before sunset and during the twilight period. Depression in the eastern part could be a correction mark for the erroneously incised outer section of the southern gnomonic line. **(C)** Dimensions of the hypothesized shadow stick to be used with the Uunartoq artefact dial. Dark circles symbolize sockets to be fitted to the tip of the gnomon at chosen solar elevation angles approximating arcs subtended by fists and fingers on the navigator's extended arm.

Figure 2: (A) A twilight board is the combination of a horizon board coding the azimuth of the setting sun and a sun-compass wearing a short conical gnomon and a matching gnomonic line (thick solid line). The base of the gnomon is tangential to the asymptotes (dashed arrows) of the gnomonic line. At low solar elevation angles Θ_s the instrument can be rotated until the edge of the shadow lies on an asymptote of the gnomonic line. The 'cast' shadow (dash-dot line) of an imaginary down-pointing gnomon (dashed circle) when 'illuminated' by the set sun from below the horizon would act likewise. **(B)** At low positive and negative solar elevation angles, when the shadow is not visible but the sun position can be estimated, a shadow stick can replace the shadow of the central gnomon (shown in dark shade) or the imaginary gnomon (shown in light shade). The stick should point away from the solar meridian, while its side representing the edge of the shadow at the given solar elevation should be fitted to the asymptote. **(C)** When the sun is below the

horizon, it is easier to derive directions by turning the compass by 180°. Now the real gnomon plays the role of the imaginary one, only it still points upward. The shadow stick can be used to represent the imaginary shadow on the underside of the compass dial. The northern incised line represents the imaginary gnomonic line. The kit functions as an efficient twilight compass.

Figure 3: (A) Optimal base diameters of conical gnomons for a twilight board at the 46th, 51st, 56th, 61st 66th latitudes providing 7.9 mm length of equinoctial noon shadow. The difference between the base diameter of a single gnomon and the daily optimal base diameter defines the longest possible season of its operation. On the 61st latitude (solid line), which is the place of the traditional Viking sailing route to Greenland, prescribing an error less than 1° defines a vernal navigation season between 24th of February and 15th of April according to the Gregorian calendar system. The season is significantly extended at more southern latitudes. **(B)** Histograms of bearings considered being true north and error of solar elevation angles estimated by six test persons (Table 1) equipped with a twilight compass kit consisting of a twilight board, a shadow stick and a pair of calcite sunstones in Budapest (47° 28' N, 19° 4' E) in clear weather during the autumnal equinoctial period. The 642 trials were performed at solar elevation angles between 10° and -8°. Solid circles mark the length of average vectors required for 1 % significance of Rayleigh statistics. Likewise, dashed circles mark the length of average vectors required for 5 % significance of Rayleigh statistics. Positive deviation marks overestimation of the solar elevation angle.

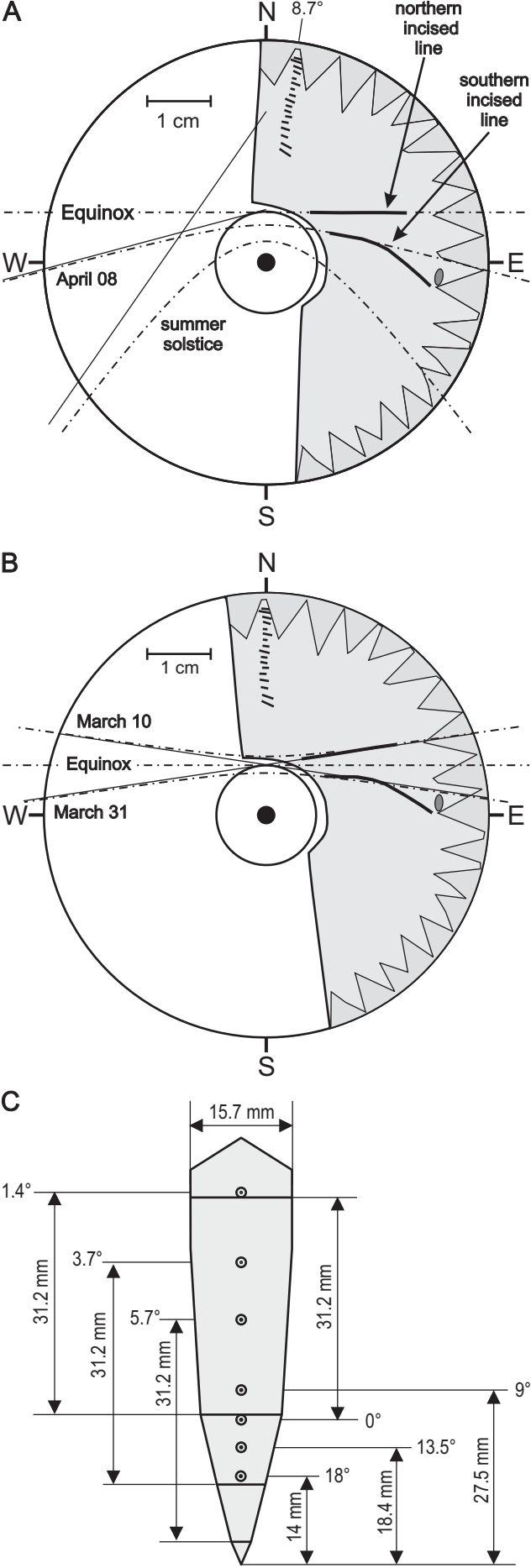


Figure 1

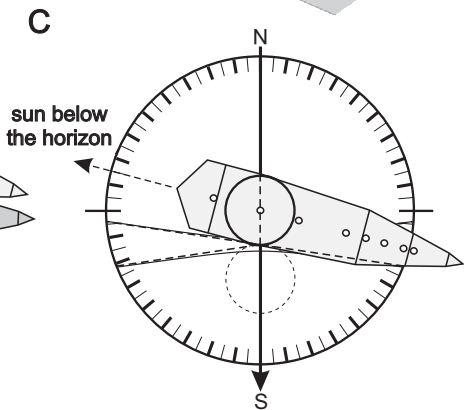
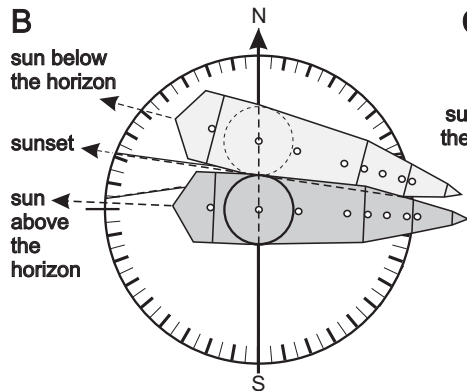
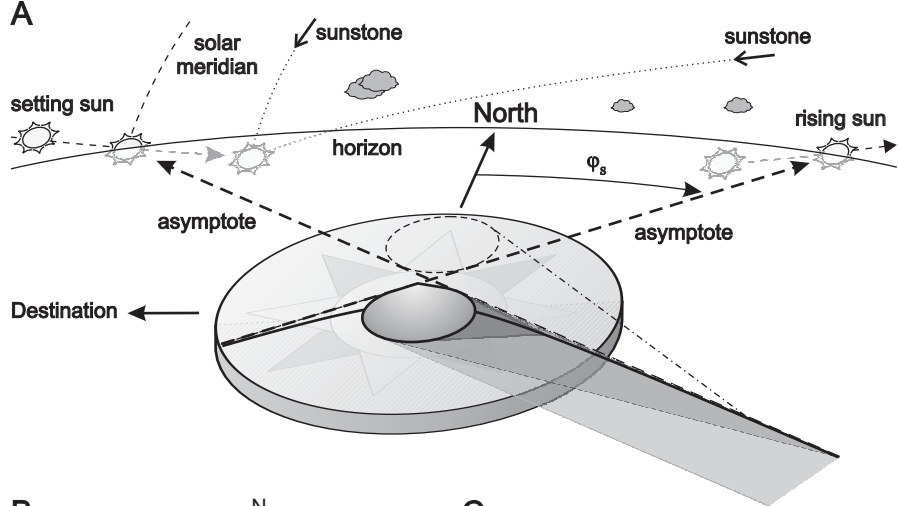


Figure 2

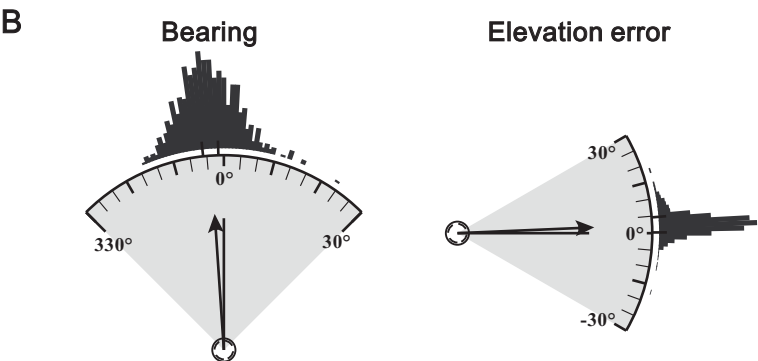
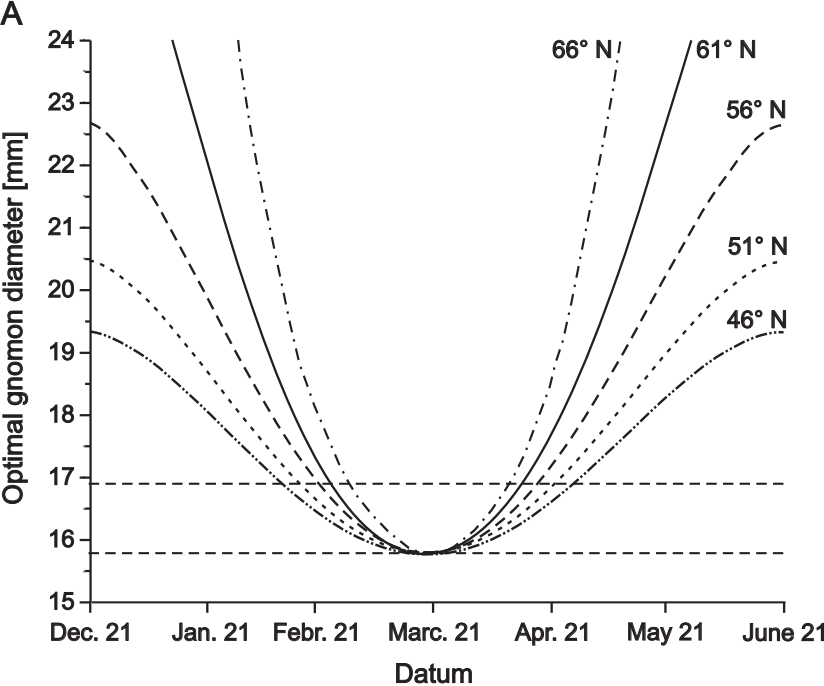


Figure 3