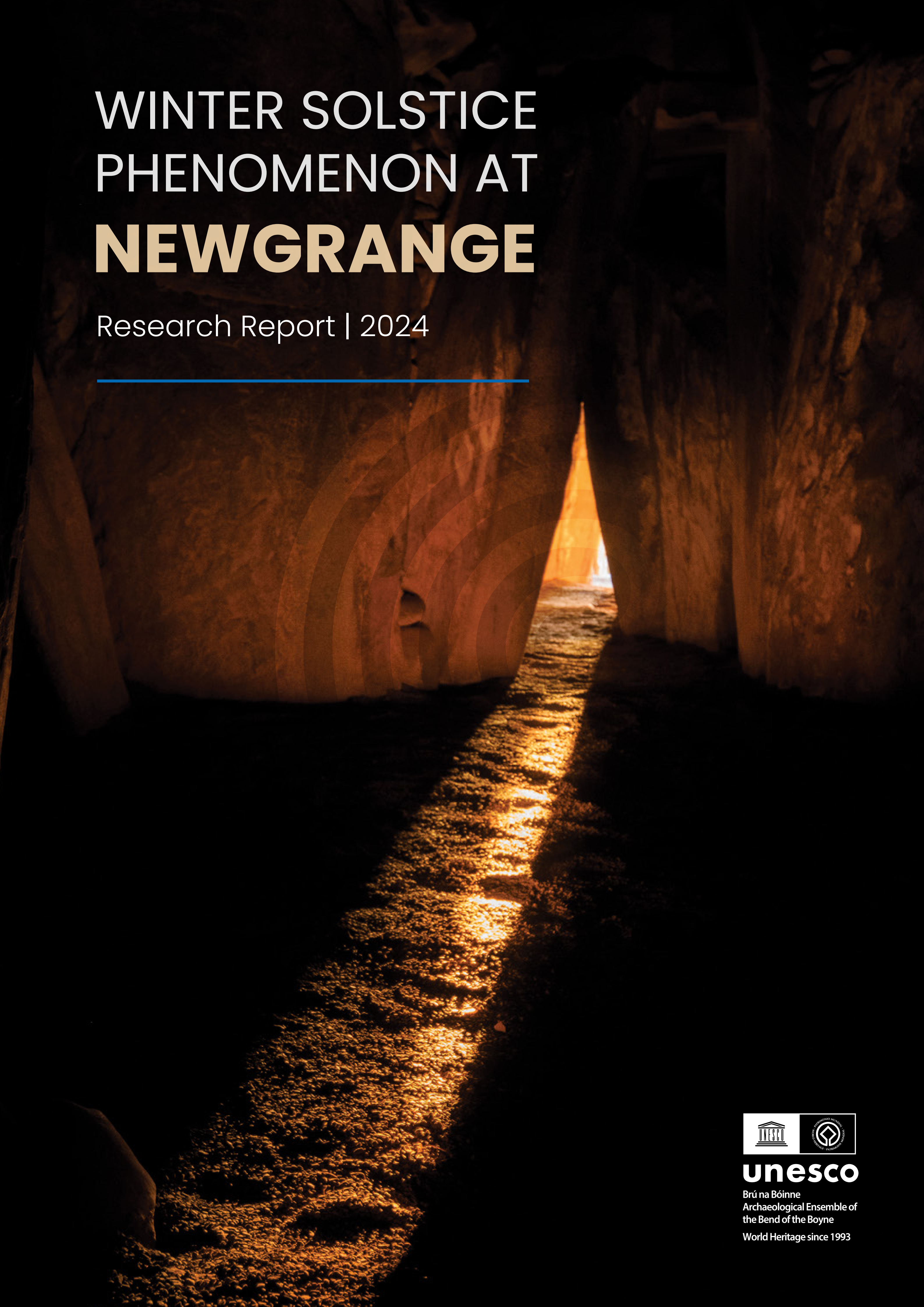
WINTER SOLSTICE PHENOMENON AT NEWGRANGE

Research Report | 2024



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Brú na Bóinne
Archaeological Ensemble of the Bend of the Boyne
World Heritage since 1993

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Acknowledgements

The author is indebted to John Lalor, Senior Photographer, National Monuments Service (NMS). John's photographic expertise, duty of care, and constant monitoring of the recording systems, often at unsocial hours, made a critical contribution to the overall success of this collaborative project.

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1 Introduction

1.1 Commissioning of work

The COVID-19 pandemic reached Ireland in late February 2020. The Government quickly introduced widespread public health and economic measures to mitigate the effects of the virus. Restrictions included closing the visitor centre in Brú na Bóinne to the public. As a consequence, Newgrange burial chamber would be vacant for the winter solstices in 2020 and 2021. This opportunity to commission new research was presented by experts and discussed among partner organisations. Consensus was quickly reached that the phenomenon could and should be recorded photographically and broadcast live to a global audience. Such a plan was immediately recognised as providing an unprecedented opportunity for open access to Newgrange at this special time of year when it would normally be restricted to 15 visitors each solstice morning.

The technological challenges of such an ambitious plan were rapidly resolved with remarkable efficiency and ingenuity. The broadcast elements spanned three consecutive mornings in December 2020 and again in 2021. These, together with the extensive archive of high-resolution images are analysed here and show the endeavour to have been justified and a resounding success.

This report, commissioned by the National Monuments Service of the Department of Housing, Local Government and Heritage, presents a comprehensive analysis of the high-resolution photographic and video recordings of the solar illumination inside the burial chamber at Newgrange passage tomb, located within the UNESCO World Heritage Site of Brú na Bóinne – Archaeological Ensemble of the Bend of the Boyne, Co. Meath, Ireland. The project was designed and carried out in partnership between the National Monuments Service, the Office of Public Works and Technological University Dublin. The research report summarising the project and its findings was compiled by Frank Prendergast. Livestreaming of the phenomenon took place 20–22 December in 2020 and again in 2021, these being the dates of the winter solstice and when the phenomenon is at its peak inside the burial chamber, shortly after local sunrise. Additional photographic and video recordings took place outside of these dates.

1.2 Research aims

The temporary closure of Newgrange passage tomb in Brú na Bóinne during the months of December and January of 2020 and 2021 provided a unique opportunity for new research using innovative approaches and thinking on how best to capitalise on the pristine observing conditions afforded by the lack of visitors to the monument. The following primary research aims were proposed, albeit developed in the remarkably short time-frame it took to expedite the project:

- Photographically record the phenomenon of direct sunlight on the floor of the burial chamber using a nadir-orientated digital camera.
- Record the same phenomenon using four video cameras located on the floor of the burial chamber, above the floor of the burial chamber, inside the roof-box, and in the entrance passage.
- Broadcast the phenomenon from multiple viewpoints in real-time over the internet.
- Augment the visual broadcasts with live commentary to describe the cultural and scientific significance of the monument(s) and landscape within the archaeological ensemble of Brú na Bóinne.
- Use GIS mapping software to analyse the exact track and diurnal limits of the sunbeam on the chamber floor.
- Measure how brightness levels change inside the chamber and correlate these data with the astronomical positions of the Sun.
- Compile a research report on all aspects and findings of the research.
- Publish the findings in appropriate media and print journals.
- Archive the data to facilitate continuing research.

2 Summary of Research Findings

- Solar illumination of the Newgrange burial chamber has been precisely recorded in the Coordinated Universal Time (UTC) time scale using photographic and video technologies.
- Spatially correct large-scale plans have been created with GIS in the ITM Mapping Reference System.
- These maps track, for the first time, the dynamic behaviour of the solstitial sunbeam on the floor of the burial chamber and permit a detailed space-time analysis of the phenomenon.
- Astronomically correct scenes, with dimensions, have been created, queried and interpreted.
- A double phenomenon has been discovered – the beam of constant ambient light whose orientation and width remain fixed, compared with the dynamic and variable solstitial beam.
- Blocking daylight entering the passage via the entrance to the monument has simulated probable conditions in the Neolithic when deposition and interment occurred; this shows that direct sunlight can only enter the burial chamber through the roof-box located above the entrance roof-stone RS1 and may have been controlled by the periodic insertion/removal of quartz blocks.
- Limiting dates for when direct sunlight enters/exits the chamber are discovered as currently being about 20 days either side of the notional date of the winter solstice on 21 December.
- How the light phenomenon has dimensionally changed in the five millennia since the monument was constructed is investigated and explained.
- Recordings of the phenomenon using digital and video cameras reveal how weak ambient light, entering via the roof-box, is ever-present in the chamber during daylight hours. This maintains a constant direction and width.
- Using long-term meteorological records, cloud amount on the horizon was analysed for its potential impact on visualisation of the phenomenon.
- Horizon cloud blocking solar illumination in the chamber could be correlated to current oceanic warming linked to climate change. This is a cause for concern and validates the wisdom of this research project which has created a high-resolution priceless cultural archive and asset of national and global importance.
- Illumination levels inside and outside the monument have been recorded in the SI *(Système International)* system of measurement units using a lux meter. Innovatively, these data provide the first-ever basis for qualitative and quantitative discussion on this topic.
- Analytics obtained from the webcasts, excluded from this report, show the geographical range and audience satisfaction ratings to have far exceeded expectations.
- Print publications to date on interim aspects of the research are similarly impressive in terms of national and international readership.
- The data contained in this report will seed a further academic publication to integrate the overall findings with current archaeological thinking on the monument by adding a new layer to current discourses on Neolithic cosmology and the archaeology of death.

3 Background

Dowth, Knowth and Newgrange are the iconic passage tombs in the archaeological ensemble of Brú na Bóinne, 40 km north-northeast of Dublin City. The latter pair are prominently located on the summit of a ridge which gives these structures vantage over the nearby River Boyne before it enters the Irish Sea, 15 km to the east. Dowth, Knowth and Newgrange were constructed around 3200 BC during the Middle Neolithic (3600–2900 BC) and are characterised by vast size and, in the case of Knowth and Newgrange, a developed external and internal architecture. Most significantly, the concentration of megalithic art on many of the structural stones elevates these sites to being the foremost of their kind in Europe and emphasises their economic, funerary, religious and social importance in prehistory.

The Brú na Bóinne cultural landscape and complex of over 40 monuments was inscribed on UNESCO's World Heritage List in 1993 for having Outstanding Universal Value. Three qualifying criteria were used: (i) the site has the largest and most important expression of megalithic art in Europe; (ii) the sheer concentration of monuments dating from the prehistoric past to the late medieval; and (iii) the passage tomb tradition is brought to its most developed and finest expression.[1] Figure 1 illustrates some of these attributes as found at Newgrange passage tomb.

Figure 1: Isometric view of Newgrange passage tomb.

1 UNESCO World Heritage Convention, "Brú Na Bóinne - Archaeological Ensemble of the Bend of the Boyne." [Accessed 24 August 2023].

The model shows the covering cairn, part of the enclosing kerbstones, the entrance facade and the 19 m-long passage leading to the corbelled cruciform burial chamber. The scene was created from laser scanning (courtesy: The Discovery Programme: Centre for Archaeology and Innovation Ireland).

The passage tomb tradition in Ireland is now better understood and documented, notwithstanding that many aspects of the culture will remain unknown given the antiquity of the era and the preliterate nature of society at that time. That has changed somewhat following recent methodological advances in the genetic sequencing of aDNA samples taken from human remains interred in the most elaborate of the three recesses at Newgrange (see Figure 4). Analysis by Dr Laura Cassidy et al. identifies the samples as belonging to the adult son of a first-degree incestuous union.[2] Such evidence points to a very rare example of a socially sanctioned mating and the existence of a dynastic elite in Neolithic times, similar to blood lines found within 'polygynous and patrilineal royal families that are headed by a god-king'. Sampling 44 whole genomes, Cassidy further discovered that relatives of this 'royal' individual had lived in Carrowkeel and Carrowmore, Co. Sligo, the location of two similarly clustered passage tomb complexes. Taken together with the elaborate monumental architecture of the tombs, megalithic art, pottery and grave-goods, these findings add weight to the theory that Neolithic society was hierarchically structured with developed ceremonies, customs and rituals.

Belief systems and world views at that time, termed ancient cosmology, can be legitimately argued to have included how people engaged with annually recurring celestial events. Of the many examples of such phenomena, the most obvious of all is the apparent seasonal movement of the Sun along the horizon. Beyond question, the Sun is, and was, the supreme cosmic body and most likely to have had god-like qualities conferred or imbued on it, especially because of its obvious apparent cyclical movement when rising and setting. If the particular alignment of Newgrange passage tomb on the rising Sun at the winter solstice can be shown to have been intentional, this would strengthen the hypothesis that a solar cosmology prevailed during the Middle Neolithic.

2 Lara M. Cassidy et al., "A Dynastic Elite in Monumental Neolithic Society," *Nature* 582 (2020).

3.1 Archaeoastronomy — cultural astronomy

According to Prof. Timothy Darvill, any evidence for basic time-keeping dictated by the annual cycle of the Sun, the solar cycle, points to the spread of regionally different solar cosmologies from the third millennium BC onwards and their use to predict and regularise festivals and ceremonies.[3] Another leading British archaeologist, Prof. Chris Scarre, urges that archaeoastronomy must be integrated into the mainstream of archaeological thought. Referencing prehistoric sites, he writes as follows:

> *Archaeologists today are increasingly concerned to understand these sites in the light of the way early communities may have observed and conceptualized their surroundings, and these must include prominent features of the sky — the sun, the moon, the major planets and stars — as much as terrestrial mountain peaks, rivers and springs.*[4]

Archaeoastronomy, then, is the investigation of astronomical knowledge possessed by all prehistoric cultures, commonly based on modern large-scale studies of typologically similar data sets. Furthermore, the established field of skyscape archaeology brings archaeology and archaeoastronomy closer together through the integration of the material record and phenomenological evidence obtained from individual sites at a local or regional level. Such unification becomes especially relevant in the case of Ireland's most impressive passage tomb, Newgrange.

The internationally recognised cultural importance of Brú na Bóinne can, in part, be attributed in modern times to two aspects related to Newgrange passage tomb. Firstly, the enduring policy of allowing visitor access throughout the year to the cruciform burial chamber.[5] Secondly, the special privilege given to a limited few to be present in the burial chamber at dawn on the days of the winter solstice when direct sunlight shines through the roof-box and illuminates the floor of the burial chamber. The roof-box is a slot opening located above the entrance to the tomb. The phenomenon lasts for less than 20 minutes and peaks for several days centred on 21 December, the date when the winter solstice is celebrated in the Gregorian calendar. Observers who are present in the chamber on cloud-free mornings (see Chapter 6) share in an experience unchanged since 3200 BC. The phenomenon is therefore not only multi-sensory but immutable, emotionally connecting the visitor with their prehistoric ancestral past. It is partly for these reasons that the research described in this report was commissioned to fully and rigorously document this unique solar alignment for posterity using modern scientific methods.

3 Timothy Darvill, "Keeping Time at Stonehenge," *Antiquity* 96, no. 386 (2022).

4 Chris Scarre, "Rows and Circles Reconsidered: Review Article of Astronomy in Prehistoric Britain and Ireland by Clive Ruggles, 1999 and Great Stone Circles by Aubrey Burl, 1999," *Cambridge Archaeological Journal* 10, no. 02 (2001).

5 National Monuments Service, *Brú Na Bóinne World Heritage Site Management Plan* (Dublin: Department of Arts, Heritage, Regional, Rural and Gaeltacht Affairs, 2017).

3.2 Research concept and strategy

Specialists from the National Monuments Service, the Office of Public Works and Technological University Dublin constituted the research team. Innovative measurement and recording techniques were pioneered to build an archive that would add to the body of knowledge mainly commenced by Prof. Michael J. O'Kelly in the late 1960s. Twenty-first-century technologies were utilised to capture and broadcast the images to a global audience over the internet in real-time. In parallel with such an ambitious undertaking, a range of research objectives were devised to take full advantage of the temporary closure of the monument to the public due to the prevailing pandemic emergency.

Research objectives are summarised as follows:

- Design and implement a photographic and video recording system to capture the winter solstice solar illumination phenomenon in the burial chamber of Newgrange.
- Broadcast the phenomenon over the internet to a global audience on 20–22 December, 2020 and 2021.
- Maintain and monitor the recording system not just on the three mornings centred on 21 December but before and after that date to establish, for the first time, the temporal limits of ingress and egress of the sunbeam in the burial chamber.
- Map the changing behaviour of the light beam by blending high-resolution photography with digital mapping using GIS software.
- Build a unique space-time archive of the phenomenon spanning the full period of solstitial illumination for later analysis and further research.
- Provide a detailed analysis of diurnal and temporal changes in the width and length of the sunbeam.
- Compare the present path of the sunbeam on the floor of the chamber with its path in 3200 BC (caused by the different obliquity of the Earth's axis in the Neolithic).
- Investigate climate and meteorological aspects of cloud amount related to the visibility of sunrise and how this impacts/impacted on the frequency and probability of solar illumination, now and in the prehistoric past.
- Measure and monitor changing light levels (in units of lux) in the burial chamber.
- Compile a report (internal) describing all elements of the research for distribution amongst the funding partners.
- Disseminate the findings of the project through further publication and on the UNESCO World Heritage in Ireland website.

4 The winter solstice phenomenon

The solstices, especially the winter solstice, have been documented globally as a significant cultural event for many cultures, now and very likely in the prehistoric past. This is a time of year when the directions of the rising and setting Sun remain fixed to the naked eye, seeming to stop momentarily on the horizon for a period of several days in every year (Chapter 5). Scholars of antiquity widely regard this apparent halting of the Sun as having profound cultural significance. In the Neolithic mind, these limits of the rising Sun at dawn probably signified rebirth and renewal, the setting Sun signifying death. Such ideas legitimise investigating prehistoric architecture for evidence of culturally meaningful alignment, motivating researchers across two centuries to explore the symbolic and ritual symbolism of the phenomenon.

4.1 History of alignment measurement at Newgrange

Early enquiry into the astronomical alignment of Newgrange passage tomb can be traced to the early years of the twentieth century. Although the burial chamber and passage were first mapped as early as 1699 by the Welsh antiquarian Edward Lhwyd, a rudimentary plan drawn by his draftsman, William Jones, only shows the internal structural stones and a sample of the megalithic art but not its true orientation.[6] Orientation is depicted in a later plan of Newgrange published in 1725 by Thomas Molyneux.[7]

Examination of that drawing, surveyed by Samuel Molyneux for Thomas Molyneux, reveals a gross error in orientation with the passage shown cardinally aligned on north–south. This is very likely as a result of Lhwyd's plan having a portrait rather than landscape orientation on the page.

Sir Norman Lockyer, an English astronomer, was the first scientist to draw attention to, although not directly measure, the possibility of solstitial alignment of the tomb to face sunrise on the winter solstice. He formed his opinion after examining an exact plan published by William Borlase in 1897, which did have true orientation.[8] Borlase, however, had merely republished a plan of Newgrange drawn by the archaeologist George Coffey in 1892.[9] Lockyer, citing Borlase, wrote:

> *Of them all Bryn Celli Ddu is the most interesting, as there is a long allée courverte or creep way, which is exceptional in Britain, so far as "cromlechs" go, though many may be still hidden in "long barrows" such as New Grange, which, so far as I can make out, is oriented to the Winter Solstice.*[10]

6 Edward Lhwyd, "Several Observations Relating to the Antiquities and Natural History of Ireland, Made by Mr. Edw. Lhwyd, in His Travels Thro' That Kingdom. In a Letter to Dr. Tancred Robinson, Fellow of the College of Physicians and Royal Society," *Philosophical Transactions of the Royal Society of London* 27, no. 335 (1712). A copy of Lhwyd's plan of Newgrange is reproduced in: Geraldine Stout and Matthew Stout, Newgrange (Cork: Cork University Press, 2008), 97; George Eogan and Elizabeth Shee Twohig, *Excavations at Knowth 7: The Megalithic Art of the Passage Tombs at Knowth, Co. Meath* (Dublin: Royal Irish Academy, 2022), 199.

7 Thomas Molyneux, "A Discourse Concerning the Danish Mounts, Forts and Towers in Ireland," in *A Natural History of Ireland, in Three Parts*, ed. G. Boate (Dublin: George Grierson, 1725).

8 William Copeland Borlase, *The Dolmens of Ireland, Their Distribution, Structural Characteristics, and Affinities in Other Countries; Together with the Folk-Lore Attaching to Them; Supplemented by Considerations on the Anthropology, Ethnology and Traditions of the Irish People* (London: Chapman & Hall, 1897).

9 George Coffey, "On the Tumuli and Inscribed Stones at New Grange, Dowth, and Knowth," *Transactions of the Royal Irish Academy* 30 (1892–1896).

10 Joseph Norman Lockyer, S*tonehenge and Other British Stone Monuments Astronomically Considered*, 2nd ed. (London:

Examination of Coffey's drawing shows the azimuth of the passage axis to be c. 132°. This falls within 2° of its true value as scientifically measured in modern times. In Coffey's era, magnetic north was c. 21° west of true north. Had magnetic north been used for orientation purposes, this would have been clearly evident because of the gross angular difference between true and magnetic north pertaining at that time. Lockyer is not known to have ever visited the monument but his astronomical expertise, and eye, allowed him to 'make out', as he puts it, the winter solstice alignment of Newgrange merely by examination of the original plan by Coffey.

The first measured orientation of Newgrange was by an American anthropologist W. Y. Evans Wentz in 1911. Importantly, he used a compass to survey many prehistoric monuments throughout Europe, including Newgrange. This led to his discovery that the entrance passage was aligned to face the rising Sun on the winter solstice, a characteristic he noted was shared by Gavrinis passage tomb in Brittany, France. On this point, Evans Wentz writes as follows:

> *It is well known that very many monuments of the New Grange type scattered over Europe, especially from the Carnac centre of Brittany to the Tara-Boyne centre of Ireland, have one thing in common, an astronomical arrangement like the Great Pyramid, and an entrance facing one of the points of the solstices, usually either the winter solstice, which is common, or the summer solstice.*[11]

In the 1970s, Claire O'Kelly described a belief or tradition then prevalent in the locality of Newgrange that the rising Sun, at some unspecified time, illuminated the three-spiral motif on the vertical face of stone C10 located in the end recess (see Figure 4 and Figure 32).[12] Stone C10 is positioned on the right-hand side of that space, its hidden aspect preventing any direct illumination by the rising Sun.[13] At about the same time, Prof. Michael J. O'Kelly, who excavated and restored the monument, was probably aware of these earlier published accounts of the solstice phenomenon. While he did visit the chamber on the winter solstice of 1967 to verify this possibility, in a subsequent visit on 21 December 1969 he documented his empirical discovery. Prof. O'Kelly was thus the first to witness the phenomenon in modern times, described by him as follows:

> *At exactly 8.54 hours GMT the top edge of the ball of the sun appeared above the local horizon and at 8.58 hours, the first pencil of direct sunlight shone through the roof-box and along the passage to reach across the tomb chamber floor as far as the front edge of the basin stone in the end recess. As the thin line of light widened to a 17 cm-band and swung across the chamber floor, the tomb was dramatically illuminated and various details of the side and end recesses could be clearly seen in the light reflected from the floor. At 9.09 hours, the 17 cm-band of light began to narrow again and at exactly 9.15 hours, the direct beam was cut off from the tomb. For 17 minutes, therefore, at sunrise on the shortest day of the year, direct sunlight can enter Newgrange, not through the doorway, but through the specially contrived slit which lies under the roof-box at the outer end of the passage roof.*[14]

Macmillan & Co. Ltd, 1909), 430–33.

11 W. Y. Evans Wentz, *The Fairy Faith in Celtic Countries* (London, New York, Toronto and Melbourne: Henry Frowde, Oxford University Press, 1911), 419.

12 C10, the three-spiral stone, is often wrongly called a triple spiral. See Michael J. O'Kelly, *Newgrange: Archaeology, Art and Legend* (London: Thames and Hudson, 1982), 177.

13 Claire O'Kelly, *Illustrated Guide to Newgrange and the Other Boyne Monuments*, 3 ed. (Blackrock, Cork: 1978), 111.

14 O'Kelly, 1982,123–24.

In the 1970s, Dr Jon Patrick, a surveyor, undertook an archaeoastronomical survey for Prof. O'Kelly and concluded that illumination of the burial chamber was of low precision, occurring when the azimuth of the Sun was between the limits 133º 42' and 138º 24'.[15] Patrick measured the angular altitude of the local horizon to be +0º 51' ±2' and from that data he calculated the astronomical declinations corresponding to his observed azimuth limits of the roof-box as being in the range –22º 58' to –25º 53'.

Patrick reported the widest azimuthal and declination limits of the roof-box framing the horizon and sky, akin to the horizontal angle of view or window of visibility perceived by an observer looking outwards from the floor of the burial chamber though the roof-box. Douglas Heggie, who was a professional astronomer focused on precision and statistical probability rather than archaeology, was sceptical of Patrick's claim.[16] Prof. Tom Ray carried out a subsequent measured survey of the tomb in the late 1980s and also reassessed Patrick's calculations. Ray found as follows:[17]

- Patrick's upper azimuth limit was 1º too high and his calculated declination window should be reduced accordingly.
- The roof-box was very probably designed in width, height and with astronomical alignment intent.
- Direct sunlight, which now penetrates only to the rear edge of the burial chamber, could have reached the back stone in the end recess of the cruciform chamber in Neolithic times due to the different obliquity ε of the Earth. Obliquity in the Neolithic was 24º.1 compared with the present value of 23º.4, a small but significant change sufficient in magnitude to cause the observed azimuth of sunrise on the winter solstice to decrease by 1º 11' or about two solar diameters.

In his discussion, Ray incorporated additional architectural and astronomical elements related to the design and alignment of the passage tomb, thereby significantly increasing the probability that the astronomical alignment of the monument was intentional.

15 J. Patrick, "Midwinter Sunrise at Newgrange," *Nature 249* (1974).

16 Douglas C. Heggie, *Megalithic Science: Ancient Mathematics and Astronomy in North-West Europe* (London: Thames and Hudson, 1981), 213.

17 T. P. Ray, "The Winter Solstice Phenomenon at Newgrange, Ireland: Accident or Design?" *Nature* 337, no. 6205 (1989).

5 Visualising the solstice alignment phenomenon

Advances in astronomical modelling tools now bring improved clarity to the digital visualisation of the winter solstice phenomenon at Newgrange. Recent developments in statistics also facilitate testing the probability that the alignment of a prehistoric monument(s) intentionally faced a particular celestial or terrestrial target.

5.1 Visualising the winter solstice at Newgrange

The term 'solstice' is defined as the time and date of maximum/minimum astronomical declination. It can also mean the direction of the turning or reversal points of the Sun on the horizon every year, mostly occurring on 21 or 22 December and 20 or 21 June. An observer at a fixed location requires only awareness and a rudimentary understanding of the solar cycle to notice this apparent movement. Tracking, memorising and referencing such visual changes against distinctive or prominent natural features on the horizon is a straightforward process. Topographic features such as a prominent hill, mountain peak or notch, or the unusual profile of a distant woodland canopy are obvious aids. This is naked-eye astronomy, or sky viewing and does not require instrumentation.

Following the winter solstice, the diurnal change in the direction (azimuth) of the rising/setting Sun is discernibly northwards. As the year progresses into January, the rate of azimuthal change also accelerates. By 20 March, or so, the direction of the rising/setting Sun will be about midway between the extreme solstitial limits occurring on the winter and summer solstices.[18] By the month of June the diurnal change in the rise/set directions of the Sun decreases to a miniscule amount as the day of the summer solstice approaches and is barely discernible to the naked eye. These terminal or limiting directions are the standstill phenomena, termed Solstitium in Latin, from the verb sistere (to stop) and the noun sol (Sun).

The solstice phenomena are widely recognised as being auspicious times for festivals and gathering.[19] The winter solstice in the northern hemisphere also occurs during the darkest period of the year and at a time which follows harvest, preceding the climatically harshest months of late winter and early spring. For societies in the Neolithic, such dramatic changes in sunrise and sunset directions probably had immense significance, not only for timing the planting and harvesting of cereal crops but also for the regulation of ceremonies and rituals related to the predictable seasonal return of the solstices.

Turning now to Newgrange, determining the direction of sunrise on the winter solstice with the naked eye for the astronomical alignment of the passage would not have been a difficult task, even in the Neolithic. This flouts the claims of some protagonists who sometimes argue that the horizontal alignment process was complex, requiring specialist skills. What is more probable is that such a task was reserved or restricted to a person(s) of high rank or status. A far more difficult undertaking would have related to the architectural and engineering challenges to position the structural stones forming the entrance, roof-box, and the lintels and supporting orthostats forming the

18 It should be noted that directional symmetry between the solstitial limits and the equinoctial midpoint of the sun is dependent on the altitude of the local horizon in east or west.

19 Clive Ruggles, *Ancient Astronomy: An Encyclopaedia of Cosmologies and Myth* (Santa Barbara, California; Denver, Colorado; Oxford, England: ABC CLIO, 2005), 384–85.

19 m-long passage on ground sloping +8% from the entrance. Added to that was the human effort to connect these elements with the cathedral-like 6 m-high corbelled cruciform burial chamber. For the monument to then capture the direct light from the rising Sun on the winter solstice and illuminate the end recess of the burial chamber can justifiably be considered nothing short of an astonishing achievement for its time.

Astronomical modelling of the Newgrange phenomenon

The astronomical alignment of Newgrange is analysed and illustrated here using three approaches. Firstly, a digital terrain model depicts the horizon scaled in azimuth and altitude for the exact latitude, longitude and elevation of the burial chamber (Figure 2). In the illustration, the horizon opposite Newgrange is shown, including two prominent topographic features – Red Mountain, and the distant Dublin Mountains, the location of a dispersed cluster of passage tombs intervisible with Newgrange. The solid archaeoline (red arc) in Figure 2 traces the Sun's trajectory on the winter solstice in 3200 BC, the known construction date of the tomb. Importantly, the software computes the azimuth and declination of sunrise applicable to the Neolithic. The dotted archaeoline plots the Sun's trajectory on the equinoxes and is shown here merely to illustrate the dramatic change in sunrise direction between the winter solstice and the vernal/autumnal equinoxes. Most importantly of all, the illustration shows the azimuth of the passage and lateral viewing limits of the roof-box projected onto the horizon and sky (grey column), and how such limits exactly frame the rising Sun on the mornings of winter solstice.

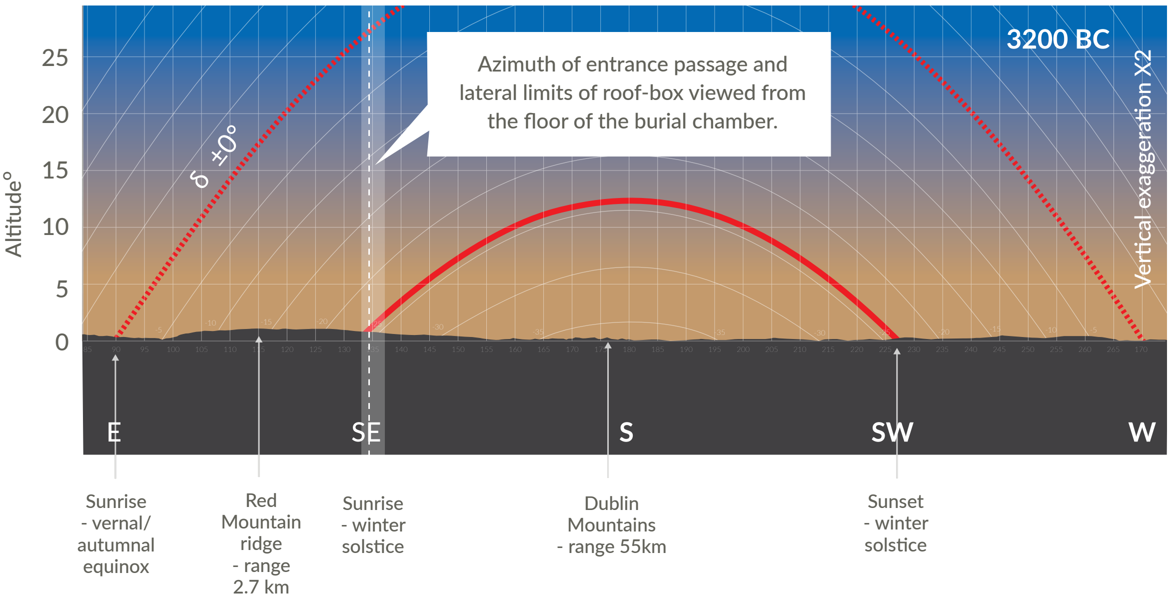


Figure 2: Horizon and skyscape at Newgrange (3200 BC).[20]

20 The illustration was generated using 30 m resolution height data obtained by NASA's Shuttle Radar Topographic Mission (SRTM) and processed using the Horizon software system to show the precise directions of the sun on the local horizon in 3200 BC on the winter solstice and vernal/autumnal equinoxes. A. G. K. Smith, Horizon: Version 0.13c [accessed 27 August 2023].

The horizon astronomical coordinates (azimuth and altitude) and the equatorial astronomical coordinates (right ascension and declination) are shown mapped onto the roof-box in Figure 3. This illustration indicates the difference between the risen Sun appearing in the roof-box in 3200 BC compared with the present. Figure 4 shows a ground plan of the cruciform passage chamber and the three basin stones created using digital photography procured by the National Monuments Service for this research report. The sunbeam's path is a digital re-creation of the phenomenon based on the azimuth and altitude of the Sun shortly after sunrise in 3200 BC. Given that five millennia have elapsed since the tomb was constructed, this is obviously different to what is witnessed today due to the change in obliquity as previously discussed.

In the Neolithic, the beam of direct sunlight would have extended to the rear of the end recess as first shown by Prof. Ray. Today, direct sunlight first enters the chamber about 18 days preceding 21 December, growing in intensity day-on-day (Chapter 8). The phenomenon is at its peak for about three to four days on mornings centred on 21 December. Beyond that date, the sunbeam will gradually egress from the chamber until its extinction about 18 days later. Direct sunlight will not begin to enter Newgrange until the following winter solstice period.

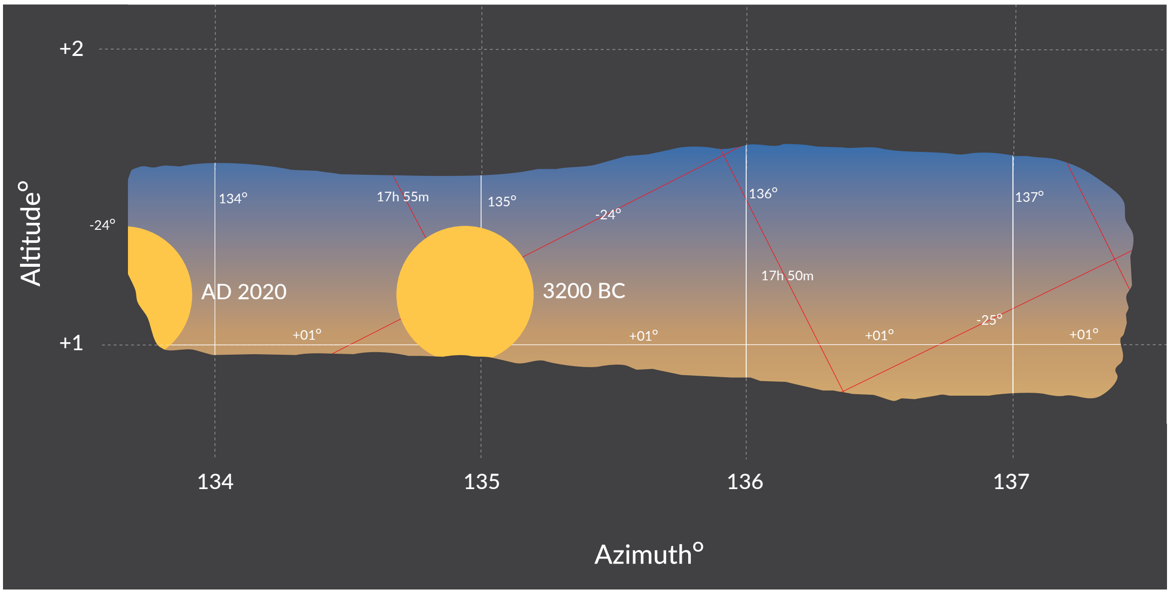


Figure 3: Newgrange roof-box—view from the burial chamber to the horizon showing sunrise in AD 2020 and 3200 BC.

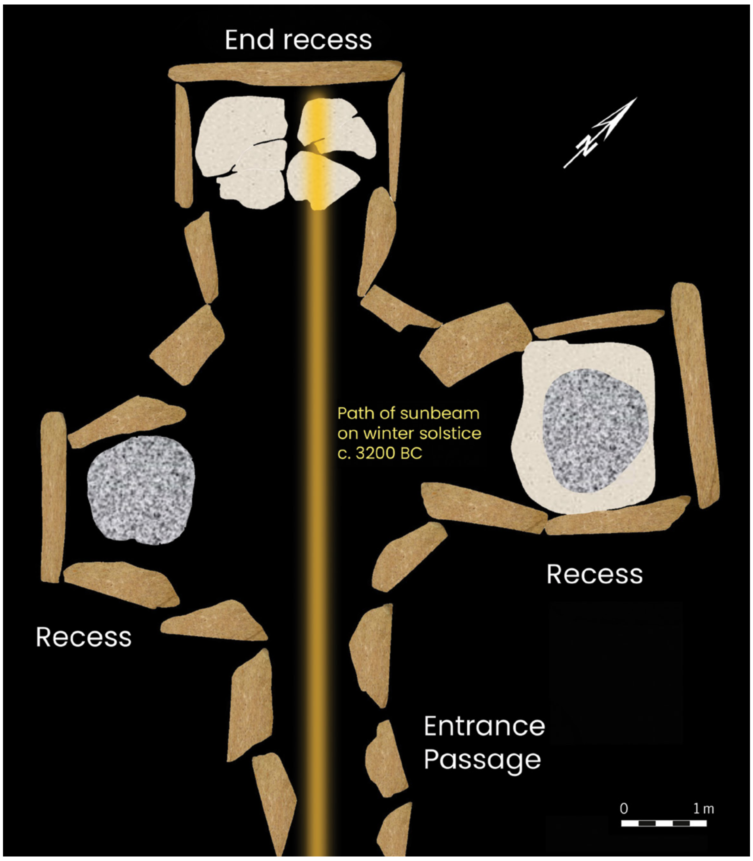


Figure 4: Path of sunbeam on ground plan of Newgrange passage and chamber.

There is evidence that darkness and light in the burial chamber could have been controlled when the tomb was in use during the Neolithic. Firstly, the door-stone now positioned on the right-hand side of the entrance has a profile which matches that of the passage. If ever used as a door, this would have blocked light entering the passage via the entrance itself. Secondly, a single quartz block was discovered in situ in the roof-box by Prof. O'Kelly during excavation works.[21] One of the archaeological excavation team, Dr Frances Lynch, describes it as being 30 cm–38 cm in length (pers. comm. 30 May, 2015). Surface scratch marks are also evident across the width of roof-stone RS1, suggesting that three such quartz blocks could have sealed the opening. If repeatedly inserted and removed, this could explain the observed pattern of scratch marks and their use to ritually control dark and light in the burial chamber (see Figure 6).

In the Irish language, *grianchloch* is the term for quartz with *grian* meaning Sun and *chloch* meaning stone. Moreover, the probable symbolic importance of quartz in the prehistoric past is well known.[22] Importantly, Prof. O'Kelly's large-scale tracing paper plans, drawn when the roof-box was discovered, are archived by the National Monuments Service. These have been forensically examined and reassessed by Ken Williams, bringing additional clarity and confidence to the belief that the astronomical alignment of Newgrange was intentional.[23]

21 O'Kelly, 1982, 96.

22 Killian Driscoll, "The Role of Quartz in Neolithic Lithic Traditions: A Case Study from the Thornhill Early Neolithic Palisaded Enclosure, Co. Derry~Londonderry, Northern Ireland," *Proceedings of the Royal Irish Academy. Section C: Archaeology, Celtic Studies, History, Linguistics, Literature* (2015).

23 Ken Williams, "Rekindling the Solstice Light," *Archaeology Ireland* 33, no. 4 (2019).

5.2 A question of probability

The number of extant passage tombs on the island of Ireland is about 220 with 136 having a chamber/passage in sufficiently good condition to allow determination of their orientation and astronomical declination. Analysis shows 23 to be aligned with astronomically interesting targets with four tombs facing the rising Sun on the winter solstice.[24] A more detailed significance test of that data using a method developed by Dr Fabio Silva is shown in Figure 5.[25] Peaks (shown in blue) could represent culturally meaningful declinations. Statistically significant deviations from randomness would also appear as blue peaks but have to be high enough to appear outside of the grey envelope which is the confidence envelope of the null hypothesis. No such peaks are evident and this shows that the empirical dataset falls inside the expected range of randomness (pers. comm. F. Silva 2 November 2021). The test allows for an azimuthal uncertainty of 2° (four diameters of the Sun) and the global p-value is 0.896. This means that if all orientations are considered as a group there is insufficient evidence to refute the null hypothesis and that passage tombs were orientated at random.

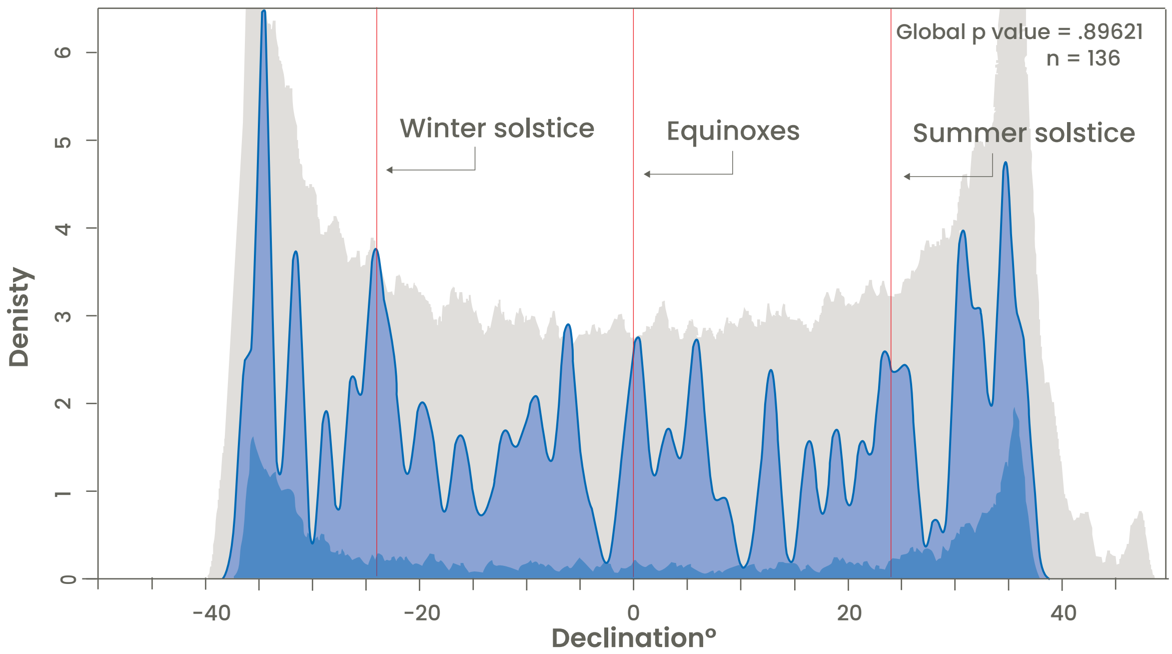


Figure 5: Frequency of observed axial alignment of 136 Irish passage tombs with sunrise and sunset on the solstices and equinoxes.[26]

24 Frank Prendergast, "The Alignment of Passage Tombs in Ireland – Horizons, Skyscape, and Domains of Power," in *Zeit Ist Macht. Wer Macht Zeit?/Time Is Power. Who Makes Time?*, ed. H. Meller, A Reichenberger, and R. Risch (Mitteldeutscher Archäologentag vom 8. bis 10. Oktober 2020 in Halle (Saale)/13th Archaeological Conference of Central Germany October 8–10, 2020 in Halle (Saale) Tagungen des Landesmuseums für Vorgeschichte Halle (Halle [Saale] in Vorbereitung), 2021).

25 Fabio Silva, "A Probabilistic Framework and Significance Test for the Analysis of Structural Orientations in Skyscape Archaeology," *Journal of Archaeological Science* 118 (2020).

26 The figure shows the confidence envelope of the null hypothesis in grey and the empirical aggregation of tomb axial orientations in blue. A tolerance band of ±1° in declination should be allowed for, this being the azimuthal equivalent of ±2° which equates to ±4 solar diameters. The illustration labels the limits of the solar declinations associated with the winter and summer solstices. These are the primary temporal division of the solar cycle likely to have been of ceremonial or ritual importance in the Neolithic.

The statistical analysis presented here cannot, and does not, consider the architectural and archaeological evidence which sets Newgrange apart from all others of the type. For example, this is the only known example of a passage tomb in the European tradition having a solar-aligned developed roof-box. The intricate motifs on the obverse face of the lintel articulate and highlight the specialness of this construct (Figure 6). This would make the astronomical orientation of Newgrange an extraordinary achievement and convincingly support the hypothesis that the solar alignment was not an accidental outcome.

Turning next to climate and Newgrange, the solar illumination of the burial chamber is completely regulated by the amount of cloud on the horizon at dawn over the period of the winter solstice. Prevailing meteorological conditions, especially the weather element constituted by cloud, crucially affect the human experience of the phenomenon. In the Neolithic when the tomb had a probable ceremonial and ritual role, the rising Sun would have held even greater religious and symbolic importance. For these reasons, a brief focus on climate and its impact on the solar phenomenon at Newgrange, both modern and in the prehistoric past, is warranted.

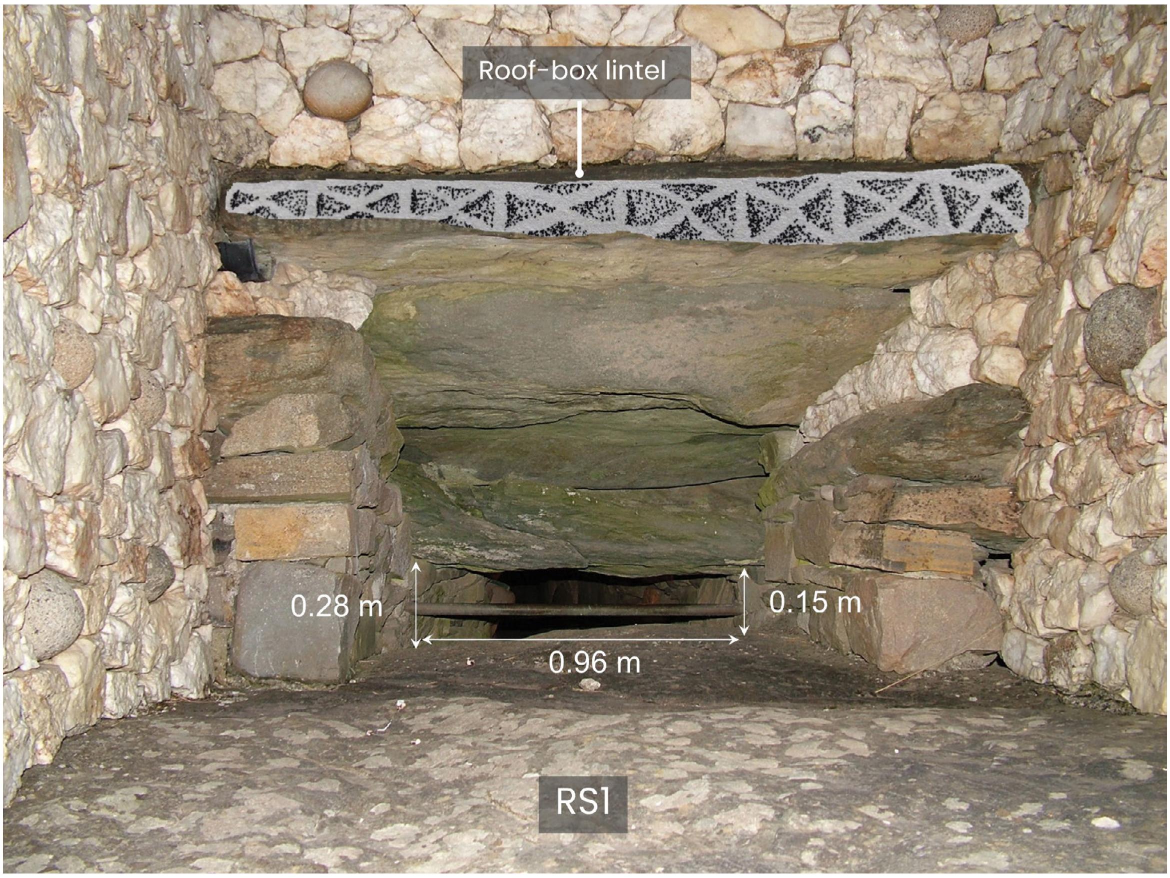


Figure 6: Newgrange roof-box looking into the tomb. (Photo and roof-box dimensions are by F Prendergast with an overlay of the lintel decoration from a drawing by Claire O'Kelly, 1973).

6 Climate change—viewing the Newgrange solstice light

Climate is the characteristic pattern of weather elements in an area over a defined period. The elements are cloud, humidity, precipitation, solar insolation, temperature and wind. Climate is controlled by geographical latitude, land versus sea mass, topographical altitude and location relative to oceanic currents. Ireland being positioned well into the Atlantic Ocean is heavily influenced by an Atlantic weather regime generated by the Gulf Stream; this results in 50% more rainfall per annum than in Britain to the east. Climate is given only brief mention in the most recent management plan for Brú na Bóinne, stating how it 'has been favourable to agriculture and settlement from the Neolithic through to the present day'.[27]

Horizon cloud has the potential to completely inhibit the winter solstice solar phenomenon in Newgrange. Because cloud is a by-product of the hydrological cycle, any increase in global surface temperature, especially in the Atlantic Ocean, will inevitably cause an increase in the cloud amount over Brú na Bóinne. With climate change and warming now the defining crisis of our time, the recent statement from the Intergovernmental Panel on Climate Change (IPCC) has relevance for the research in this report.

> *Earth's climate has always changed naturally, but both the global extent and rate of recent warming are unusual. The recent warming has reversed a slow, long-term cooling trend, and research indicates that global surface temperature is higher now than it has been for millennia.*[28]

In the following sections, cloud amount empirically observed in Newgrange during the winter solstice periods of 2020 and 2021 is first considered alongside similar long-term meteorological data recorded nearby by Met Éireann since 1943. Secondly, selected archaeological literature is reviewed in order to ask and attempt to answer two questions. What was the prevailing climate in Brú na Bóinne during the Middle Neolithic? What is the probability that the burial chamber was more frequently illuminated on winter solstice mornings in the prehistoric past compared with the present?

27 National Monuments Service, 16.

28 IPCC, "Climate Change 2021: The Physical Science Basis," Working Group I Contribution to the IPCC Sixth Assessment Report.

6.1 Cloud amounts at Newgrange 2020 and 2021

The number of days when direct sunlight entered the burial chamber during the 2020 winter solstice verifies how cloud on the horizon can significantly inhibit the phenomenon. Constant photographic and video recording show that the rising Sun was visible on 12 of the 37 mornings monitored (Figure 7). That number decreased to two mornings over the same period in 2021. As a long-term proxy for weather at Newgrange, historical records of cloud amount measured by Met Éireann at 0900 UTC at the nearby Dublin Airport meteorological station since 1943 (when records began there) are shown in Figure 8.

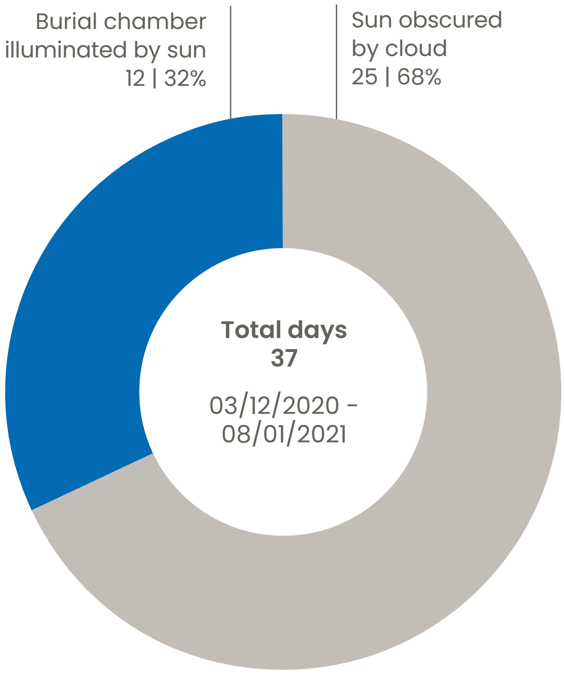


Figure 7: Sun visibility at Newgrange 2020 Dec 03–2021 Jan 08, 0900 UTC.

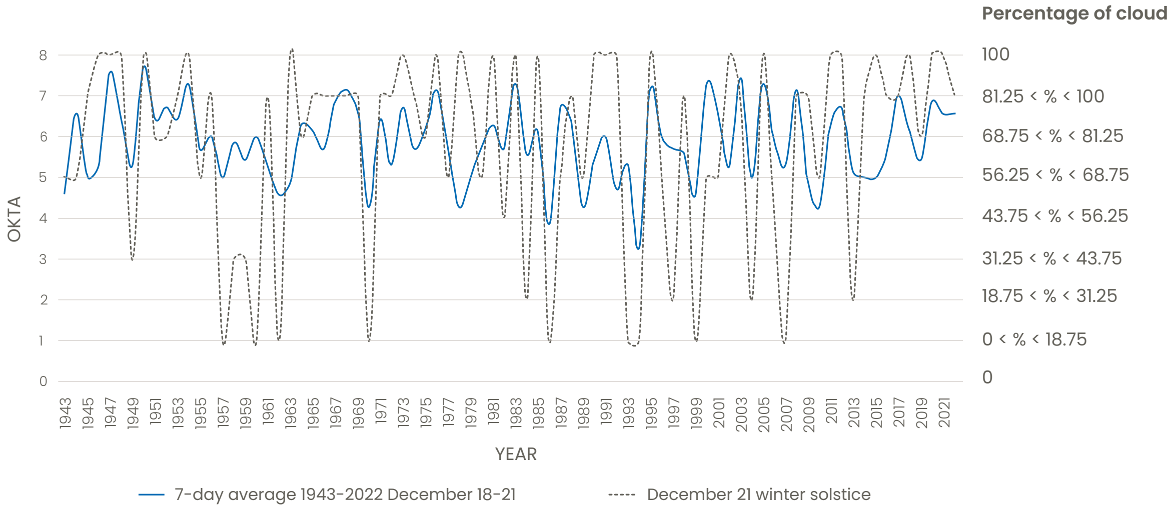


Figure 8: Cloud amount (long-term) at Dublin Airport meteorological station.

The unit of measurement in Figure 8 is the okta where zero indicates the complete absence of cloud and eight represents total cloud cover with no breaks.[29] The left-axis scale is shown converted into continuous percentages of cloud cover on the secondary right-axis scale using a method which allows for human estimation errors of ±1–2 okta.[30] The chart plots the cloud amount for 21 December (1943–present) as well as the average value of cloud amount for the seven-day period centred on 21 December over the same yearly range. All readings are for 0900 UTC, this being about the time when the Sun has cleared the local horizon in the Boyne Valley and when direct sunlight can illuminate the burial chamber. Peaks and troughs in the data indicate maximum and minimum percentages of cloud amount, respectively. It could be suggested that from about 2015 to 2022 there is a discernible increase in cloud amount to about 80%. However, separate analyses of both data sets using linear regression and the sigmoid function (pers. comm. A. Griffin 9 January 2023) fail to provide any statistically significant evidence of any trend or ramp. Empirical evidence obtained in the last five years, however, suggests that cloud amount in December and January in Brú na Bóinne is likely to cover at least 80% of the sky. This trend will pose a significant inhibitor to the solar illumination of the burial chamber, a cultural phenomenon of international renown and which has endured for 5200 years.

Met Éireann will continue to monitor Ireland's climate for evidence of significant change, including cloud amount, and whether this can be linked to current observed changes in the global climate model.[31] The International Satellite Cloud Climatology Project (ISCCP) carries out similar research.[32] Taken together, these type of data will be crucial for informing the National Monuments Service and Office of Public Works on the potential negative impact of climate change on the winter solstice phenomenon at Newgrange. Disquiet on this matter is already evident while recognising that changes in weathering rates and climate mechanisms are gradual, barely visible in the short term but more so in the long term. Additional research by Dr Cathy Daly on the impact of climate change on built heritage and the intensity of precipitation projections has found that current climate models predict drier summers, increasingly wet winters and greater escalation of heavy rain in Brú na Bóinne.[33]

29 Met Éireann, "Historical Data," [accessed 1 September 2023].

30 R. Boers et al., "Optimized Fractional Cloudiness Determination from Five Ground-Based Remote Sensing Techniques," *Journal of Geophysical Research* 115, no. D24 (2010).

31 C. A. Walther, Cámaro García, and Ned Dwyer, *The Status of Ireland's Climate, 2020* (2021), 24, 41–43.

32 International Satellite Cloud Climatology Project, "Cloud Climatology," [accessed 1 September 2023].

33 Cathy Daly, "A Framework for Assessing the Vulnerability of Archaeological Sites to Climate Change: Theory, Development, and Application," *Conservation and Management of Archaeological Sites* 16 no. 3 (2014).

6.2 Climate in the Middle Neolithic

Hubert Lamb (1913–1997) was a British climatologist and the first scientist to raise awareness in the 1940s that the Earth's climate could be influenced by anthropogenic emissions of greenhouse gases. His ground-breaking book entitled Climate, History and the Modern World was published in 1982, bringing meteorological expertise to the study of climate regimes in the prehistoric past, including northern Europe. His claims were based on the available climate science data and tools of the time and applied to the latitude and altitude limits of forests and grasslands, human habitation and farming practices. Research by Prof. Alexander Thom on the astronomy of British Bronze Age stone circles interested Lamb because this suggested such monuments had ceremonial and ritual use linked to a solar cosmology.[34] Lamb was also familiar with the upland siting of many Irish megalithic monuments having been employed by Met Éireann as a meteorologist from 1936–1945.[35] According to Lamb, many prehistoric monuments were located in what are now the cloudiest districts of the British Isles with 'the sun being visible only between 20 and 30 percent of the time'. His reconstructions of the prevailing climatic patterns in the Neolithic and Bronze Age led him to suggest that anticyclones with more frequently clear skies were a common feature of prehistoric weather regimes.

The twenty-first century has ushered in a new era of intense interest in, and more robust research on climate history and human responses to climate change in the prehistoric past.[36] Investigative tools used by paleoclimate researchers include multiple environmental proxies and records obtained from dendrochronology, lake sediments, palynology, aDNA analysis and AMS radiocarbon dating technologies. Integrating such diverse data sources requires interdisciplinary and multidisciplinary approaches, driving new theoretical perspectives to overcome the immense challenges posed by reconstructing distant past climates and inform our understanding of the social practices of people who lived over 5000 years ago. A general decline in the archaeological and palynological record after 3400 BC is reported, possibly associated with a shift in the climate to wetter conditions.[37] Notable exceptions to this wet phase are reported by Plunkett et al. with drier conditions from around 3350 BC in certain regions of Ireland. Indicators include reduced tree-ring growth in oaks and pines, associated with a more widespread drought phase along the so-called Atlantic facade. A similar shift to drier conditions around 3200 BC is evident in English and Scottish tree-ring chronologies. With relevance to the research aims set out in this report, Plunkett et al. write as follows:

34 H. H. Lamb, *Climate, History and the Modern World* (London: Methuen, 1982), 124–30.

35 Mick Kelly, "Hubert Horace Lamb (1913–97)," *Nature* 388, no. 6645.

36 Carleton Jones, "Review Article: Climate Change and Its Consequences in the Past," *Journal of Irish Archaeology* 24 (2015).

37 Meriel McClatchie and Aaron Potito, "Tracing Environmental, Climatic and Social Change in Neolithic Ireland," *Proceedings of the Royal Irish Academy: Archaeology, Culture, History, Literature (Special Issue: Climate and Society)* 120C (2020).

> *Quite possibly, however, a shift in climate regime could have stimulated an ideological transformation, including a greater preoccupation with seasonal cycles, encapsulated in monument orientations on key solar events and megalithic art, the most spectacular examples of which emerge after 3200 BC. Such conjecture may not be testable, of course, but serves to draw attention to an alternative mode by which environmental changes could play a role in social transformations.*[38]

Half a century ago, commentary on the extensive Neolithic field systems discovered by Prof Seamus Caulfield in Céide, Co. Mayo, suggested that forest clearance in that region could have sustained up to six 40-acre farms. Caulfield argues that the post-glacial climatic optimum reached over 2° C above present day temperatures during the Middle Neolithic, allowing grass growth between 10 and 12 months in every year.[39]

Considering all of the available climatic evidence, fair use of the data can point to a greater proportion of cloud-free days prevailing around the winter solstice when Newgrange was built. This suggests a ceremonial use for the monument in tandem with its function as a sacred space for the interment of an elite.

38 Gill Plunkett, David M. Brown, and Graeme T. Swindles, "Siccitas Magna Ultra Modum: Examining the Occurrence and Societal Impact of Droughts in Prehistoric Ireland," *Proceedings of the Royal Irish Academy (Special Issue: Climate and Society)* 120C (2020).

39 Seamus Caulfield, "Forest Clearance and Land Use in Mayo around 3000 B.C.," *Irish Forestry* 38, no. 2 (1981).

7 Research methods

The research aims were to capture a comprehensive set of high-resolution still and video images of the phenomenon over the extended winter solstice period in 2020 and 2021, provide live broadcasting augmented by expert commentary to a global audience over the internet on 20– 22 December 2020 and 2021, followed by analysis and publication of the results (Figure 9).

Overall, the method of research can be described as space-time analysis, meaning an exploration and understanding of the what-where-when-why related in this instance to the solstitial illumination of the burial chamber in the Middle Neolithic and which continues to function to this day.[40]

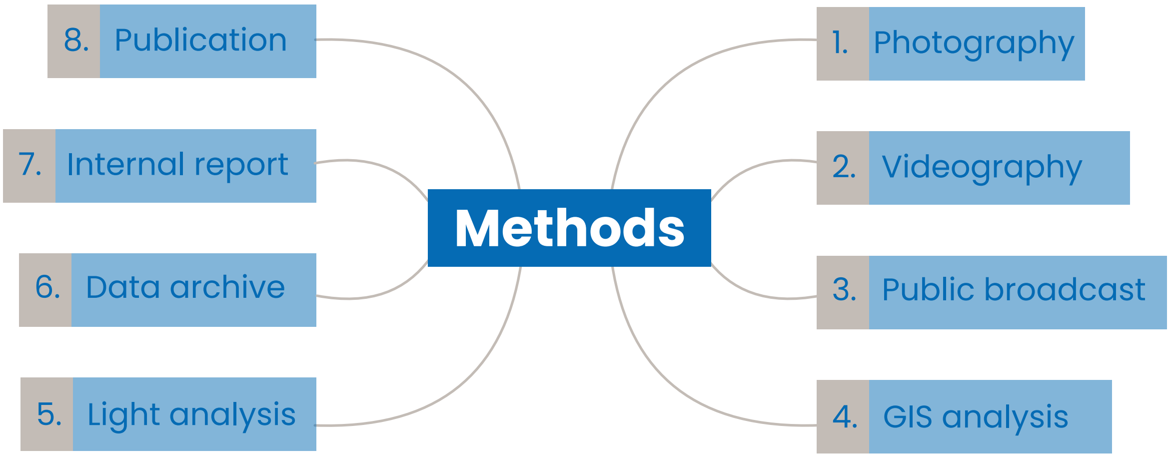


Figure 9: Space-time analysis of the Newgrange phenomenon.

A description of the technical elements of the research methods follows.

40 Li An et al., "Space–Time Analysis: Concepts, Quantitative Methods, and Future Directions," *Annals of the Association of American Geographers* 105, no. 5 (2015).

7.1 Photography

System design and installation was by John Lalor, Senior Photographer with the National Monuments Service. A Nikon D850 camera was attached to a timber rig positioned high above the floor of the burial chamber. A 16–35 mm wide-angle lens was zoomed to frame the maximum possible area of the chamber floor below. The axis of the camera was aimed and fixed in the nadir direction for the duration of the project (Figure 10). Exposure settings were remotely monitored and controlled by Lalor on a daily basis by connecting the camera to an Apple Mac Mini linked by a network cable running from the burial chamber to the Ethernet port of a network switch/router connected to a second computer located in a hut outside the cairn. Two computer applications, 'TeamViewer' and 'Camera Control' allowed Lalor to remotely control and adjust camera aperture, ISO and shutter speed settings over the internet in response to rapidly changing light conditions in the chamber. This approach ensured image consistency throughout the recording sessions, especially as the intensity of light increased after dawn each morning (Chapter 10).

A minimum of three photographic images per minute were required to optimally record the solstice light beam and analyse its dynamically changing properties as it tracked across the floor of the burial chamber. Images were downloaded to an SSD drive connected to the computer which was also remotely accessed by Lalor. All data on the SSD drive were backed up and renamed with the date and time of exposure. Detailed metadata added to all images are archived in the National Monuments Service Photographic Data Archive (Chapter 7.6).

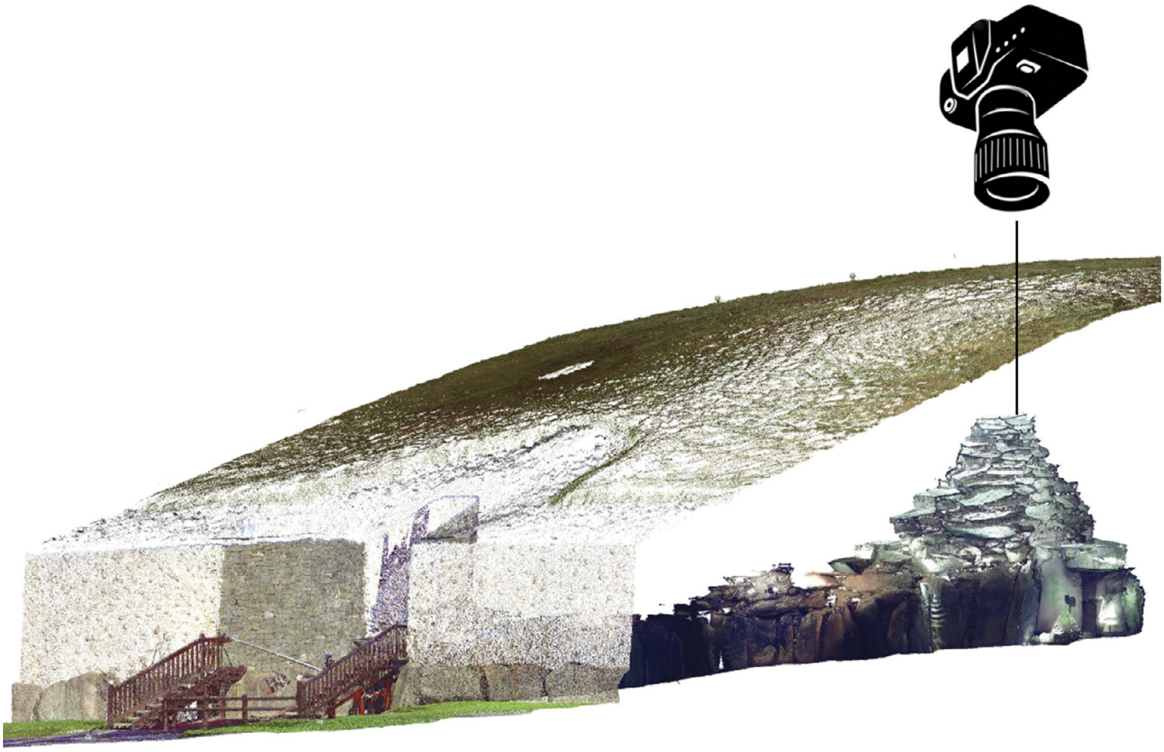


Figure 10: Location of the digital camera in Newgrange burial chamber.

Ambient and direct sunlight in the burial chamber

Office of Public Works (OPW) staff fabricated a timber door to exactly fit the profile of the entrance to Newgrange. This had the effect of shutting out ambient daylight in the passage, an idea suggested by the presence of the so-called 'door-stone' now located outside the monument. Archaeologists believe that this stone may have functioned likewise in the Neolithic, in part, to maximise the darkness inside. Sealing the entrance in this manner guaranteed that only ambient light and direct sunlight via the roof-box could illuminate the floor of the burial chamber.

An example of how the roof camera revealed the narrower shaft of intense direct sunlight relative to the broader static band of ambient light is shown in Figure 11. Mapping the light in this manner was carried out using GIS software (Section 7.4).

GIS maps were time-stamped with date, time and the azimuth and true zenith distance of the Sun, these being essential parameters for the scientific method used here.[41] A fuller explanation of the technique is given in Section 7.4.

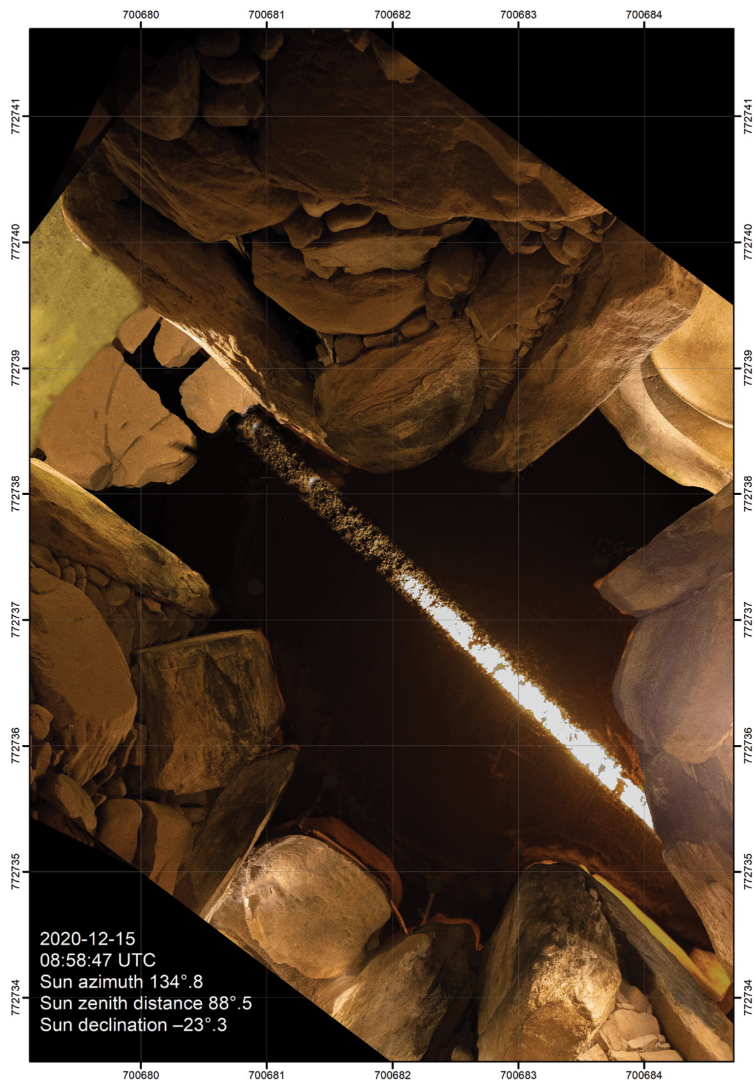


Figure 11: Ambient light and direct sunlight on the floor of the burial chamber.

41 True North on each plan is 1°.2 west of Grid North, this being the direction of the Local Meridian (True North) at Newgrange.

Several discoveries have been made because of the high quality and quantity of the photography, including how the beam of ambient light remains fixed in direction, intensity and width. By comparison, the beam of direct sunlight is found to change dimensionally and spatially, correlated with the apparent movement of the Sun. Moreover, its colour and luminosity also change according to the aspect of the Sun at the instant of camera exposure and the transparency of the prevailing atmosphere. Selected extracts from the complete photographic archive are shown in Chapter 8. These provide the first-ever high-definition temporal record of the phenomenon in progress and document ingress, culmination and egress of the sunbeam on the floor of the burial chamber.

7.2 Videography

Four cameras (CAM) with the following specification and location were installed in the monument in late November 2020 (see Figure 25).

- **CAM 1:** A motorised dome network camera in an IP66-rated heated weatherproof enclosure, positioned on the floor at the rear of the burial chamber. This provided a view of the light in the passage as it entered the burial chamber.
- **CAM 2:** A motorised dome network camera in an IP66-rated heated weatherproof enclosure, installed with the aid of temporary Acrow bars above the floor of the burial chamber.
- **CAM 3:** A fixed dome 4k network camera in a weatherproof enclosure. Mounted inside, but not obstructing, the roof-box, it provided a view of the horizon.
- **CAM 4:** A fixed dome 4k network camera in a weatherproof enclosure. Mounted inside the entrance but not obstructing the roof-box, it provided an internal view of the passage looking towards the burial chamber and a view of the floor of the chamber.

A comprehensive description of the system technology is provided in Section 12.1.

7.3 Livestream

Temporary Outside Broadcast (OB) facilities were installed outside the monument to facilitate three mornings of livestreaming the winter solstice, described as follows:

- Temporary power (independent of on-site power) with redundancy to facilitate OB production elements.
- Three-camera high-definition OB Unit with on-board vision mix and data control.
- Interface and control to allow for the footage from the live cameras inside the chamber to be integrated into the broadcast.
- Technical staff installed and operated all equipment – OB Unit Manager, Programme Director, Vision Engineer, Camera Operators, Floor Manager.
- Temporary outdoor 'studio' including furniture, temporary lighting (for broadcast) and essential technical supports for presenters.
- Supervisory staff to manage the broadcast event, interface with on-site OPW staff and programme presenters.
- Temporary microwave data link and associated network integration both on and off site was installed, tested and fully supported on site by OPW ICT.
- All footage was edited live on site, transmitted to a host platform and subsequently distributed to various digital platforms and social media platforms.

A comprehensive description of the system technology is provided in Section 12.2.

7.4 GIS

The procedures used to transform digital photographic images into large-scale plans were as follows:

- Photography was geo-referenced to the Irish National Grid (ITM Reference System) using six permanent control points located on the chamber floor. Each was pre-marked with reflective tape making these visible as discrete points even if darkness prevailed in the chamber.
- A separate fully illuminated image of the chamber showing archaeological detail viewed from above (visible structural stones and basin stones) was similarly geo-referenced.
- The chamber floor in this second image was digitally deleted in Adobe Photoshop. This allowed archaeological detail of the structural stones to be layered above/over the digital images showing the solstice illumination of the floor.
- Artificial paraphernalia in the chamber such as timber props, video cameras, cables and guard rails were digitally removed for aesthetic reasons.
- Additional photography of the basin stones (credit: John Lalor) were retro-fitted into these images to make archaeological detail in the three recesses more visible.
- Geo-referencing was undertaken with GIS software using an affine 1st order polynomial transformation (RMS error of c. 2–3 cm).[42]
- A grid interval of 1 m was deemed appropriate to provide visible reference lines for digitally illustrating and measuring spatial changes in the length and direction of the sunbeam in the GIS environment.
- Dimensions of the sunbeam were scaled from the plans using GIS COGO (coordinate geometry) tools.
- The astronomical coordinates of the Sun applicable to the time of each photographic exposure were determined using proprietary astronomical software.[43]

7.5 Light analysis

Opportunities afforded by the research project included the pioneering investigation of changing light levels in the burial chamber – before, during and after local sunrise. Two methods were used. The first utilised the capabilities of Photoshop image processing software to digitally extract the average luminosity value of each photograph for the UTC of the exposure. Luminosity, however, is not an SI unit of measurement. Accordingly, a C.A 1110 lux meter was acquired to record illumination levels in the chamber. This instrument has a measuring range of 0.1–200,000 lux and the capability to remotely record light if connected to a laptop computer running the data logger software supplied with the instrument (see Figure 29). Results of the light measurement experiments are discussed in Chapter 10.

7.6 Data archive

Photographic and video content recorded at Newgrange for the Winter Solstice Phenomenon at Newgrange research project of 2020 and 2021 are copyright 'Photographic Archive, National Monuments Service, Government of Ireland'. Data files are stored on secure servers in the Custom House, Dublin 1 at the office of the National Monuments Service, Department of Housing, Local Government and Heritage. Derivative data contained in this report such as GIS maps and related information are similarly archived.

42 Esri Inc., Arcgis 10.4.1 for Desktop (Licensed to Tu Dublin).

43 U.S. Naval Observatory, Multiyear Interactive Computer Almanac, 1800–2050, 1.50. ed. (Richmond, Va.: Willmann-Bell, 1998–2005).

8 Photography results

Scheduled photographic recording of the phenomenon began two hours before local sunrise and was terminated about one hour after direct sunlight had left the burial chamber on dates from 12 December 2020 to 8 January 2021. From the 37 session dates, visible sunrises only occurred on 12 mornings (Table 1 and Table 2).

Table 1: Photographic recording dates before and including winter solstice

Date	UTC local sunrise h:m	Sun declination°	Comment
2020-12-03	08:36	-22.2	–
2020-12-04	08:38	-22.3	–
2020-12-05	08:39	-22.4	–
2020-12-06	08:40	-22.6	–
2020-12-07	08:42	-22.7	–
2020-12-08	08:43	-22.8	–
2020-12-09	08:44	-22.9	–
2020-12-10	08:45	-23.0	–
2020-12-11	08:46	-23.0	–
2020-12-12	08:48	-23.1	Sunrise visible (see 8.1)
2020-12-13	08:48	-23.2	–
2020-12-14	08:49	-23.2	–
2020-12-15	08:50	-23.3	Sunrise visible (see 8.2)
2020-12-16	08:51	-23.3	–
2020-12-17	08:52	-23.4	Sunrise visible (see 8.3)
2020-12-18	08:53	-23.4	–
2020-12-19	08:53	-23.4	–
2020-12-20	08:54	-23.4	Sunrise visible (see 8.4)
2020-12-21	08:54	-23.4	–

Photographic sessions are tabulated in Tables 1 and 2 according to their calendar date (year-month-date), UTC of local sunrise and the associated astronomical declination of the Sun. Because excellent meteorological conditions prevailed on only seven mornings, digital images recorded on these dates were selected for GIS processing to generate the scaled illustrations of the phenomenon shown in Sections 8.1–8.7.

Table 2: Recording dates after winter solstice 2020-12-21

Date	UTC local sunrise h:m	Sun declination°	Comment
2020-12-22	08:55	-23.4	Sunrise visible
2020-12-23	08:55	-23.4	—
2020-12-24	08:56	-23.4	Sunrise visible (see 8.5)
2020-12-25	08:56	-23.4	—
2020-12-26	08:56	-23.4	—
2020-12-27	08:57	-23.3	Sunrise visible
2020-12-28	08:57	-23.3	Sunrise visible
2020-12-29	08:57	-23.2	—
2020-12-30	08:57	-23.1	—
2020-12-31	08:57	-23.1	Sunrise visible
2021-01-01	08:57	-23.0	Sunrise visible
2021-01-02	08:56	-22.9	—
2021-01-03	08:56	-22.8	Sunrise visible (see 8.6)
2021-01-04	08:56	-22.7	—
2021-01-05	08:56	-22.6	—
2021-01-06	08:55	-22.5	—
2021-01-07	08:55	-22.3	—
2021-01-08	08:54	-22.2	Sunrise visible (see 8.7)

Sections 8.1–8.7 show a selected sample of the GIS plans of the solstice phenomenon with an accompanying table of the critical astronomical parameters for the Sun's position specified by azimuth, zenith distance and declination. Each photograph is named using a National Monuments Service code assigned by Lalor (these are shown abbreviated in the figure captions). The complete set of photography, captured at one-minute intervals on the 37 dates, is stored in the National Monuments Service archive.

8.1 2020 December 12

This was the first morning with clear skies and shows that direct sunlight in the chamber would be possible even before this date. The sunbeam is initially recorded about two minutes after ingress. Culmination occurs seven minutes after local sunrise. Compare its path and width of 9 cm with that of the ambient light beam which maintains a constant direction and a width of 26 cm (Table 3 and Figures 12 and 13). Dimensions of the sunbeam and ambient light were measured using GIS COGO tools.

Table 3: Date and time coordinates for Sun 2020 December 12

NMS photo code	Sun azimuth°	Sun true ZD°	Sun declination°	Comment
20201212-08-54-44	134.2	88.6	-23.1	1–2 minutes after ingress to chamber
20201212-08-55-51	134.4	88.5	-23.1	—
20201212-08-57-32	134.7	88.3	-23.1	—
20201212-08-59-46	135.2	88.1	-23.1	—
20201212-09-01-44	135.7	87.9	-23.1	Egress from chamber

Note: ZD = zenith distance

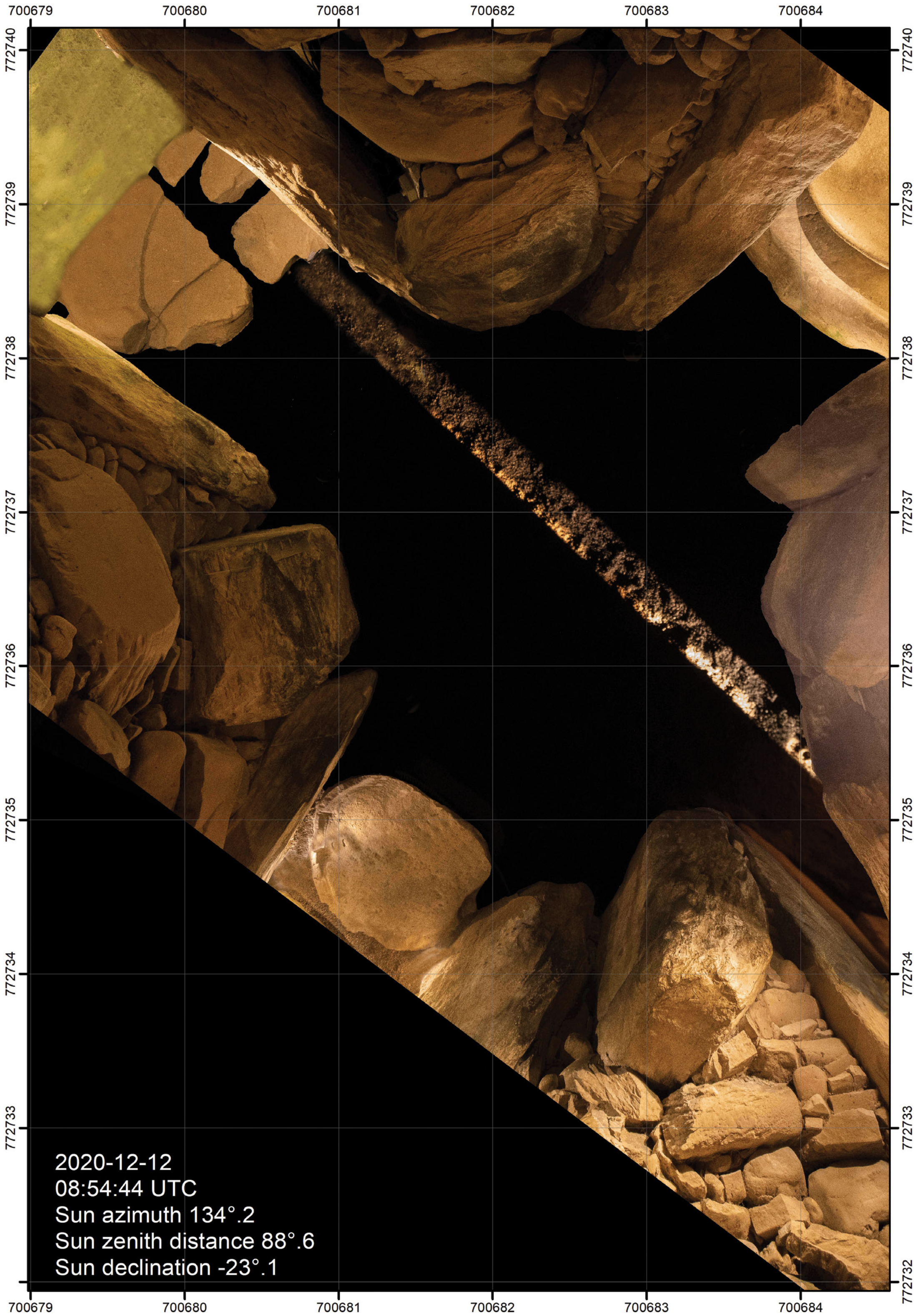


Figure 12: Direct sunlight after ingress, 12 December 2020 at 08:54:55 UTC.

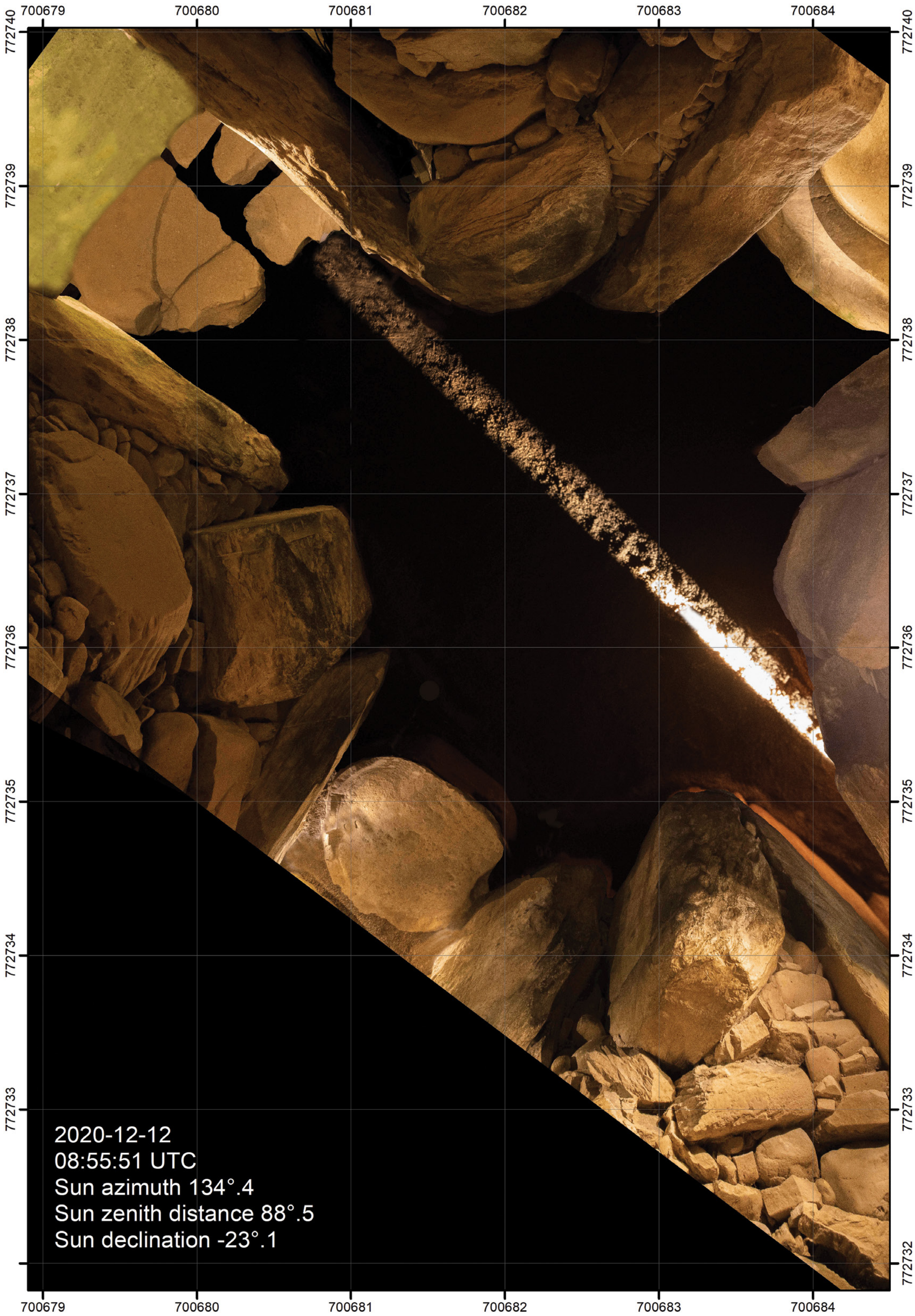


Figure 13: Direct sunlight recedes from chamber, 12 December 2020 at 08:55:51 UTC.

8.2 2020 December 15

Ingress of direct sunlight on the left-hand side of the ambient light is c. four minutes after local sunrise. Culmination is reached five minutes after local sunrise; the sunbeam width is 9 cm. Egress occurs at 09:07 UTC (Table 4, Figures 14 and 15).

Table 4: Date and time coordinates for Sun 2020 December 15

NMS photo code	Sun azimuth°	Sun true ZD°	Sun declination°	Comment
20201215-08-53-37	133.7	89.0	-23.3	Ingress to ambient light
20201215-08-54-10	133.8	89.0	-23.3	—
20201215-08-54-44	133.9	88.9	-23.3	Culmination
20201215-08-58-13	134.7	88.5	-23.3	—
20201215-08-58-47	134.8	88.5	-23.3	—
20201215-08-59-40	135.0	88.4	-23.3	—
20201215-09-00-48	135.2	88.3	-23.3	—
20201215-09-01-55	135.4	88.2	-23.3	—
20201215-09-04-09	135.9	87.9	-23.3	—
20201215-09-06-24	136.3	87.7	-23.3	Egress from chamber

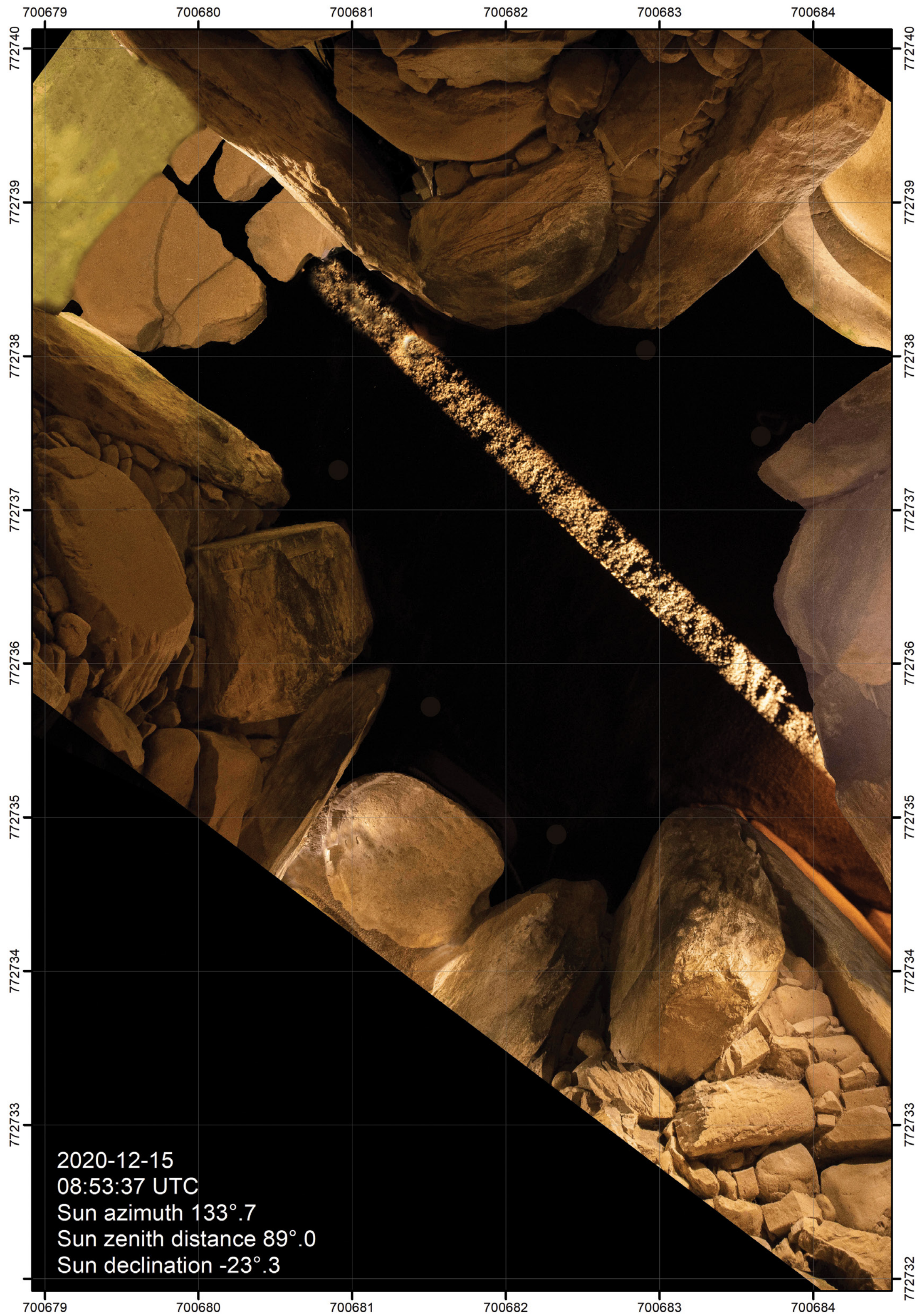


Figure 14: Light ingress in the chamber, 15 December 2020 at 08:53:37 UTC.

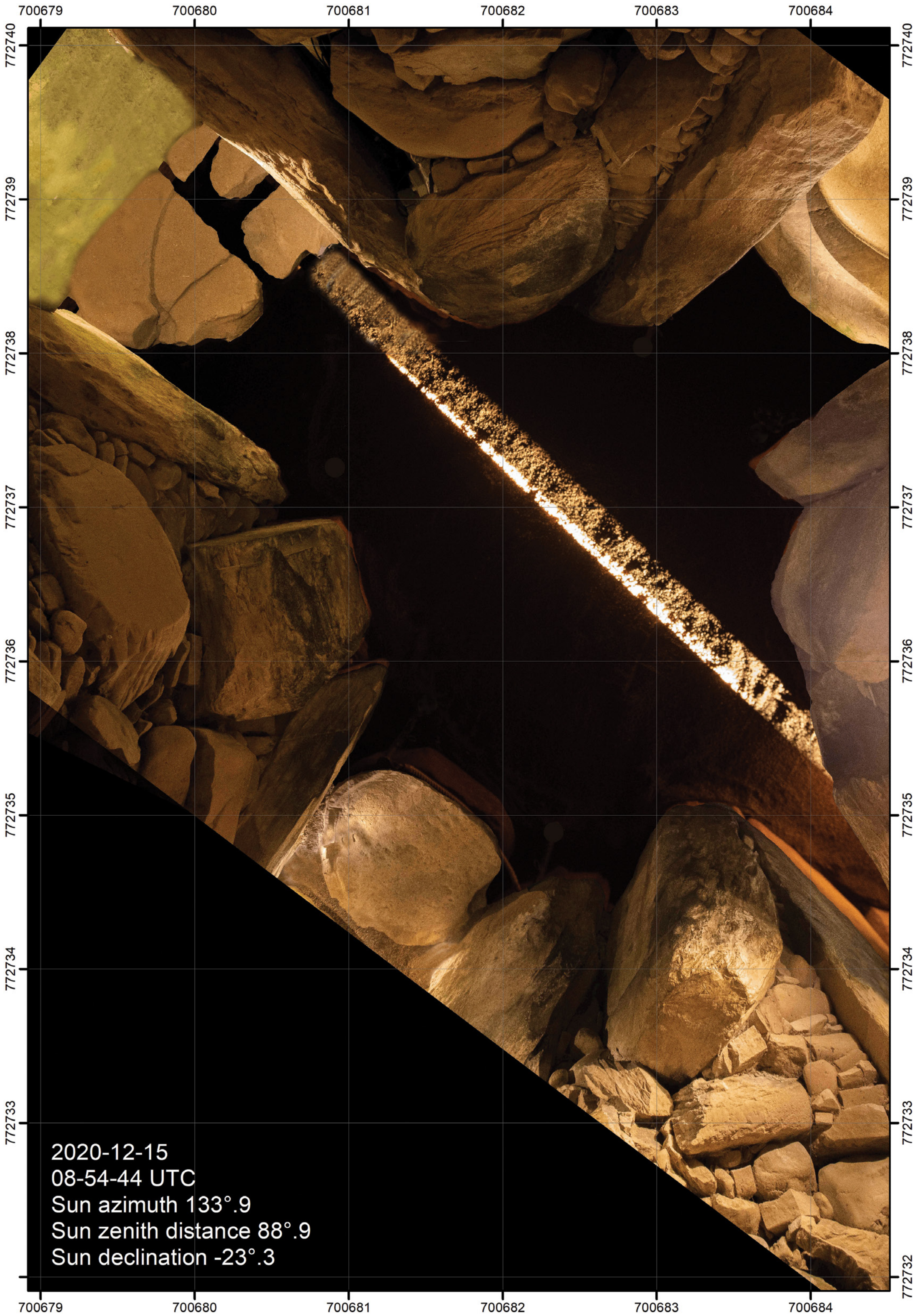


Figure 15: Light culmination in the chamber, 15 December 2020 UTC at 08:54:44.

8.3 2020 December 17

On this morning, horizon cloud blocked the view of sunrise which resulted in only two images being acquired close to egress on that date (Table 5 and Figure 16).

Table 5: Date and time coordinates for Sun, 2020 December 17

NMS photo code	Sun azimuth°	Sun true ZD°	Sun declination°	Comment
20201217-09-06-12	136.1	87.9	-23.4	—
20201217-09-08-01	136.5	87.7	-23.4	Egress from chamber

Figure 16: Light in chamber, 17 December 2020 at 09:06:12 UTC.

8.4 2020 December 20

Fourteen of the available 64 images were mapped for this date using GIS, the day before the winter solstice. It is very evident from the images that the beam of direct sunlight reaches culmination in the chamber about two minutes after ingress. By c. 09:13 UTC the beam has almost egressed from the chamber (Table 6, Figure 17 and Figure 18).

Table 6: Date and time coordinates for Sun, 2020 December 20

NMS photo code	Sun azimuth°	Sun true ZD°	Sun declination°	Comment
20201220-08-56-31	133.9	89.1	-23.4	Ingress into chamber
20201220-08-57-05	134.0	89.1	-23.4	—
20201220-08-58-48	134.3	88.9	-23.4	Culmination of light beam
20201220-09-00-04	134.6	88.7	-23.4	—
20201220-09-01-13	134.8	88.6	-23.4	—
20201220-09-02-15	135.0	88.5	-23.4	—
20201220-09-03-45	135.3	88.3	-23.4	—
20201220-09-04-55	135.6	88.2	-23.4	—
20201220-09-06-04	135.8	88.1	-23.4	—
20201220-09-07-03	136.0	88.0	-23.4	—
20201220-09-08-11	136.3	87.9	-23.4	—
20201220-09-09-00	136.4	87.8	-23.4	—
20201220-09-10-09	136.7	87.7	-23.4	—
20201220-09-12-29	137.1	87.5	-23.4	Egress from chamber

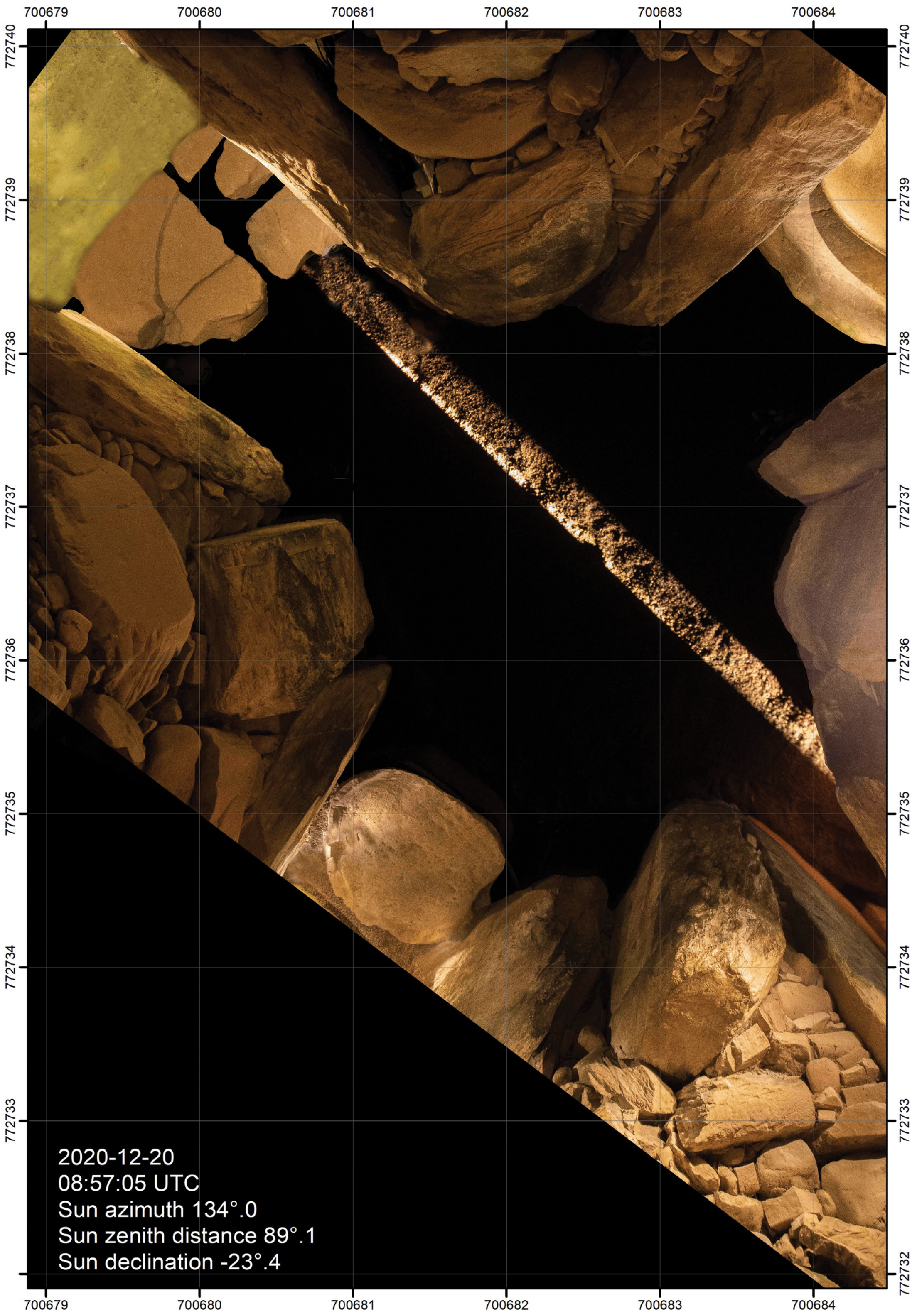


Figure 17: Ingress of light in the chamber, 20 December 2020 at 08:57:05 UTC

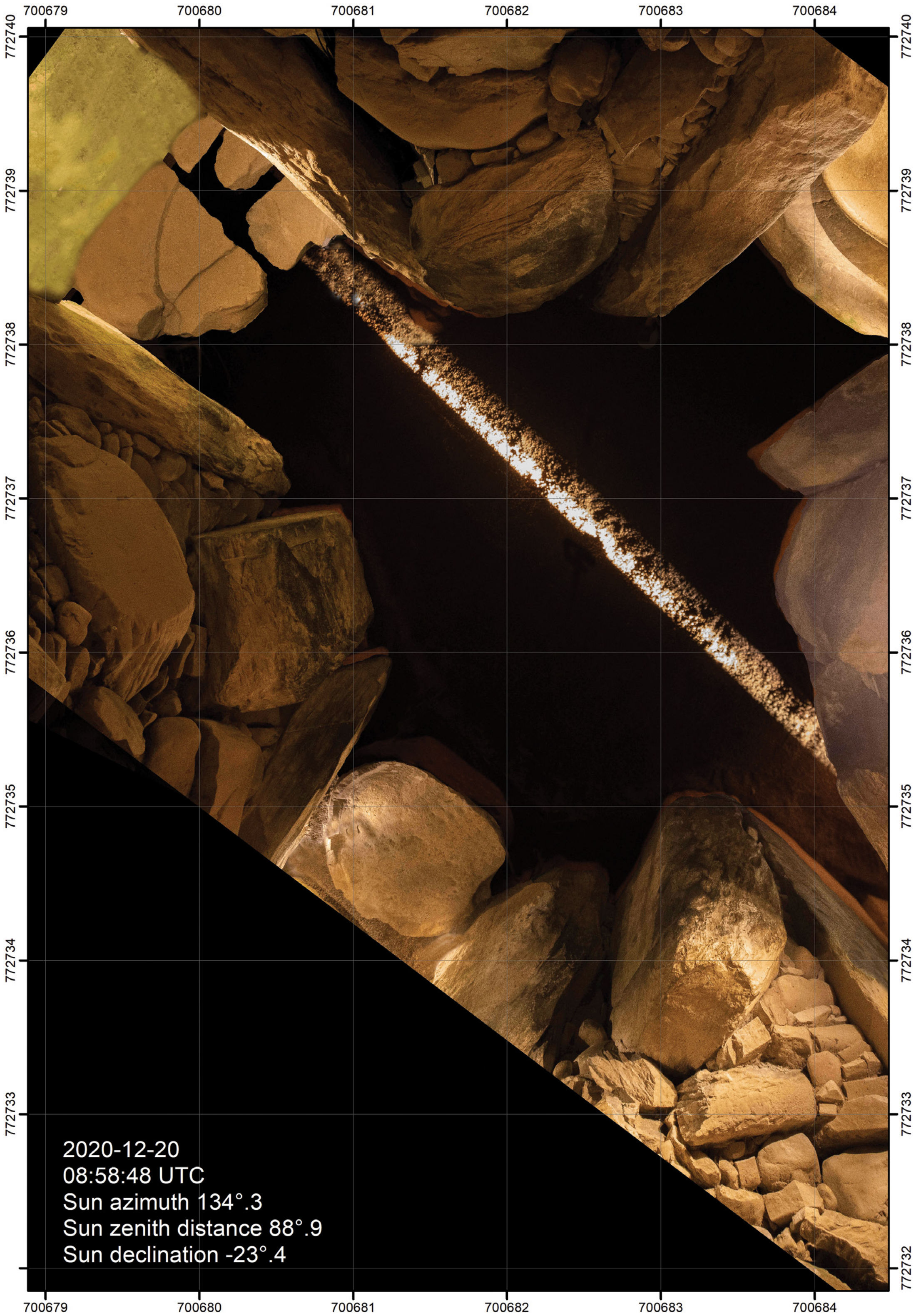


Figure 18: Light culmination in the chamber, 20 December 2020 at 08:58:48 UTC

These data validate the observations and timings of Prof. O'Kelly.

8.5 2020 December 24

Sixteen of the available 198 images for this date were selected for mapping, being three days after the day of winter solstice. Again, culmination of the sunbeam occurs c. two minutes after ingress. After an additional 15 minutes, the beam has egressed from the chamber.

Measurements of the sunbeam using GIS tools show that the average width is 0.26 m, varying from 0.29 m to 0.25 m. The maximum current length of the sunbeam within the bounds of the chamber floor is 3.49 m (Table 7, Figure 19 to Figure 22).

Table 7: Date and time coordinates for Sun, 2020 December 24

NMS photo code	Sun azimuth°	Sun true ZD°	Sun declination°	Comment
20201224-08-58-02	133.8	89.1	-23.4	Ingress into chamber
20201224-08-58-55	133.9	89.0	-23.4	–
20201224-09-00-06	134.2	88.9	-23.4	Culmination of sunbeam
20201224-09-00-59	134.4	88.8	-23.4	–
20201224-09-01-52	134.5	88.7	-23.4	–
20201224-09-03-20	134.8	88.6	-23.4	–
20201224-09-04-31	135.1	88.4	-23.4	–
20201224-09-06-00	135.4	88.3	-23.4	–
20201224-09-07-11	135.6	88.2	-23.4	–
20201224-09-08-04	135.8	88.1	-23.4	–
20201224-09-09-15	136.0	88.0	-23.4	–
20201224-09-10-08	136.2	87.9	-23.4	–
20201224-09-11-19	136.5	87.7	-23.4	–
20201224-09-12-30	136.7	87.6	-23.4	–
20201224-09-14-16	137.1	87.4	-23.4	–
20201224-09-15-09	137.3	87.4	-23.4	Egress from chamber

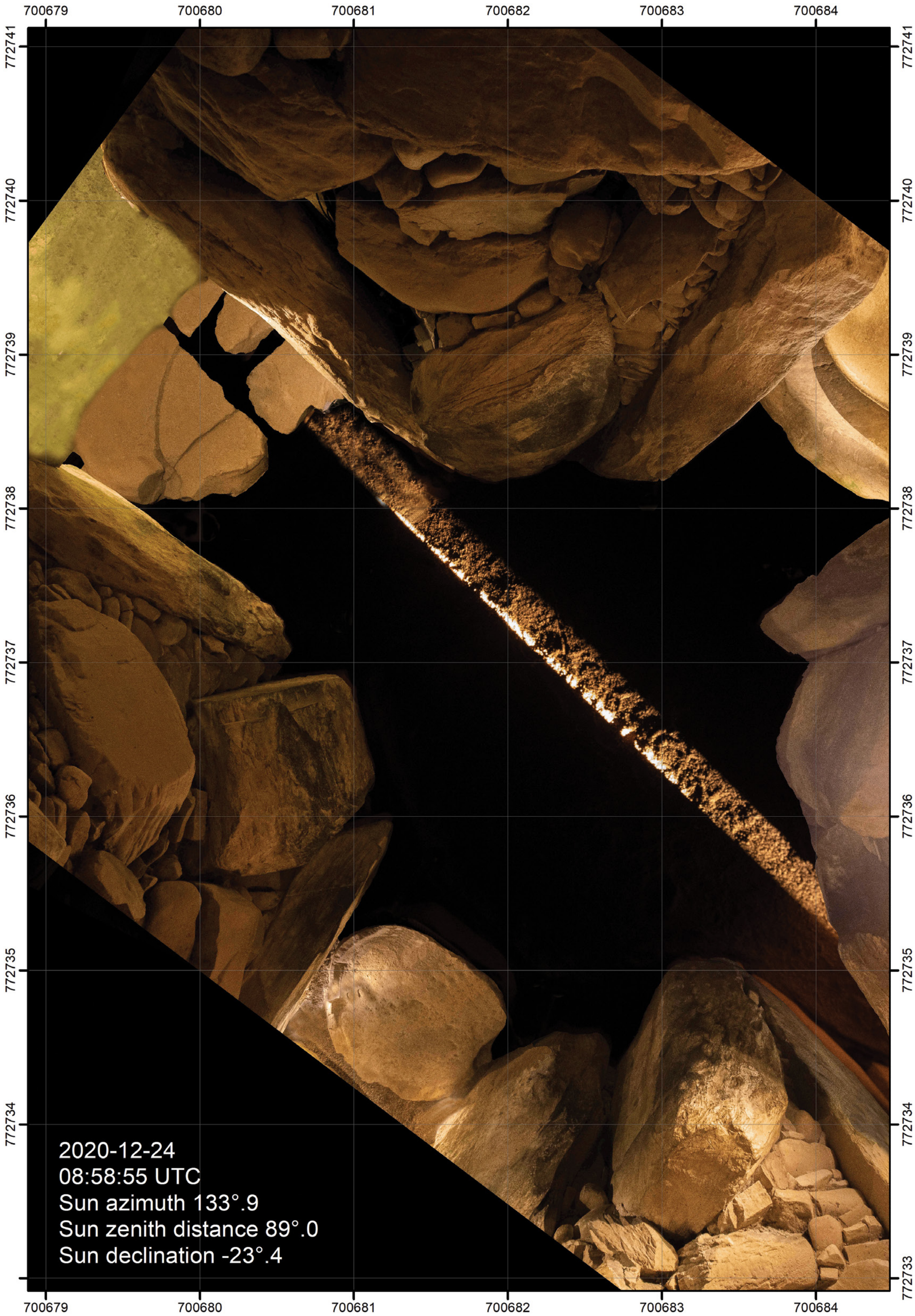


Figure 19: Light ingress in the chamber, 24 December 2020 at 08:58:55 UTC.

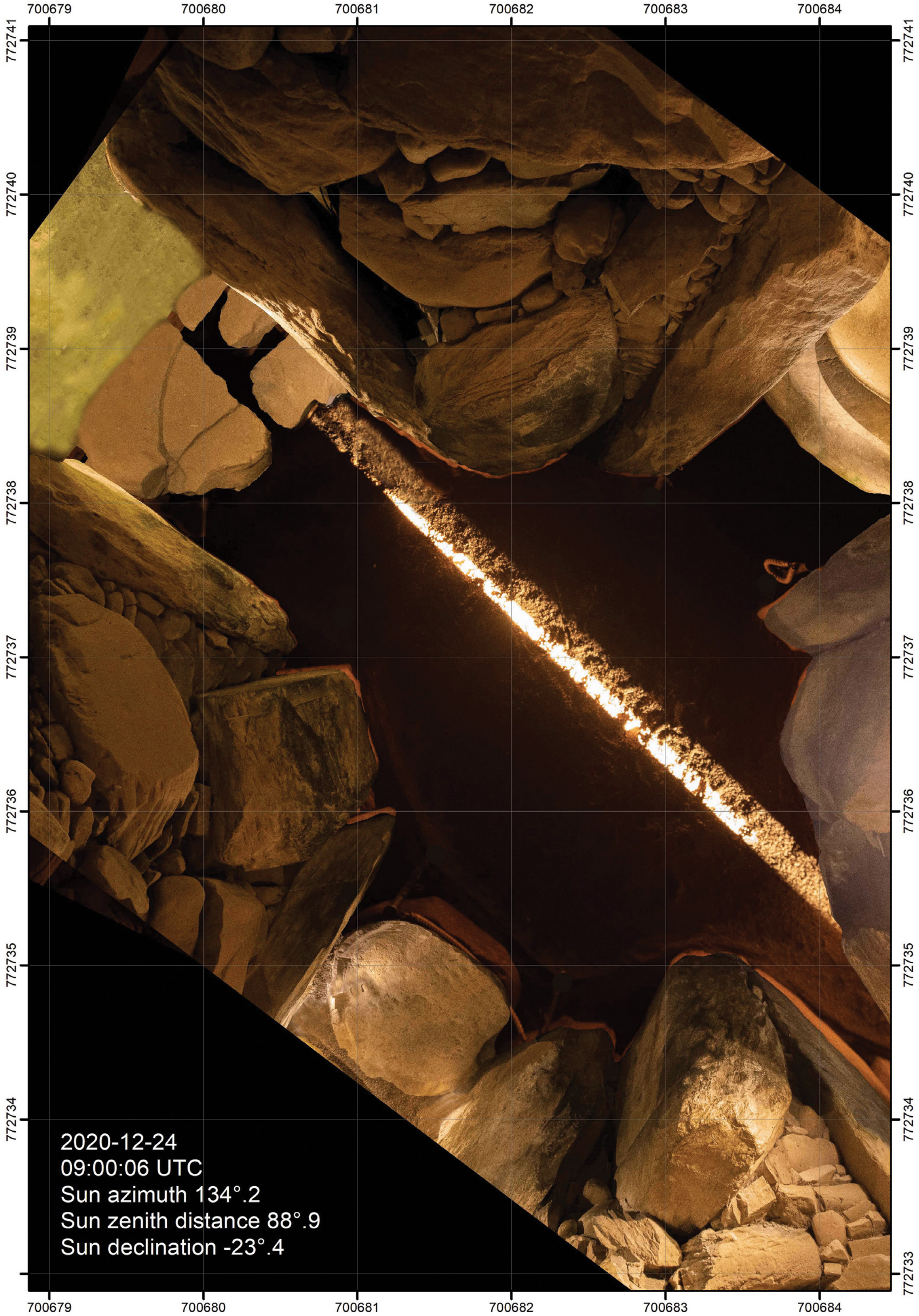


Figure 20: Light culmination in the chamber, 24 December 2020 at 09:00:06 UTC.

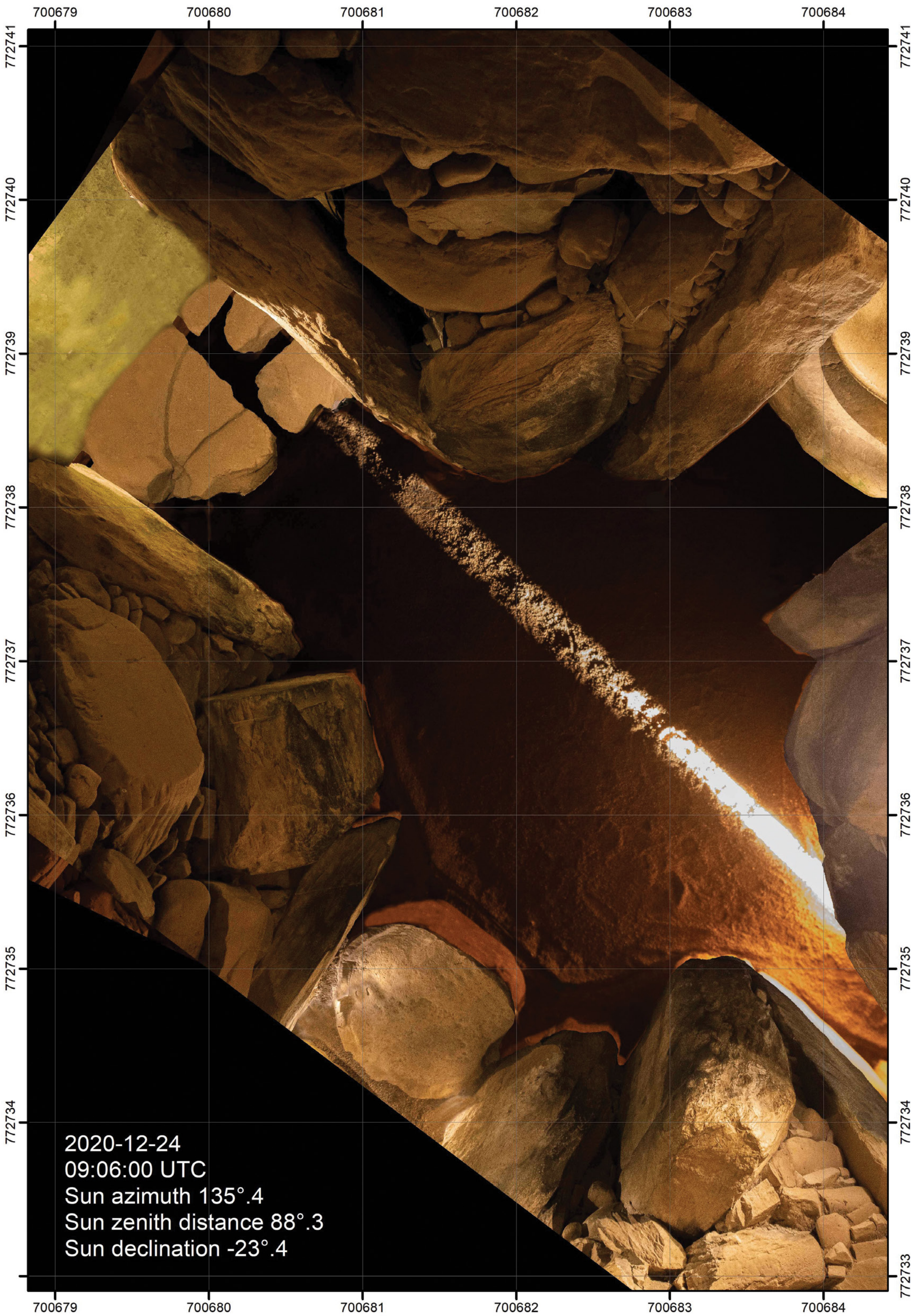


Figure 21: Light receding from the chamber, 24 December 2020 at 09:06:00 UTC.

Figure 22: Light egress from the chamber, 24 December 2020 at 09:10:08 UTC.

8.6 2021 January 03

This was the penultimate date with a clear sunrise for photography purposes. Four photographs were mapped from a total of 89 recorded on that morning. These show that the duration of direct sunlight in the chamber lasts for c. six minutes on that date (Table 8 and Figure 23).

Table 8: Date and time coordinates for Sun, 2021 January 03

NMS photo code	Sun azimuth°	Sun true ZD°	Sun declination°	Comment
20210103-09-05-10	133.9	88.3	-22.8	Ingress into chamber
20210103-09-06-15	134.2	88.2	-22.8	Culmination
20210103-09-09-08	134.8	87.9	-22.8	—
20210103-09-11-14	135.2	87.7	-22.8	Egress from chamber

Figure 23: Light egress from the chamber, 3 January 2021 at 09:09:08 UTC.

8.7 2021 January 08

This was the terminal date for successful photography of the phenomenon. Results indicate that direct sunlight in the chamber has effectively ended by this date, 19 days after the notional date of the winter solstice on 21 December 2020. These data show that due to symmetry, direct sunlight will also enter the burial chamber 19 days before solstice, albeit minimally (Table 9 and Figure 24).

Table 9: Date and time coordinates for Sun 2021 January 08

NMS photo code	Sun azimuth°	Sun true ZD°	Sun declination°	Comment
20210108-09-06-25	133.5	87.9	-22.2	Ingress of sunbeam
20210108-09-10-45	134.4	87.4	-22.2	Egress of sunbeam

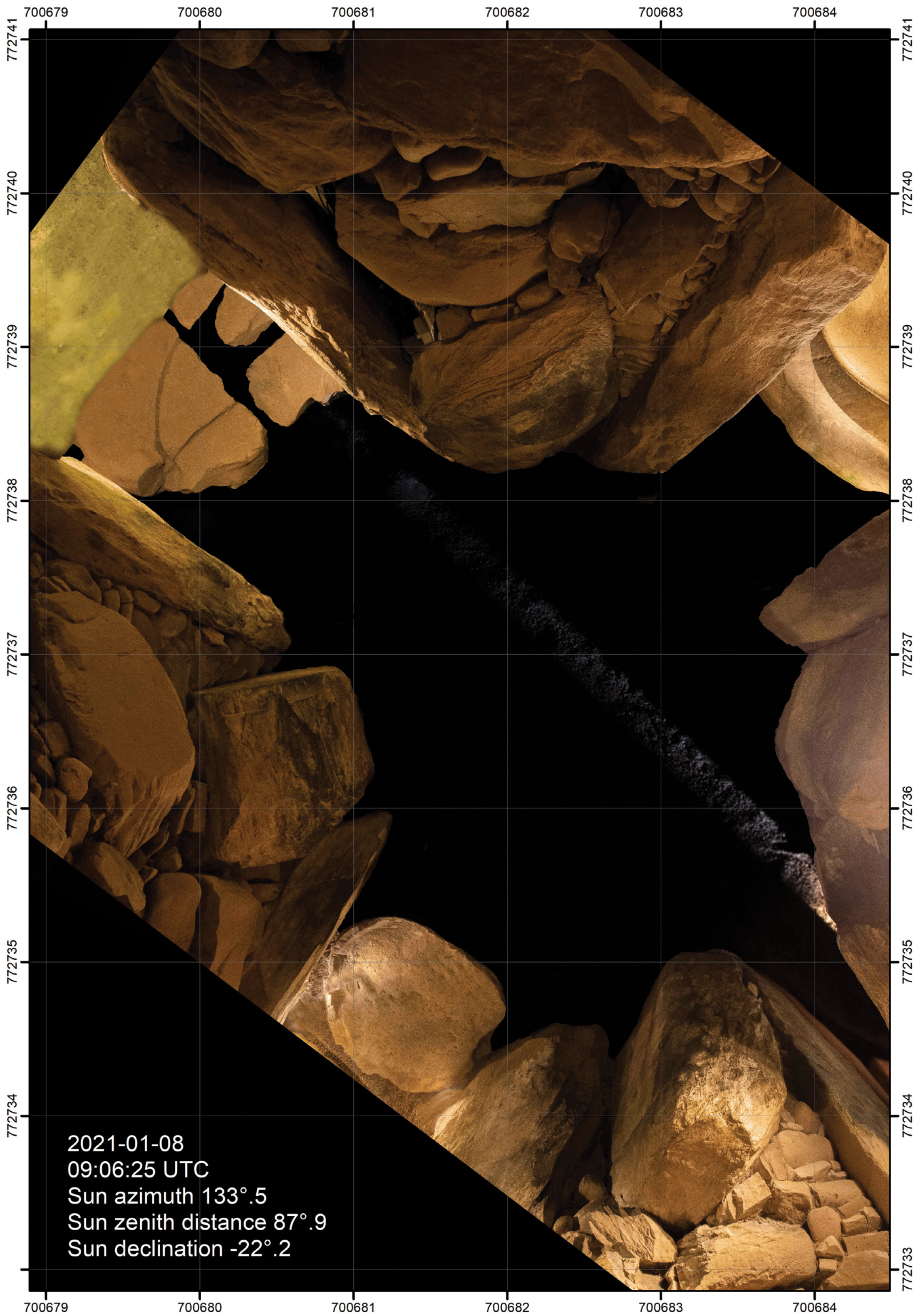


Figure 24: Light ingress into the chamber, 8 January 2021 at 09:06:25 UTC.

9 Videography results

Four motorised dome network cameras (CAM) were installed at key locations in the monument, designed to record and transmit the solar phenomenon in the chamber and passage as well as local sunrise (Figure 25; and see Section 7.2). Recording commenced about one hour before local sunrise on Red Mountain and terminated about two hours later.

- **CAM 1** Placed on the floor of the burial chamber in front of the end recess; aimed at the roof-box and entrance to the tomb.
- **CAM 2** Suspended above the chamber floor; aimed vertically (nadir) at floor.
- **CAM 3** Placed on RS-1 (see Figure 6); aimed at the sunrise sector of horizon in southeast.
- **CAM 4** Suspended above the passage floor; aimed at the burial chamber.

Exact camera orientations and views, deemed critical for communicating the light phenomenon to the audience viewing on livestream, are described in Table 10.

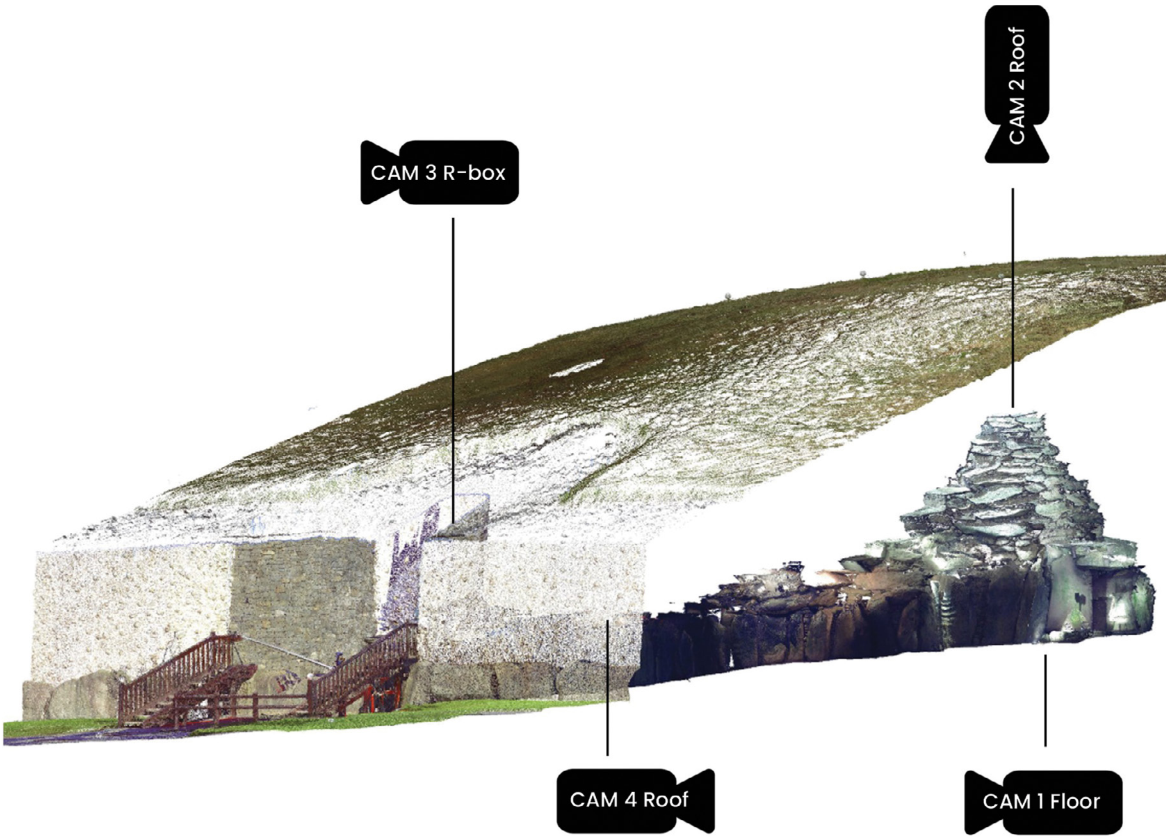


Figure 25: Location and orientation of video cameras in Newgrange passage tomb.

Table 10: Video CAM orientations

CAM 1	Ground-level view from back of chamber to entrance.
CAM 2	Aerial view of the chamber floor showing ambient and direct sunlight.
CAM 3	Horizon view of local sunrise from the roof-box.
CAM 4	Inward view from roof of passage to chamber.

Recordings from CAMs 1–4 were partitioned by Lalor into time segments of approximately half an hour each; files are named according to their duration in UTC and calendar date (Figure 26). The directory structure for CAM 2 data files and the video segments for 24 December are shown in the figure; all other CAM files are similarly structured in the archive.

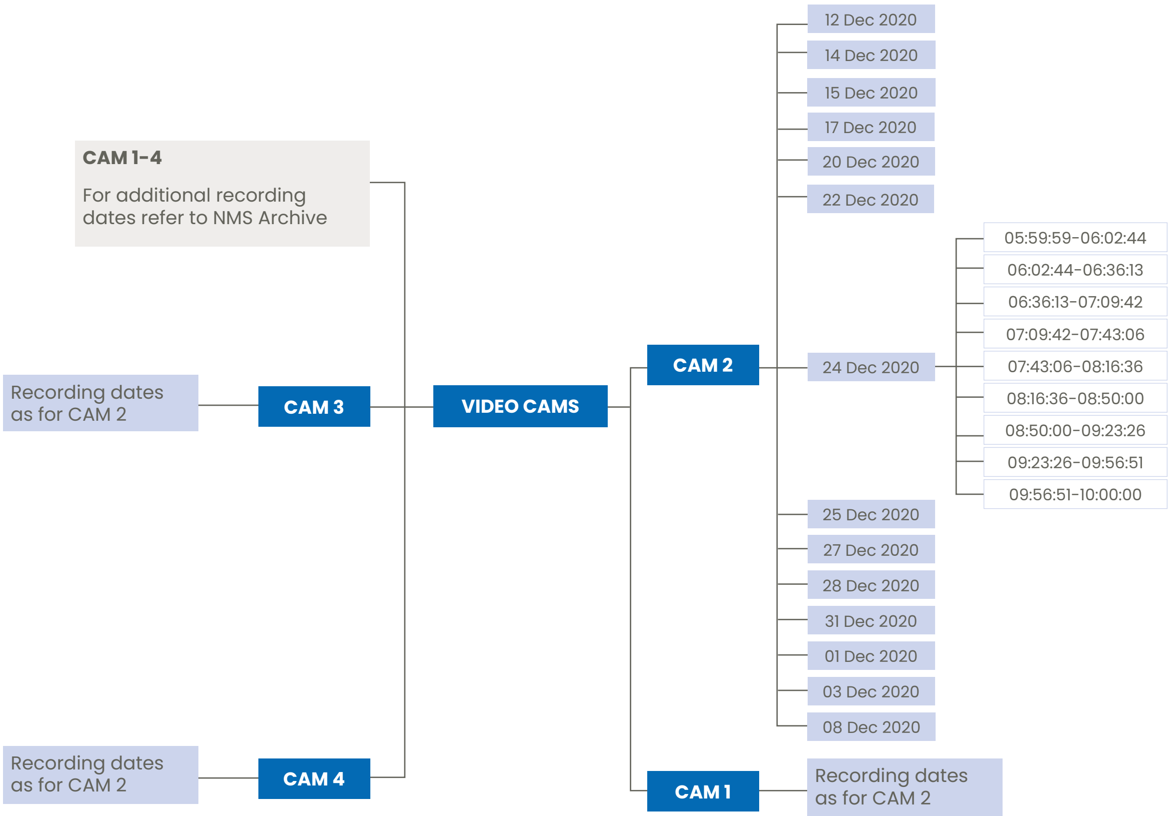


Figure 26: Video CAM directory structure and file naming convention in NMS archive.

The archive of images from CAMs 1–4 provides unprecedented views of the winter solstice phenomenon as sampled in Figure 27.

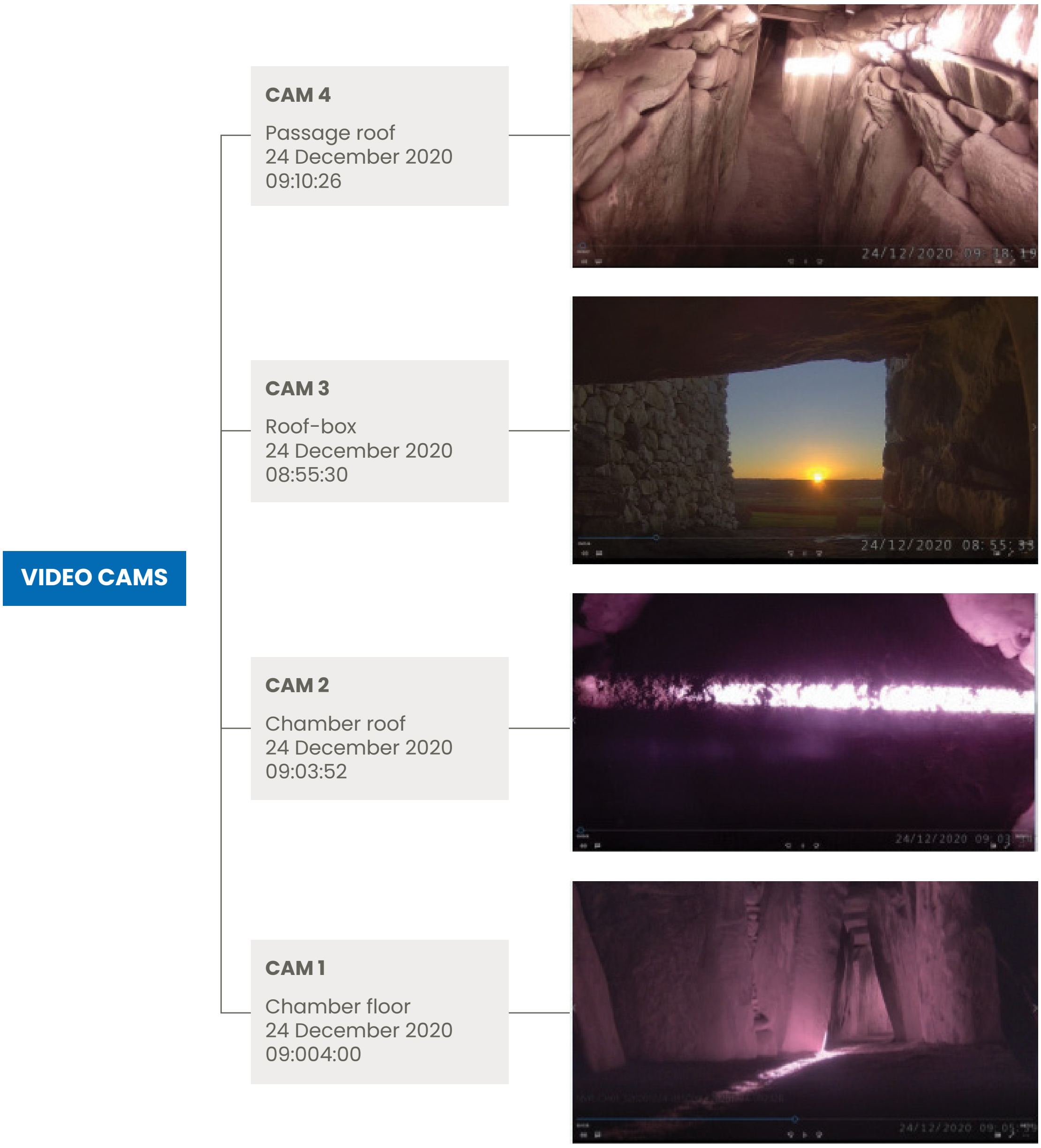


Figure 27: Representative images from Video CAMs 1–4.

Collectively, the photographic and video archives have delivered a new assemblage of visual data to supplement the archaeological record for Newgrange compiled over many decades.

10 Light measurement results

The interior of Newgrange passage tomb is and was a sacred space. According to Gabriel Cooney, 'part of the purpose of building a monument may have been to replicate the notion of a sacred space, such as a cave, that had a special link with the otherworld'.[44] Such a claim and inference are strengthened by recent archaeological findings which now reveal how the Newgrange monument was used to contain the interred remains of an elite who lived and ruled in the Middle Neolithic. Entry into that space embodies transition from the light of day outside to being gradually enveloped by the darkness inside. With the entrance to the tomb sealed by the door-stone, as was probably the case in the Neolithic, the only light to penetrate the innermost regions of the cruciform chamber came through the roof-box opening. That has been shown in this report. Significantly, no other example is currently known in the European passage tomb tradition of a developed lithic structure of this kind being explicitly designed to let direct solstitial sunlight illuminate an inner sacred space.

The type of light perceived on the floor and passage of the burial chamber is twofold: diurnal ambient light cast every day and direct light from the rising Sun which can only penetrate the chamber for less than 20 minutes for about 18 days either side of the date of the winter solstice.[45] Discovery of these temporal limits is, importantly, as a direct result of the data obtained by the collective efforts of the research partners contributing to this report.

Darkness and light are primary phenomena obviously related to the rotation of the Earth. Being binary fundamental opposites, or antithetical, such natural contrasts have a primary effect on the human psyche, causing humans to variously categorise, interpret and pair the phenomena in different ways such as evil with good, dread with optimism.[46] To an observer situated inside the Newgrange burial chamber in the prehistoric past, darkness and light can be legitimately argued to have had symbolic meaning when contextualised with the funerary role of the monument, housing, as it did, the spirits of the ancestors. Thinking more deeply on this point, the liminal horizon framed by the roof-box on winter solstice mornings strongly suggests that the remains, and spirits, of the interred elite were intentionally illuminated by a shaft of direct light emanating from a deified Sun. This would arguably render the whole spectacle numinous and imbued with power in a religious sense.

The phenomena of darkness and light are now better understood and rationalised. Scientific measurement of their opposing qualities is possible too, enabling such data to potentially become part of the narrative for any illuminated archaeological space, especially Newgrange. In the following sections, two differing approaches will show by what method light within the burial chamber can be analysed and interpreted. Such data become highly relevant to our understanding of how society may have

44 Gabriel Cooney, Death in Irish Prehistory (Dublin: Royal Irish Academy, 2023), 131. And see Frank Prendergast, "An Architectural Perspective on Structured Sacred Space – Recent Evidence from Iron Age Ireland," in Skyscapes: *The Role and Importance of the Sky in Archaeology*, ed. Fabio Silva and Nicholas Campion (Oxford & Philadelphia: Oxbow Books, 2015); Frank Prendergast, "The North Sky and the Otherworld: Journeys of the Dead in the Neolithic Considered," in *Advancing Cultural Astronomy: Studies in Honour of Clive Ruggles*, ed. Efrosyni Boutsikas, Stephen C. McCluskey, and John Steele (Switzerland AG: Springer, 2021).

45 Light from a rising summer full moon in years coinciding with the south major declination limit in the 18.6-year lunar node-cycle could have weakly illuminated some of the passage and chamber.

46 Frank Prendergast, "The Meaning of Dark, Light and Shadows: Inferences in Art, Materiality and Cultural Practices," *Culture and Cosmos* 26, no. 1 (2022).

engaged with the monument simply because the relationship between the physical monument and the ephemeral astronomical phenomenon is immutable. This provides an important and incredibly powerful avenue of enquiry to access and assess elements of a lost belief system and ancient solar cosmology – not just in Brú na Bóinne but more widely where the passage tomb tradition, or other type of prehistoric burial structure, is encountered.

10.1 Luminosity analysis of Nikon digital photography

Contrast in colour or texture is central to our visual perception. In a building such as Newgrange, this may have been an intended part of a phenomenological experience restricted to the winter solstice. Viewing, as we now can, the chamber floor directly from above, our eyes, and probably those who used the tomb in the Neolithic, are drawn to three primary zones of contrast – the darkest portions of the cruciform chamber, the 30 cm-wide beam of ambient light and the ephemeral shaft of golden solstice sunlight.

Photography recorded inside the chamber was initially analysed for luminosity using Adobe Photoshop image processing software. This technique measures the brightness of every pixel perceived by the camera lens and returns an average value for the whole image or scene. Luminosity values shown here are relative only, dependent on the time of recording, and cannot be converted into the SI system of measurement. The method is, however, a convenient way to visualise the transition from total darkness to peak brightness to reduced brightness inside the chamber – correlated to the changing aspect of the Sun.

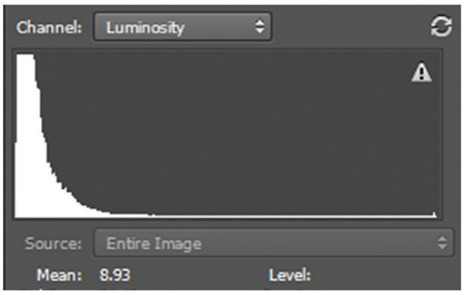
Luminosity inside Newgrange—the view from above the chamber floor

Analysis of the images recorded on 24 December 2020 shows luminosity increased from a minimum of 1.15 on this arbitrary scale of measurement at 08:54 UTC to a peak of 41.3 when the Sun had fully risen above the horizon on Red Mountain (Figure 28).

The top and middle images visualise luminosity from ingress of direct sunlight into the burial chamber to when the phenomenon is at its peak. The chart additionally shows how luminosity rapidly increases at 08:58 UTC, peaks around 09:04 UTC, tails to a value of 3 or less after c. 09:30 UTC and remains so until sunset. Undulations in the data are due to fluctuating cloud amount on the horizon. This method of analysis quantitatively captures the transition from darkness to brightness to darkness inside the burial chamber. To record brightness levels in SI units of illuminance, lux or foot-candle, which are the metric and imperial unit of measurement respectively, a lux meter was used in situ. The results are described in the following section.

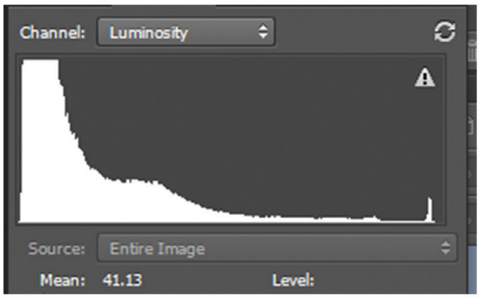
08:58 UTC

Sun risen



09:04 UTC

Moment of maximum brightness
in burial chamber



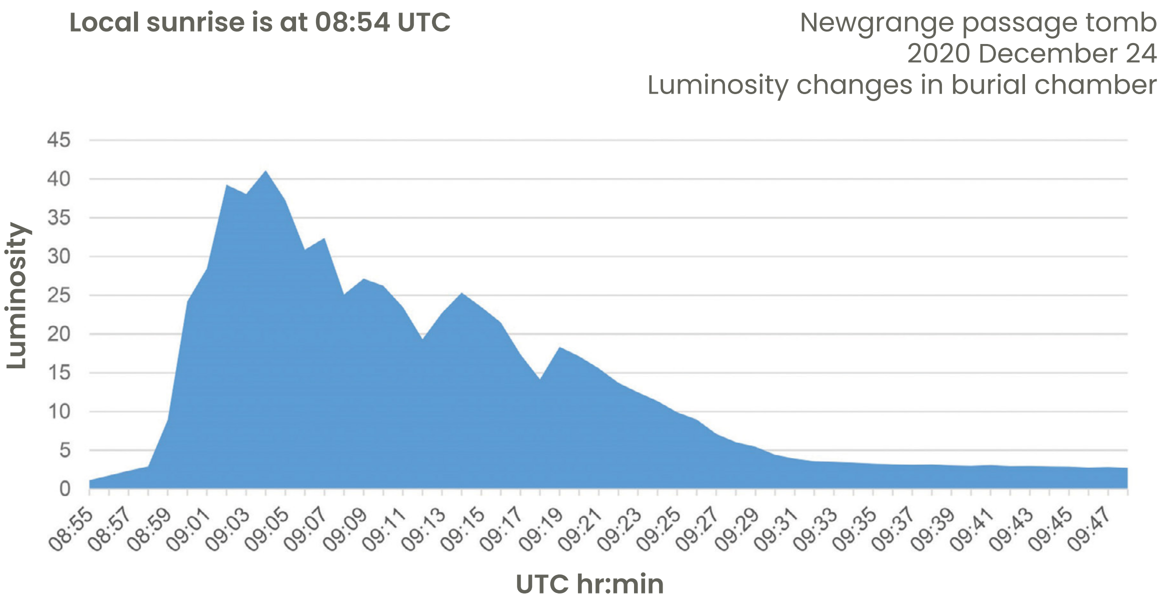


Figure 28: Luminosity inside Newgrange burial chamber, 24 December 2020, 08:54–09:50 UTC.

10.2 Illumination intensity using a lux meter

Absolute values of illumination were recorded at Newgrange using a calibrated industry-standard lux meter, the C.A 1110 light sensor attached to a data logger (Figure 29).[47] The instrument's sensor measures light intensity up to 200,000 lux with a resolution of 0.1 lux. Connecting the device to a laptop computer running the data logger transfer software (supplied with the unit) allows recording at scheduled start-stop times and user-specified time intervals.

The data in Table 11 show lux values typical of a range of conditions related to astronomical aspects of the Sun – before, during and following sunrise – and give meaning to how lux values can change by day and by night.

Figure 29: C.A 1110 lux meter with data logger.

Table 11: Lux values for a range of astronomical conditions and times at Newgrange

Condition	Illumination (lux)	Comment (time in h:mm UTC)
Absence of light	0	Total darkness
Night (no cloud)	<0.01	—
Night (full moon)	0.01	—
Astronomical twilight*	<0.01	Sun 18° below the horizon 06:28
Nautical twilight*	<0.01	Sun 12° below the horizon 07:11
Civil twilight*	0.9	Sun 6° below the horizon 07:57
Sunrise*	585	Sunrise - astronomical horizon 08:41
Local sunrise* (dawn)	1155	Sunrise - Red Mountain horizon 08:54
Sun aligns with roof-box*	1335	Sunbeam ingress into the burial chamber
Local noon*	>50,000	Variable by date, time and cloud amount

*Data recorded with C.A 1110 lux meter, 2 December 2021 (lat. +53°.6944, long. -6°.4752).

47 Chauvin Arnoux, "Logger Luxmeter C.A 1110."

Sky brightness at Newgrange on winter solstice morning

Outside Newgrange on 21 December 2021, the transition from darkness to daylight was first sensed by the lux meter at 07:53 UTC which is four minutes before civil twilight on that morning (Figure 30).

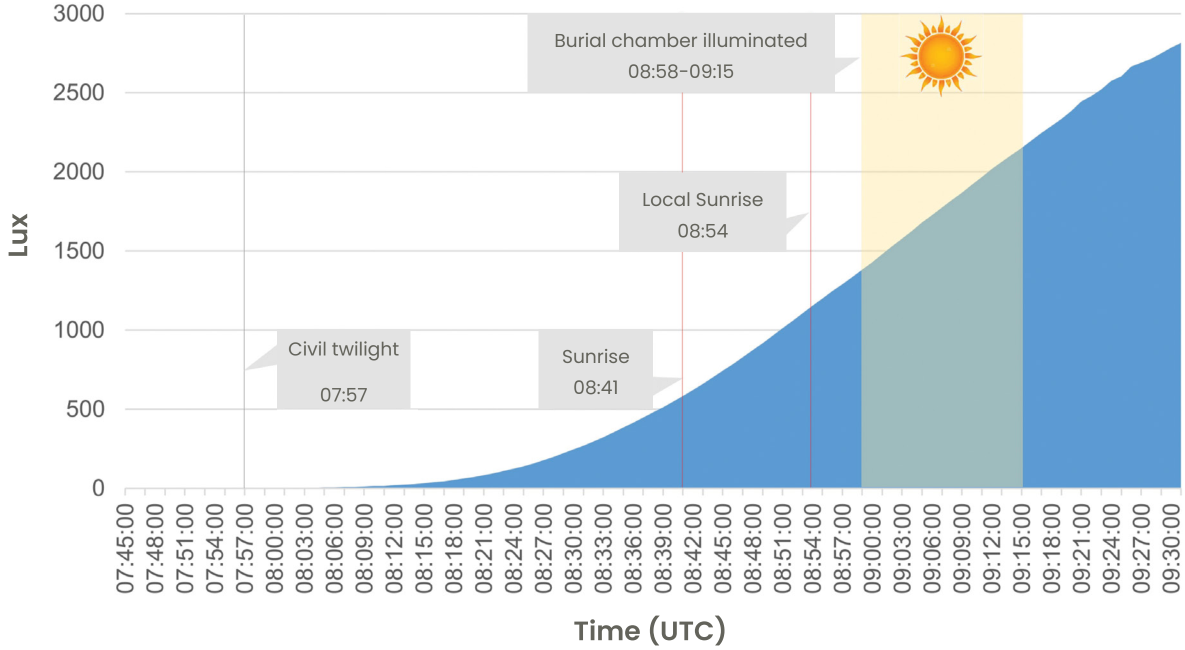


Figure 30: Sky brightness versus time outside Newgrange. Data recorded with C.A 1110 lux meter, 21 December 2021 (+53°.6944, -6°.4752).

From astronomical sunrise at 08:41 UTC to local sunrise on Red Mountain at 08:54 UTC, the sky brightened from 585 lux to 1155 lux. Four minutes must elapse, however, before the first rays of the rising Sun come into alignment with the left-hand limit of the roof-box as viewed from the burial chamber floor (see Figure 3). Daylight at c. 08:58 UTC then measured 1335 lux. Inside the tomb at this time, the sunbeam has begun ingress into the floor of the burial chamber and rapidly grew in intensity, reaching culmination at 09:01 UTC (see Figure 20) when daylight measured 1480 lux. When the phenomenon receded at c. 09:15 UTC (see Figure 22), daylight measured 2200 lux. At local noon, 12:24 UTC, daylight measured c. 50,000 lux.

Burial chamber brightness

Lux measurements inside the burial chamber were recorded by the author on 13 December 2023, a date when sunrise was not obscured by cloud. The sensor was variously placed in the path of the sunbeam and inside the recesses (Table 12).

Table 12: Lux measurements recorded inside Newgrange burial chamber on 13 December 2023

Condition	Illumination (lux)	Comment (time in h:mm UTC)
Sunrise	<0.1	Sun on astronomical horizon 08:35
Local sunrise	<0.1	Sun on local horizon 08:43
Sun climbing	0.8	Sensor in path of sunbeam 08:51
Sun climbing	2.8	Sensor in path of sunbeam 08:53
Sun climbing	1996.7	Sensor in path of sunbeam 08:56
Sun climbing	420.2	Sensor in path of sunbeam 08:59
Sun climbing	6.6	Sensor in path of sunbeam 09:05
Sun climbing	<0.1	Sensor in path of sunbeam 09:14
Recesses in darkness	<0.1	Sensor in side recesses 08:43–09:14
Artificial chamber lighting on	0.3	Sensor in different chamber locations

Visible cloud amount and equivalent values in okta recorded at hourly intervals from 08:00–10:00 UTC on 21 December 2021 are shown in Figure 31.[48] Implicitly, for direct sunlight to enter the burial chamber, cloud must not obscure the small sector of sky coincident with the direction of the rising solar disc.

2021 December 21, 0800 UTC
Cloud amount 8 okta

2021 December 21, 0900 UTC
Cloud amount 8 okta

2021 December 21, 1000 UTC
Cloud amount 7 okta

Figure 31: Cloud amount at Newgrange 21 December 2021. Cloud amount (okta) recorded at Dublin Airport meteorological station supplied by Met Éireann; cloud cover images supplied by Met Office UK Weather App (public domain).

48 Met Office, "Met Office Weather App."

Referencing Table 12, comparison of the illumination values measured outside the burial chamber with those obtained inside clearly shows that average ambient light within the tomb is never likely to exceed c. 2–3 lux, even on mornings of exceptionally clear skies. By contrast, levels of illumination in the left and right recesses remain below 0.1 lux, meaning that these sacred spaces endure perpetual darkness. Conversely in the Neolithic, the end recess could have received direct sunlight on winter solstice mornings due to the more southerly alignment of the Sun (by two solar diameters) and the probable vertical inclination of the passage orthostats immediately in front of the burial chamber. This raises a key question – might the end recess have been reserved for the interment of an individual(s) characterised by rank or social specialness? Interestingly, basin stones are known to have originated in passage tombs found in County Meath and to have been used as containers for human remains.[49] Any further consideration of these ideas is beyond the scope of this report but is advanced in recent literature.[50]

To gain a better understanding of the Newgrange light phenomenon, additional experimental readings were recorded with the lux meter in a controlled environment to determine the relationship between brightness and increasing distance from the light source (Figure 32). A standard candle was used, noting that if 1 candle (1 lumen) is placed 1 m from a surface 1 m^2, the area is illuminated to 1 lux.

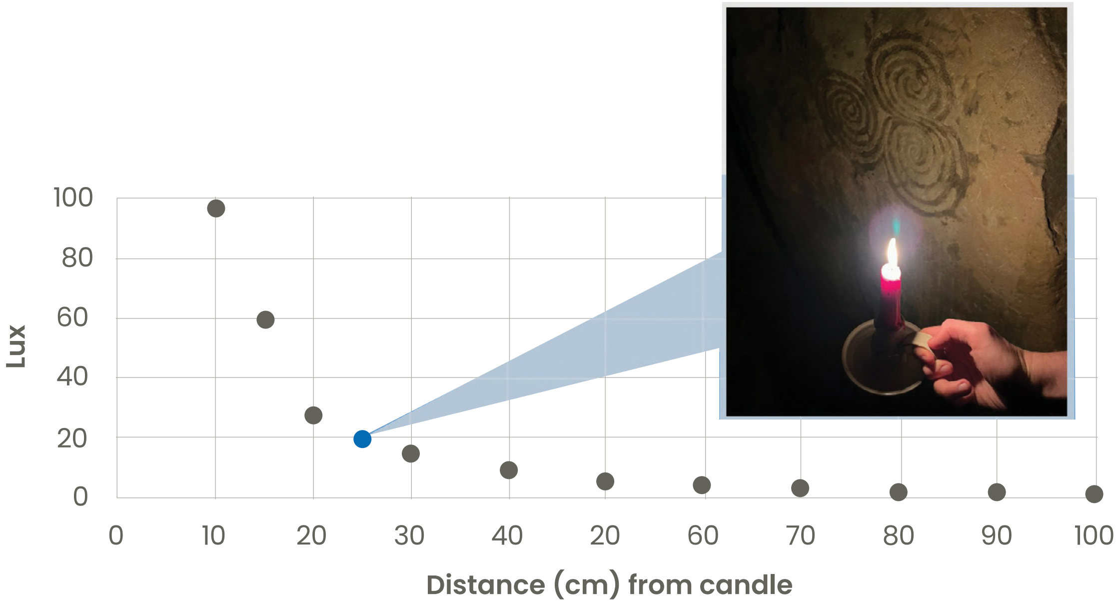


Figure 32: Lux units plotted against distance from a 1 candle light source. Inset photo: candle held 25 cm from stone C10 in Newgrange illuminates the megalithic art with c. 20 lux (credit: Andrew Downie).

This experiment shows an exponential decrease in illumination with increasing distance from a 1 candle light source. Beyond c. 70 cm, illumination drops to < 0.1 lux. The author is grateful to Andrew Downie, an OPW guide at Brú na Bóinne, who demonstrated how 1 candle could illuminate the three-spiral motif on stone C10 located in the end recess in Newgrange (Figure 32, inset). Downie's image captures the mystical qualities of this enigmatic motif, even in low levels of light.

49 George Eogan, Elizabeth Shee Twohig, and Ken Williams, "Containing the Dead in Irish Passage Tombs," in *Reflections on the Past: Essays in Honour of Frances Lynch,* ed. W. Britnell and R. Silvester (Vale of Glamorgan: The Cambrian Archaeological Association, 2012).

50 George Eogan and Kerri Cleary (Archaeological Editor), *Excavations at Knowth 6: The Passage Tomb Archaeology of the Great Mound at Knowth* (Dublin: Royal Irish Academy, 2017), 752–59 (and see references therein); Cooney, 2023. Chapter 4.

11 Concluding remarks

For the hundreds of visitors who gather annually outside Ireland's most iconic archaeological monument on the mornings of winter solstice, the spectacle of the Sun rising on Red Mountain is arguably the greatest example of collective on-site engagement with Irish prehistoric cultural heritage. Of interest here is the union of monument with skyscape and anticipation of the event to come (Figure 33). As the sky reddens minute-by-minute shortly after civil twilight, what astronomers term the 'first-flash' of the Sun's upper limb emerges from the waning darkness of an imagined, to some, underworld, inspiring those present to greet the dawn with an almighty cheer! That sound will reverberate to the small gathering privileged to be inside the burial chamber at that time, a sign that the impending phenomenon of solar illumination of the burial chamber is just minutes away.

Figure 33: Facing sunrise on the winter solstice at Newgrange, 21 December 2013 (Photo: Ken Williams).

In comparison to those outside the monument, the gaze of those inside the darkened burial chamber is fixed on the dagger-like shaft of sunlight as it begins tracking across the chamber floor towards the back recess (Figure 34). On such mornings, in the minds of many, the supreme celestial body seems to be at its most powerful, having reached standstill at the time of reversal and renewal in the year-long solar cycle.

Following the period of winter solstice, the rising Sun will begin its apparent journey northwards on the horizon, heralding the advent of longer days with darkness increasingly banished by lengthening daylight. The inverse happens inside the tomb – the chamber will return to a state of perpetual darkness until the return of the Sun one year later.

In the Neolithic, direct sunlight within the tomb would have touched the back stone of the end recess and have illuminated the burial chamber more than in the present as previously explained. It is also probable that with the entrance sealed by the door- stone, extraneous light in the passage was blocked thereby increasing the intensity of solar illumination entering the chamber via the roof-box. This has been proven by insertion of the temporary door designed by the OPW.

Looking to the future, Newgrange will not receive direct sunlight on the winter solstice indefinitely due to the obliquity cycle. Century by century, the southerly limit of the direction of the rising Sun is drifting northwards towards the next minimum in the 40,000-year cycle in c. AD 12,000 (Figure 35).[51] As a consequence, the solar alignment of the passage and roof-box will temporarily diminish over the next few thousand years.

Figure 34: Watching the solstice light in the burial chamberon 22 December, 1994 (Frank Miller, © Irish Times).

Archaeoastronomy has captivated the public imagination ever since it became prominent in the 1960s because of the highly controversial theories and vigorous debates concerning megalithic astronomy and the claimed high-precision alignment of Stonehenge in particular. Today, modern archaeoastronomy is more archaeologically grounded and, with ancient cosmology and ethnoastronomy, is one of the three pillars of cultural astronomy. Each of these interrelated fields of research brings rigorous and theoretical perspectives to examining how people and societies throughout history and prehistory perceived the changing sky, shaping their ideologies and world views.

51 A. L. Berger and M. F. Loutre, "Noaa/Wds Paleoclimatology – Orbital Variations and Insolation Database," NOAA National Centers for Environmental Information.

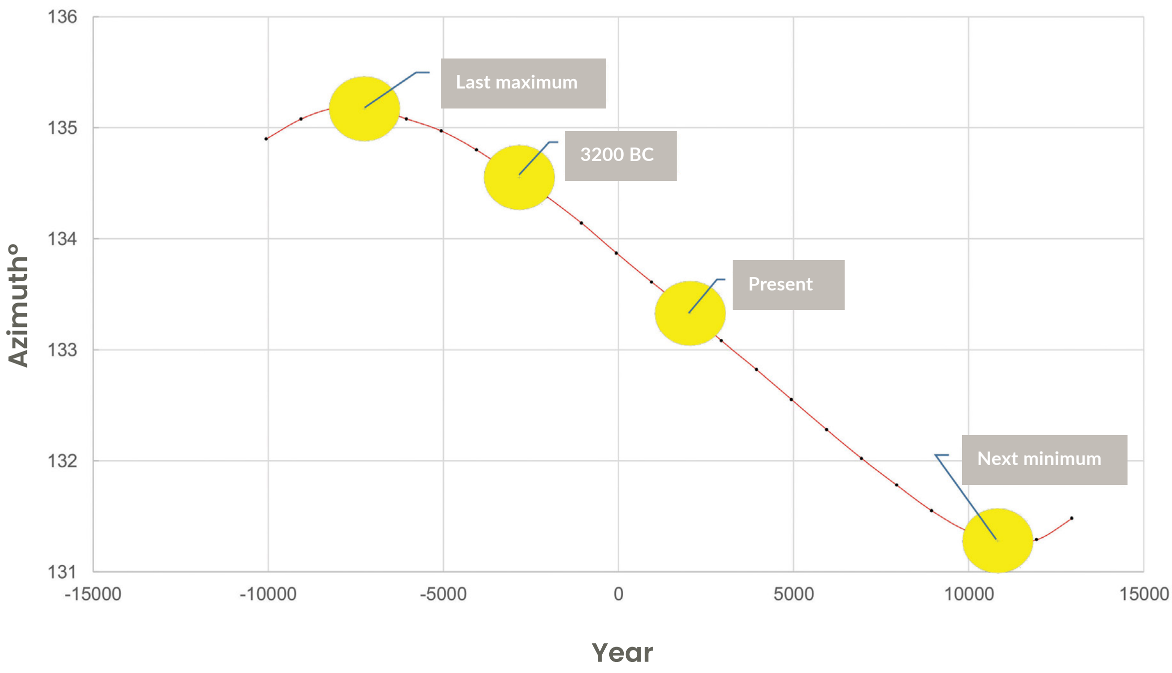


Figure 35: The obliquity cycle at Newgrange—azimuth of Sun (altitude +1°) from previous maximum to next minimum.[52]

Eminent scholars who have made significant advances in cultural astronomy in recent decades include Clive Ruggles and Nicholas Saunders. In their seminal paper 'The Study of Cultural Astronomy', they argue that 'a society's view of and beliefs about the celestial sphere are inextricably linked to the realm of politics, economics, religion and ideology'.[53]

The solstitial phenomenon in Newgrange is now better understood and comprehensively recorded for posterity. Exact documentation and analysis of its attributes as carried out by the research team from the National Monuments Service, OPW and Technological University Dublin will facilitate further research. Importantly, this rich spatial data resource provides the nation with priceless imagery and a database which has enabled exact digital reconstruction of an immutable phenomenon which endures even after five millennia.

52 Computed by the author using data from the NOAA/WDS Paleoclimatology – Orbital Variations and Insolation Database. The cycle has a half-period of c. 20 ky. Horizon coordinates are calculated for the astronomical horizon. Based on high-precision surveys of the roof-box limits by the author, it is estimated the Sun will be out of alignment with the roof-box.

53 C. L. N. Ruggles and Nicholas J. Saunders, "The Study of Cultural Astronomy," in Astronomies and Cultures: Papers Derived from the Third "Oxford" International Symposium on Archaeoastronomy, St. Andrews, UK, September 1990 (Niwot, Colo.: University Press of Colorado, 1993).

12 Appendix

The text in the following sections was kindly provided by Alisha Naughton and Des Swords, OPW.

12.1 Video camera installation and specification

The OPW was presented with a unique opportunity to conduct research on site and also to webcast footage of the winter solstice from an empty chamber in Newgrange.

Objectives

- To capture live footage of the illumination of the passage and burial chamber over the course of approximately six weeks for the purpose of research and analysis.
- To facilitate the installation and remote operation of live cameras to capture the illumination from inside the chamber as part of three days live webcast of the winter solstice event from the site.

Challenges

Achieving the objectives presented unique challenges with regard to technology as follows:

- Extreme low light environment.
- Extreme low temperature.
- Installation of equipment and cabling that would not obstruct the passage of light and not interfere with the archaeological structure.
- Maintaining full access to the chamber and the site at large.
- Establishing sufficient internet connectivity and network integration for both the research project and for the webcast element.

Proof of concept and execution

Equipment testing was carried out off site in a black environment with a single light source equivalent to 1 candle. All digital enhancement was disengaged from the camera devices further to which the 1/2.8" Progressive Scan CMOS image sensors were maximised to provide the most accurate reference image.

Note: All electronic camera enhancement was disabled from the system before individual cameras were positioned and adjusted, according to their location, to allow for the recording of the daily illumination 08.00–09.30 UTC or thereabouts.

Cabling

A powered data network cable infrastructure was installed from the chamber along the passage floor to the entrance from where it ran externally along the front of the monument. Sixty metres of temporary cable management was installed so that all cables could run to the nearest fixed structure (Professor O'Kelly's Hut) where the local control system was located.

Recording, power supply and connectivity

A 4k H.265 Network Video Recorder positioned in O'Kelly's Hut allowed four cameras to be controlled and monitored locally while having the internal storage capacity for all isolated daily recordings to be stored.

Universal Power Supply units were installed to ensure continuity in the event of local power failure.

A temporary 4G data connection was installed and integrated to the Network Video Recorder in order to facilitate remote monitoring and control.

12.2 Webcast system description

Temporary facilities were installed to facilitate three days' live webcast of the winter solstice from a position immediately outside the monument, as follows:

- Temporary power (independent of on-site power) with redundancy to facilitate OB production elements.
- Three-camera HD OB unit with on-board vision mix and data control.
- Interface and control to allow for the footage from the live cameras inside the chamber to be integrated into the broadcast.
- Technical staff to install and operate all equipment including OB Unit Manager, Programme Director, Vision Engineer, Camera Operators, Floor Manager.
- Temporary outdoor "studio" including furniture, temporary lighting (for broadcast) and essential technical supports for presenters.
- Supervisory staff to manage the broadcast event, interface with on-site OPW staff and programme presenters.
- Temporary microwave data link and associated network integration both on and off site was installed, tested and fully supported on site by OPW ICT.
- All footage was edited live on site, transmitted to a host platform, and subsequently distributed to various digital platforms and social media platforms.

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14 Glossary

aDNA Ancient DNA retrieved from ancient human or animal specimens.

Align Where the axis of a built structure is considered to be non-random and faces an identifiable target such as the rise/set of a prominent celestial body, cairn, or a distinctive topographical feature, then the structure can be described as being intentionally 'aligned'.

Alignment Generally taken to mean a straight line formed by connecting three or more significant or related points such as a prehistoric stone row. Compare with Orientation.

Altitude h° The angular distance of a body or point above (+) or below (-) the horizon and measured through the zenith plane. See Horizon Coordinate System, Zenith Distance.

AMS Accelerator Mass Spectrometry (for dating of samples).

Archaeoastronomy The investigation of the astronomical knowledge and world views of cultures throughout time.

Archaeoline An arc which traces the path of the Sun or any celestial body from rise to set. Used in planetarium software.

Azimuth or A° The angular distance of an object measured clockwise from true north along the horizontal plane (see Horizon Coordinate System).

Coordinated Universal Time UTC The time scale made available by broadcast for civil use (formerly known as GMT or Greenwich Mean Time). Conventionally, winter time in Ireland is UTC and summer time is UTC+1 hour.

Cosmology – ancient A conceptual framework which addresses how humans sought to answer the fundamental questions about the world and their relationship to it. Related to world view.

Culmination The climactic moment when direct sunlight reaches furthest into the burial chamber after the short period of time following ingress.

Declination – astronomical δ° The angle of altitude of any celestial body measured above (+) or below (-) the plane of the Earth's equator. Declination for the Sun now ranges from +23° 26′ (summer solstice) to – 23° 26′ (winter solstice), and 0° at the true equinoxes (see Equatorial Coordinate System).

Diurnal motion The apparent daily motion of the heavens from east to west caused by the true rotation of the Earth from west to east.

Elevation H m Height above Mean Sea Level datum.

Equatorial Coordinate System The equatorial coordinate system describes an object's position with respect to the celestial equator and the vernal equinox. The celestial equator is the projection of the Earth's equator on the celestial sphere. The vernal equinox is the Sun's position at the start of spring in the Northern Hemisphere.

The equatorial coordinate system's coordinates are termed right ascension (RA) and declination (Dec).

Egress Direct sunlight leaving the ambient light beam and the moment of extinction of the sunbeam.

Equinox The date or the direction of the Sun at sunrise or sunset when it is midway between its extremes (winter and summer solstice or, either of two points on the celestial sphere at which the ecliptic intersects the celestial equator).

Extinction The near complete reduction of light in the chamber.

GIS Geographic Information System A software system that combines digital maps, spatial data and their attributes, graphical and analytical functionality.

Height H m Elevation above mean sea level (MSL).

Horizon The plane that is perpendicular from the line joining the observer and the zenith (point defined on the celestial sphere by extending the plumb line upwards) i.e. the astronomical horizon.

Horizon Coordinate System The horizon coordinate system describes an object's position with respect to the horizon and the direction of true north. The horizontal coordinate system's coordinates are called azimuth and altitude.

Ingress The moment when direct sunlight enters the beam of ambient light on the floor of the burial chamber.

Luminosity The brightness of an object or scene perceived by a human observer or a camera lens.

Lux The SI metric unit of illuminance.

Lunar major and minor declination limits (for Moon rise and Moon set) The range in declination achieved by the Moon in a month alters from c. ±18º.5 (minor limit N & S) to c. ±28º.5 (major limit N & S) over an 18.6-year period – the synodic cycle. To an observer, the effect of this changing amplitude is to cause the azimuth of the rising and setting points of the Moon on the horizon to oscillate from inside to outside of the solstitial rising and setting points on the Sun which are achieved over 12 months (the solar year).

Lumen SI unit of flux of light.

Nadir The point directly below the observer.

Obliquity ε° Angle between the planes of the equator and the ecliptic – currently 23° 26′ but in the Neolithic was about 24º. To an observer on Earth, this translates into a long-term (c. 40,000 years) cyclical change in the sunrise and sunset positions at the solstices. In the intervening 5000 years since the Neolithic, the effect at the latitude of Ireland is to cause the directions of sunrise and sunset at the solstices to contract by about two solar diameters, a little more than 1º.

Ordnance datum OD or AOD Intersection of the mean level of the sea with the coast. Elevations or heights are measured with respect to this datum (AOD).

Orientation The direction of an object from an arbitrary or absolute reference point (local, true north or magnetic north). See 'align' and 'alignment'.

Passage tomb A form of megalithic tomb in which the burial chamber is accessed by means of a narrow passage. Most such tombs have only a single chamber. Found throughout Europe.

Precession The motion of the Earth's pole of rotation. To an observer on the Earth, this translates into a long-term (c. 26,000 years) cyclical movement of the celestial pole against the star background. In the intervening 5000 years since the Neolithic, the effect is to cause the apparent positions of the stars to significantly change on the celestial sphere and with respect to the mean pole.

Refraction – astronomical The angular displacement of astronomical objects from their true position, due to the bending of light rays in the Earth's atmosphere. At local sunrise/sunset this will amount to the diameter of the Sun itself (c. half a degree or 30 arc minutes).

Solstice events The date or the direction of the turning or reversal point in the Sun's apparent motion on the horizon or, either of two points on the ecliptic at which the apparent longitude of the Sun is 90ºor 270º (see astronomical declination). This gives the winter and summer solstice.

Space-time analysis Seeking to understand events and phenomena related to how these occur in space and time.

Sun/star transit The passage of the body across the local celestial meridian.

Sunrise, sunset The times or the event at which the upper limb of the Sun is on the astronomical horizon or, from the centre of the Earth, when the true zenith distance of the centre of the Sun is 90º 50' (based on a semi-diameter of 16' and refraction of 34'). In the vertical plane, the Sun is described as having an upper limb, a centre and a lower limb (sunrise = first visible flash; sunset = last visible flash). See Refraction.

Sunrise, local When the Sun's upper limb appears on the topographical horizon.

Zenith Point directly overhead the observer.

Zenith Distance ZDº Angular distance of a body measured from the zenith point to the celestial body/point and measured in the vertical plane. Zenith distance is 90º–altitudeº.

About the author

Frank Prendergast is a chartered geodetic surveyor, archaeoastronomer and holds a PhD awarded by the School of Archaeology, University College Dublin (2011). His work blends archaeological findings with spatial data mainly collected in the Irish landscape to ask and answer theoretical questions related to how prehistoric societies perceived their world and skyscape. Research methods include site surveys, spatial data processing and probability analysis. By layering these data onto the archaeological record, meaning can be extracted to advance our understanding of the cosmologies and symbolic perceptions of preliterate societies who lived during the Neolithic, Bronze Age and Iron Age. He continues to publish his findings, lecture internationally and advises heritage organisations on relevant cultural matters.