A NORTH-FACING POLARIZATION SUNDIAL OF VARYING HUE

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Historically, the Sun is our prime timekeeper, fundamentally by measuring its apparent position in the celestial sphere. But it is far too bright for direct viewing – and there are no calibration marks in the blue sky – so long ago mankind discovered that shadows were the answer and the sundial was born. Over the centuries, the instrument has been developed and refined by many different cultures, and a remarkable range of designs testifies to the success of the basic idea.

It is interesting to enquire if any alternative methods are possible for measuring the position of the Sun against an agreed scale. For example, the Sun is a source of radio waves in the MHz to GHz regions, particularly when solar flares are present, so it is feasible to devise a radio sundial. However (even though it would work when the sky is completely covered with cloud) the size, complexity and cost of the equipment required has meant that solar radio astronomy has always been devoted to the study of the Sun as a star rather than to mundane terrestrial timekeeping.

Polarization of Light from the Sky

Linearly polarized light is a form of light where all the constituent waves vibrate in the same plane, rather than the random planes characterizing ordinary light from incandescent sources. This condition is induced by the molecular scattering that gives us the blue sky, with the content of polarized light being a maximum at right angles to the beams from the Sun. Apparently, it is never more than about 75% of the total sunlight, even in the clear skies above tropical deserts.[1-3] It will be considerably less in the hazy skies of the UK (even in the absence of obvious white clouds with their known depolarizing effects) but there appears to be little quantitative data for Europe as a whole. This matter will be examined in a companion paper.[3a] Meanwhile, it has been established that, if a conventional shadow sundial is working, then there is probably sufficient polarization in the light from the circumpolar sky for sundials based on the phenomenon to be effective.

Many years ago I presented in a sister journal[4] a lengthy account of how in 1848 Charles Wheatstone used this phenomenon to create a polarization sundial that was independent of shadows, and went on to show that a modern version reading to ±2 minutes of time was possible by using 'Sellotape' as a 'half-wave plate' and manually moving a disc to obtain a match across two fields. Patches of white cloud did not degrade this accuracy and it could even work for a short period after sunset!

Wheatstone also designed a simpler, non-mechanical device to demonstrate the principles used in his polarization dial. This employed a number of 15° sectors of mica or selenite arranged in a fan to face the northern celestial pole so that when the sky was mostly blue it was possible to estimate the relative brightness of each segment to give the time of day to ±30 minutes. I showed that 'Sellotape' could again be used instead of natural minerals, being readily available and easily cut without producing a ragged edge. An account was published in this journal.[5] It is urged that reference be made to these papers, for space does not allow the rather complex and lengthy technical explanations to be repeated here. Other authors have also presented accounts of modern polarization sundials.[6,7]

The Northern Equatorial Dial

The polarization dials described above face the northern celestial pole, a 'difficult' direction for the dial of a conventional shadow-based system. Polarization dials are also generally intended to be viewed from *below* the dial plane, in this respect resembling the much-admired stained glass sundials. I therefore decided to attempt to design and make an experimental dial taking the form of a translucent equatorial dial. Lacking any gnomon, time was to be estimated by visual comparison as in Wheatstone's demonstration dial. No great precision was expected so the equation of time was initially ignored, but it could be presented as the usual correction curve.

Arranging the numeration around the circumference is best for clarity and accuracy, and leads to an unoccupied central region that lends itself to any desired decorative motif. However, rather than using coloured glass, the natural polarization of the blue sky could again be used to produce colours by the interference of light. This carries the intriguing possibility of having the colours vary as the plane of polarization rotates about the pole in the course of the day.[5] It has already been mentioned that the intensity of the po-

Fig. 1. Cellophane strip at 45° between crossed polars.

Fig. 2. 1 to 7 superimposed strips of cellophane at 45° between crossed polars.

Fig. 3. As figure 1, but between parallel polars.

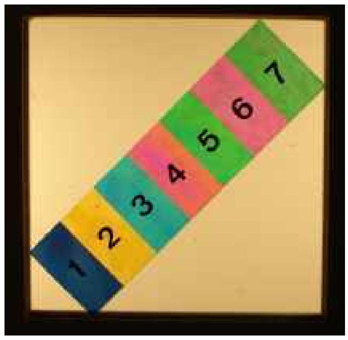


Fig. 4. As figure 2, but between parallel polars.

larized component of the light from the sky is generally considerably less than that of the ordinary unpolarized light, so the resulting interference colours are expected to be less saturated than stained glass or oil paints – more like water-colours.

Another factor to be considered is that in the ordinary sundial the shadow of the gnomon is thrown upon the plane bearing the hour lines and numerals, and has no 'thickness'. Therefore, it does not matter from what direction the dial is viewed: the position of the shadow with respect to the calibration pattern does not change. However, the axis of the polarization sundial is required to point at the celestial pole, so is sensitive to changes in the position of the eye away from a central viewpoint. In the instruments described in references 4 and 5, the eyepoint is located by the eyepiece, but in a 'window-like' design there is no such constraint. It would appear that a locating device (such as a ring supported by a rod or a wire tripod) might be advantageous. This must be investigated experimentally.

Control of Intensity in Polarized Light

Most crystals incorporate a directionality or 'grain' in their structure so that linearly polarized light passing through them moves more easily – and so faster – in one given direction than in another at right angles to it. The emerging orthogonal beams therefore differ in phase.

The transparent film known as 'cellophane' that is used in Sellotape is made from regenerated cellulose and is returning to popularity in packaging because, unlike its competitors, it is biodegradable. Manufacture of cellophane involves stretching, so it shares with crystals a strong directionality ('birefringence') to transmitted polarized light.[8] Faint striae along the stretch direction distinguish cellophane from more modern transparent films. Like the well-known polarizing sheet known as 'Polaroid'[9] it is 'length slow' but, lacking the preferentially absorbing dyestuff incorporated in the latter, beams moving in both orthogonal directions emerge from the film.

Normally these orthogonal beams cannot be distinguished by the eye, but interposing another piece of Polaroid at right angles to the first resolves both components in the plane of this second 'analyzing' Polaroid. If the 'slow' beam has been delayed by half a wavelength of light the net effect is to turn the resolved beam through 90°, so that it now passes through the second, crossed, Polaroid. The effect is at a maximum – and most dramatic – if a strip of the adhesive-coated cellophane known as Sellotape is inserted at 45° between crossed polars: it 'scrapes away the darkness' produced by the crossed polars and appears brightly illuminated against a black background (Fig.1). If the cellophane strip is then slowly turned between the crossed polars the intensity of light it transmits will diminish, until after 45° (then becoming parallel to one of the polars) it will almost disappear. Further rotation increases the transmitted light until after a total movement of 90° it lies along the opposite diagonal and intensity is again at a maximum. This cycle repeats to give maxima every 90°, separated by minima after a further 45°.

Interference Colours in Polarized Light

The word 'wavelength' in the above account is insufficiently defined. Visible light varies in wavelength between 400 nm in the violet to 750 nm in the red, and a single thickness of the 0.001 inch (25.4 μm) cellophane commonly used in adhesive tape acts as a half-wave plate only for a wavelength in the blue. This wavelength (and those nearby) are therefore subtracted, but the remainder of the incident light is transmitted. The Sellotape therefore appears a weak amber colour. Stacking layers of Sellotape or cellophane one on top of the other, all in a common direction, results in more intensive absorptions at a greater number of wavelengths.[10,11] This phenomenon leads to bright colours for a limited number of thicknesses, but gradually they are replaced by an alternation of faded pinks and greens (Fig. 2). The entire range of colours is known as Newton's scale of interference colours[12] and is illustrated by the Michel-Lévy chart.[13] The tint produced by a given number of thicknesses remains the same as the multiple stack is rotated between crossed polars but its intensity always reaches a maximum at 45° where the two components are equal. However, rotating the Polaroids from the ‘crossed’ to the ‘parallel’ orientation gives rise to the complementary colour against an illuminated background (Figs. 3 and 4).

The above phenomenon is related to the colours seen in oil films, soap bubbles and peacocks’ feathers, all being parts of the extensive field of interference colours in white light. Thorough discussion would be much too long for an article such as this; it requires specialist textbooks. Nowadays, only a few physics students (or departments) study optics, so the application of interference colours in polarized light has mostly passed to the mineralogist. The reader seeking a more comprehensive explanation is therefore also referred to textbooks used by geologists.[13,14]

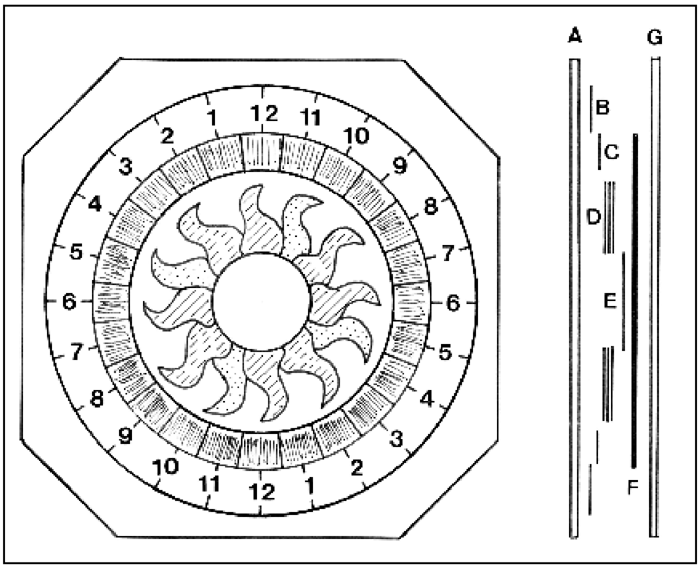


Fig. 5. Construction of the basic polarization dial. The exploded view on the right shows: A: Glass; B: Tracing film; C: Keystones of single thickness tape; D: Multiple layers of tape, all at 45°; E: Crumpled cellophane; F: Polaroid, polarizing in the vertical plane; G: Glass.

A Basic Polarization Dial

A dial intended to face the northern celestial pole and be viewed from the rear is shown in figure 5. The support consists of a 10 inch square of thin glass (nominal 1.5 mm, as used for pictures) with its corners removed. Upon this is mounted an annulus of tracing film secured with spray adhesive, carrying two sets of numerals 1–12. (The rub-down type are very convenient, but must nowadays be obtained from drawing office suppliers.) The dial is designed to be viewed from below, with this working face at the rear, so the numbers progress in an anti-clockwise direction.

Within the hour number annulus is the sundial proper. It consists of 24 keystone-shaped segments cut from 50 mm wide clear parcel tape (I used that retailed by Rylands Ltd) with its length direction arranged radially. This tape is based upon an identical gauge of cellophane to that used for Sellotape but has the considerable advantage over the latter of being waterproof and resistant to long-term oxidation. If the glass plate is first polished with wax polish and then placed over a full-size template, it will be found practicable to stick a length of tape across the centre, cut around opposite segments with a sharp craft knife, and then peel away the unwanted material.

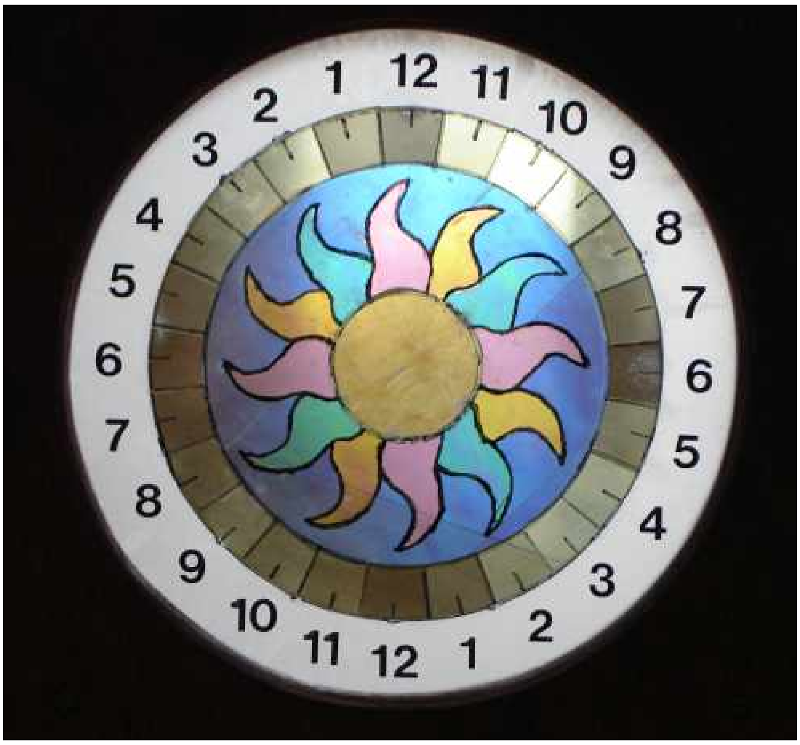
A disc of Polaroid[15] equal in diameter to the outer circumference of these wedges is in due course to be placed on top of the dial, but first hold it on temporarily and check that viewing a blue sky through the assembly gives rise to a ring of keystones of varying intensity. They will be arranged in a 90° cross, reflecting the behaviour described above for a single strip of cellophane. The assembly may be rotated to give the darkest segments opposite the ‘12’s and ‘6’s, and bright segments at the ‘3’s and ‘9’s. This demonstrates the timetelling function of the dial, with the opposing segments acting as a check on each other.

Fig. 6 (far left). Completed dial from the front, in ordinary light.

Fig. 7(left). Completed dial from the rear, in ordinary light.

Fig. 8 (above). Dial viewed indoors by light partially polarized horizontally.

Fig. 9 (right). Close-up of dial in figure 8.



Within the otherwise unused central portion of the disc, I placed artwork activated by the partially polarized light from the sky. I chose a stylized 'Aztec Sun' design, with areas containing up to six superimposed layers of parcel tape arranged at 45° to the horizontal. These multiple layers were found to be best produced by placing one length of tape upon a waxed piece of heavy plate glass, sticking up to five additional layers lengthwise upon it, and then peeling each stack as a whole from the plate. Placing the waxed dial over the pre-drawn design enables a chosen stack to be applied at 45°, cut around, and the surplus peeled away. Some prior experimentation between crossed polars will enable blue, yellow, magenta and green areas to be generated, remembering that in the final model, using only sky polarization on the incoming side, the colours will be much less intense. Complementary colours will appear as the analysing Polaroid is turned from 'crossed' to 'parallel' with respect to the incoming skylight. Cellophane discs that have been crumpled and then roughly flattened will give both colour and structure to the central region – try material from various sources. The junctions between differently-coloured areas may be painted with black household paint to hide the joins and give the impression of a stained glass window.

The dial was completed by fixing the disc of Polaroid on top with a few tiny drops of 'instant' adhesive around its circumference,[16] orienting it with its polarizing direction vertical to give 'crossed' colours at noon and the keystones then indicating the time where they were at minimum intensity – like shadows. A top sheet of glass, with a tape binding around the edge to keep out dust, completes the dial proper, but it should be mounted within a wooden protective frame. It may be convenient to suspend the latter between vertical wood pillars in the manner of an old-fashioned dressing table mirror, and to incorporate an altitude scale plus a magnetic compass and spherical level (Figs. 6 and 7). The polarizing dial may then be set to face north and finally angled upwards so that it faces the northern celestial pole with what was previously called the 'top' sheet of glass now on the underside. Raise and mount the dial while maintaining its orientation, so that it may be conveniently viewed from below.

This construction is obviously unsuitable for continuous exposure outdoors but might perhaps be adapted to a north-facing angled skylight. The long-term stability of Polaroid to sunlight is problematic so it would probably be wise to make the dial conveniently removable.

Appearance of the Dial in Polarized Light

Fig. 8 shows the dial viewed indoors by the partially polarized light reflected from a shiny table top. A measured content of 43% polarization parallel to the intercept of the incoming light with the plane of the table gave a situation comparable to a clear northern blue sky in the UK – but against a comparatively dark background. The outer ring indicates a time of about 12:15 local time (LAT) while the Aztec sun displays an amber disc with red, green and yellow rays against a blue sky (Fig. 9). This photograph may be compared with Fig. 10, where we are viewing the dial at noon against the blue sky. With a content of 33% horizontally polarized light, the colours are much less saturated.

Fig. 11 illustrates the situation three hours later, at 3pm LAT. As the polarization vector has moved through 45° it

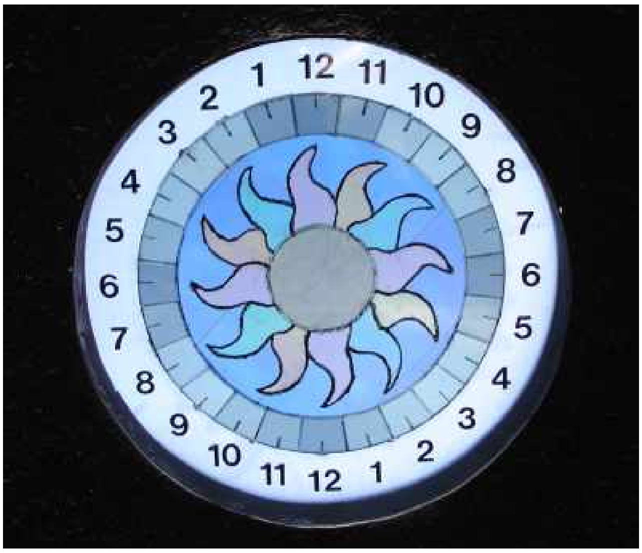


Fig. 10. Dial viewed outdoors at 12:15pm local time against the partially polarized light from a blue sky.

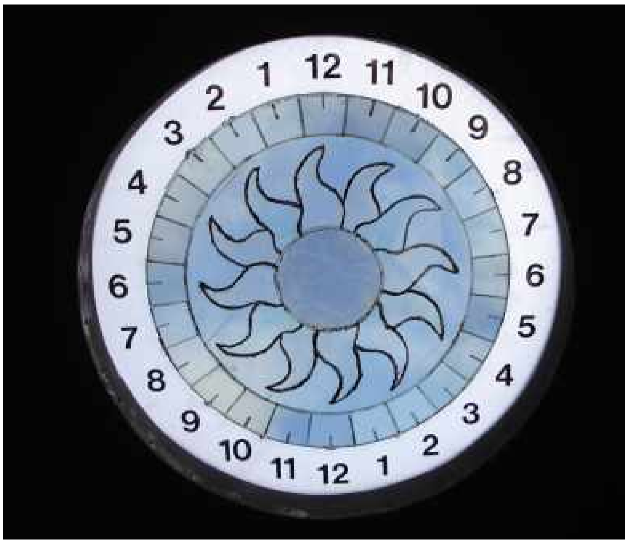


Fig. 11. View through the dial at 3pm local time.

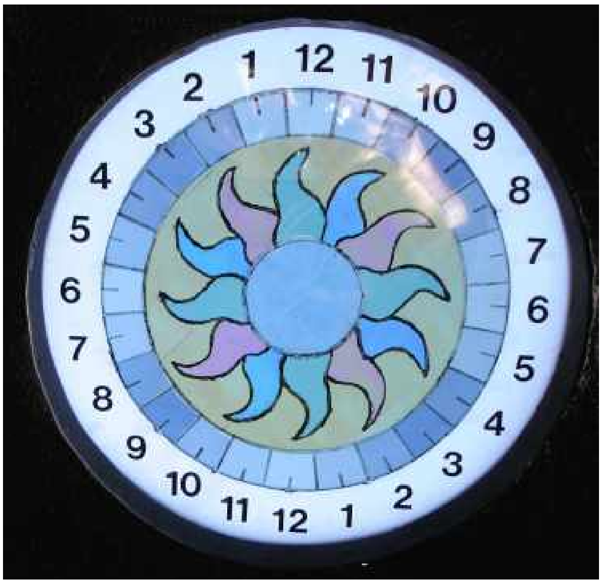


Fig. 12. View through the dial at 6pm local time.

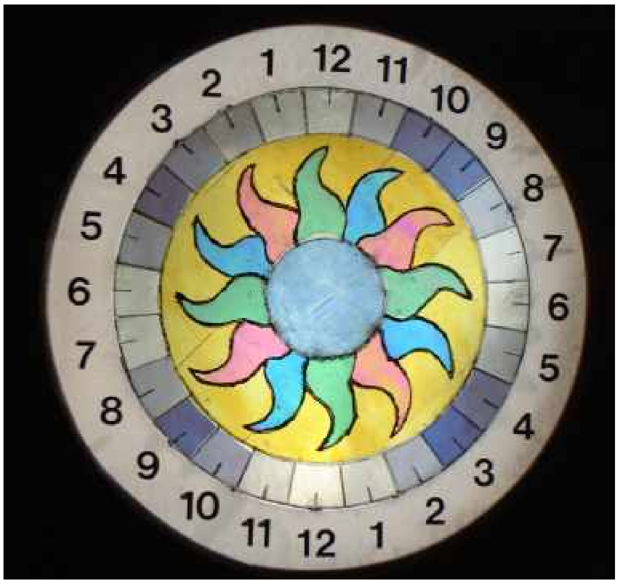


Fig. 13. Dial illuminated by light partially polarized in a vertical plane, indoors.

is now parallel to the axis of the cellophane design and we see very little colour against the blue sky. Compare Figs. 6 and 7, taken in ordinary unpolarized light.

Fig. 12 shows the result when at 6pm LAT the skylight is polarized vertically, parallel with the analyzing Polaroid. We see the complementary colours to the noon appearance. These colours are more intense in the polarized light reflected from a polished – and comparatively dark – table (Fig. 13).

Other Observations

(i) Observation of the ring of wedge-shaped segments gives a poor assessment of the time when the dominant eye is not obliged to look through a ring positioned around the axis aligned to the northern celestial pole.

(ii) The polarization of skylight proved to be low and/or anomalous towards the horizon,[2] resulting in poor performance by the dial. This would be the direction viewed by a vertical north-facing dial, so there appears to be little point in making such a thing.

Conclusions

The polarizing sundial might make an intriguing novelty for a sloping skylight that happened to face the celestial pole but, as a timeteller, it is no rival to the shadow dial with a conventional gnomon.

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3a. see page 14 of this issue.

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11. Jearl Walker: 'More about polarizers and how to use them, particularly for studying polarized sky light', *Scientific American,* **238,** pp.132-36 (Jan 1978).
12. 'Newton's scale of interference colours'. This name is used in all textbooks but is rather inappropriate because Newton could never have seen the phenomenon generated in polarized light and could not have accounted for it by his favoured corpuscular theory of light. What he did describe (*Opticks* Book II, Part I, 1704) were the coloured circular interference fringes that appear beneath a long-focus convex lens resting upon a plane glass support when the combination is viewed in white light. It appears that David Brewster (*A Treatise On Optics*, pp.103-4, 1831) was the first to apply this anomalous title to the related phenomena seen in polarized light, probably being influenced by his great admiration for Newton.
13. C D Gribble & A J Hall: *Optical Mineralogy: Principles and Practice* UCL Press, pp.215-231 (2001). A Michel-Lévy chart is reproduced in colour on the back cover. See also 'Michel-Lévy chart' on Google, especially the excellent explanatory text by J G Delly.
14. P Gay: *An Introduction to Crystal Optics,* Longmans, (1967). Ch. 9 and Appendix B.
15. Available from Edmund Optics (Europe) Ltd, Tudor House, Lysander Close, York YO30 4XB. e-mail for a catalogue and prices (including p&p and VAT) to *uksales@edmundoptics.co.uk.*
16. This was a mistake – cyanoacrylate evolves vapours leading to an unsightly white deposit around the point of application. Better to use tiny spots of old-fashioned cellulose acetate adhesive ('balsa cement').

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