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A linear differentiating refractometer

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Abstract. A new version of the linear critical-angle refractometer for liquids is described: a 1728 element linear CCD array is used to scan the intensity profile of the output image, within which the position of a cut-off edge is a linear function of refractive index. The precision in locating this cut-off edge is greatly increased, especially for milky liquids, by differentiating the intensity profile numerically. Further information about complex particulate liquids is found to be given by the shape of the differentiated profile, and alternative internal and external illumination modes are provided which may give more information; the interpretation will be discussed in a later paper. The present instrument covers the refractive index range 1.3000 to 1.4700, with an accuracy of ±0.0001 for transparent liquids. The light source is an LED at 635 nm. The intensity profile, the differentiated intensity profile, and the refractive index value are all computed, displayed and printed by a desk-top computer.

1. Introduction

The linear critical-angle refractometer has been described in several possible versions by Geake (1969, 1970, 1975) and Geake and Smalley (1983). These were all visual instruments, and the position of the cut-off edge, which indicates the refractive index was read against a graticule. We have now added an electronic readout based on a charge coupled device (CCD) array; this permits the intensity profile to be displayed on a video monitor. The position of the cut-off edge can then be measured electronically, to give the value of the refractive index. However, it can be measured to a higher precision by differentiating the intensity profile and measuring the position of the peak, which is found to occur very close to the true position of the cut-off edge, as explained later.

The significance of differentiating the intensity profile in order to increase the accuracy was appreciated in our earlier work, but this was not relevant to the visual instruments, except that it was realized that the cut-off edge looked sharper to the eye than appeared to be justified by the shape of the intensity profile, and this was ascribed to the fact that the eye tends to differentiate. Over the last few years we have developed versions of the instrument with an electronic read out, and have found that differentiation increases the accuracy, even for clear liquids, but especially for milky ones. Furthermore, we have found that differentiation permits measurements to be made for some milky liquids that could not be measured with visual refractometers, or with commercial electronic refractometers not using differentiation.

However, we have now found that there is an additional advantage in differentiation, as the shape of the differentiated peak appears to contain useful information about the nature of complex milky or particulate liquids. This too is displayed in the present instrument, and examples are shown in figure 6. Furthermore, we find that additional information may be given by using two alternative illumination modes: one LED illuminates the active face from inside, giving the reflection mode, and the second alternative LED illuminates it from outside, giving the transmission mode. The interpretation of the profile shapes, and the type of information thus obtained, will be discussed in a later paper.

The aim of the present paper is to describe the basic instrument in its different modes of operation. In the present version of the instrument the intensity and first differential profiles, and the refractive index value, are all computed, displayed and printed by a desk-top computer, using software on disk.

An instrument similar in principle, but quite different in construction, has been developed for a space application (Geake and Mill 1992). It is to be carried by the Cassini spacecraft in the Huygens probe, which will land on the proposedly liquid surface of Titan. However, the present paper describes the version for general laboratory use.

2. Optical principle

The principle and optical properties of the linear critical-angle refractometer (LCAR) are discussed elsewhere

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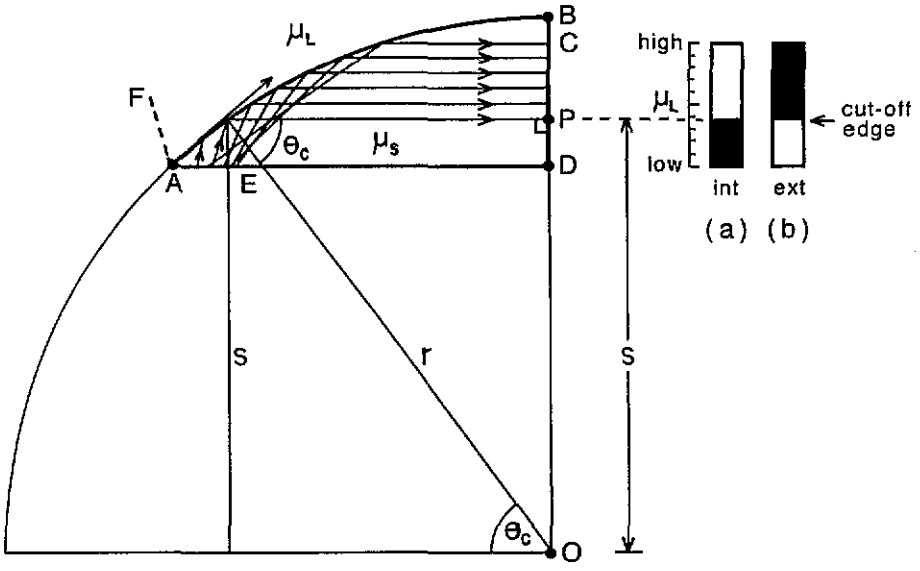

Figure 1. Optical principle. Output image with (*a*) internal and (*b*) external illumination.

(Geake 1970, 1975). It is very simple, with a single glass prism and no lenses, and it has a linear scale of refractive index. The principle is summarized here in figure 1. If a liquid of refractive index μ_L is in contact with the convex cylindrical surface AB of the transparent prism ABD of refractive index μ_s, then the view in through surface BD is as shown in figure 1(*a*). One sees an extended light source, placed along AE, by total internal reflection in AB, but the angle of the reflected rays to the normal progressively decreases across the field from C to D, and reflection ceases when this angle reaches the critical angle θ_c, given by $\sin\theta_c = \mu_L/\mu_s$. A cut-off edge is therefore seen, and its position is given by: $s = r\sin\theta_c = (r/\mu_s)\mu_L = (\text{constant})\mu_L$, giving the instrument its linear scale of refractive index.

So far, only exit rays normal to BD have been considered, whereas the eye will collect light over a range of angles. However, detailed analysis (Geake 1970) shows that the normal ray still defines the position of the cut-off edge, and that the simple theory is therefore valid. Furthermore, the location in space of the cut-off edge is determined by the place where the skew rays, having each been reflected at the critical angle to the surface normal, appear to cross. The analysis shows that although there is no single point where they cross, their spread is least near to the plane BD, called the 'normal radius plane', and this crossing of the rays constitutes a real image of the cut-off edge, without the use of a lens. With a visual instrument, the graticule should therefore be placed in this plane to be seen in 'no parallax' with the cut-off edge, and in the present photoelectric instrument a CCD array is placed in this plane. Furthermore, it is found that if the normal ray crosses the plane BD at P, then the skew rays, although not crossing exactly at P, all cross above P. The normal ray through P thus still defines the position of the cut-off edge, and this is why the simple theory demonstrating the linearity of the instrument is still valid. Also, all the rays crossing above P fall in the already bright part of the image, and do not therefore affect the sharpness of the cut-off edge. The instrument is therefore aberration-free, in the limited sense that the skew rays do not affect the accuracy to which the cut-off edge can be located.

This reflection mode of operation, with the active face AB illuminated from inside by an extended source along AE, is found to work well with a visual instrument in clear liquids, giving a sharp aberration-free cut-off edge. However, the dark part of the image (below P in figure 1(*a*)) only occurs because light has been transmitted into the liquid instead of being internally reflected at the prism face. If the liquid contains scattering material, then some of this light may be scattered back in again, which reduces the image contrast, and makes such an instrument difficult or impossible to read visually with a milky liquid. However, the present photoelectric instrument can still make useful measurements, as discussed later.

The alternative transmission mode of operation uses an external extended source AF. This has the effect of reversing the image light-for-dark, as shown in figure 1(*b*), but it still gives a cut-off edge at the same place, P. As all the light is now coming from outside the active face AB, the fact that some light is also being scattered in by the liquid makes no difference to the contrast, and a high-contrast cut-off edge is obtained, even in a milky liquid.

The disadvantage of the external illumination mode is that it is not aberration-free: the skew rays still cross BD above P, but they now fall in the dark part of the image, and do affect the profile of the cut-off edge. This effect can be minimized by some form of collimation, for example by the use of an eye-piece slit as in the visual version of this refractometer (Geake and Smalley 1983). Collimation is possible but more difficult to arrange when a photodetector is used. However, the aberration rays are not uniformly distributed, and the

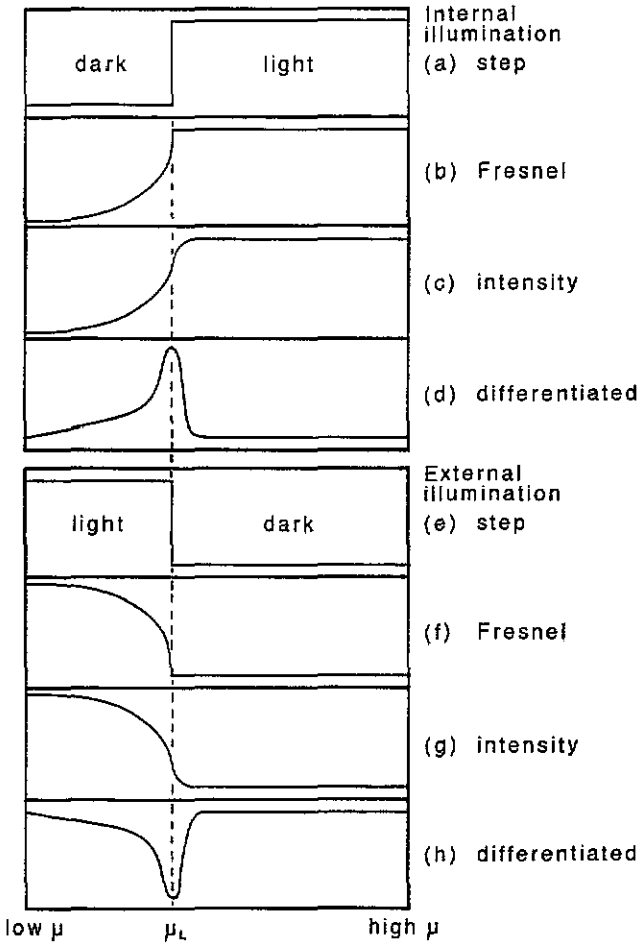

Figure 2. Image profiles.

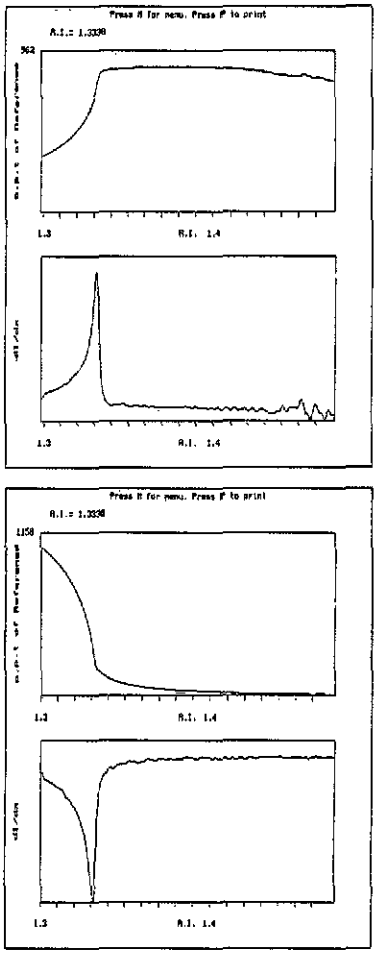

Figure 3. Computer printouts of the image intensity profile and its first differential, for water, with: (a) internal and (b) external illumination.

intensity reduces with distance from the cut-off edge, so their effect is simply to change the intensity profile as the light falls off into the dark region; it is still the case that the position of the true cut-off edge is at the point where the intensity is changing most rapidly, so differentiation removes the need for collimation.

The essential feature of the present instrument is that the intensity profile is differentiated numerically, and a sharp peak is found to occur very close to the position of the true cut-off edge; its position then constitutes the output signal, giving the value of the refractive index. The reason for this is illustrated in figure 2.

Figure 2(*a*) shows the idealized step-function intensity profile of the image for the internally illuminated reflection mode, as shown in figure 1(*a*). What is found in practice, even for clear liquids, is far from this ideal shape, and is more as shown in figure 2(*c*). Several factors combine to produce this shape: Fresnel's equation, as plotted in figure 2(*b*), explains the more gradual fall-off into the dark region. Other factors have the effect of rounding the corner at the cut-off edge—these include a finite value of the imaginary component of the complex refractive index (see Meeten *et al* (1984)), surface imperfections or contamination, and the aberration rays as discussed above. However, it is found that the true position of the cut-off edge is very close to the point of maximum gradient, which is the peak of the differentiated profile as shown in figure 2(*d*). This arises because the gradient of the Fresnel curve in figure 2(*b*) is infinite at the cut-off edge (see Geake (1970)), and this dominates the other factors that combine to degrade the sharpness of the cut-off edge. The position of the resulting peak in the differentiated profile therefore gives the numerical value of the real component of the refractive index, which is computed and displayed.

With milky liquids, where it is difficult or impossible to make visual measurements in the internal illumination mode, it is found that useful measurements can still be made with the present instrument, by using differentiation. Although the image is then of very low contrast, the differentiated peak, enhanced by auto-scaling, still occurs at the position of the cut-off edge.

In the externally illuminated transmission mode, the step-function image is reversed light-for-dark as in figure 1(*b*), with a profile as in figure 2(*e*); its actual profile tends to be as shown in figure 2(*g*), with a differentiated profile as in figure 2(*h*).

Figure 3 shows actual printouts from the instrument: the intensity and differentiated profiles are shown, for water, with internal and external illumination. It is notable that for clear liquids the peak positions in the two modes are found to be the same, to within about ±0.0002. This tends to validate, to this precision, the supposition that, at least for clear liquids, the position of the true cut-off edge is indeed at the point of maximum

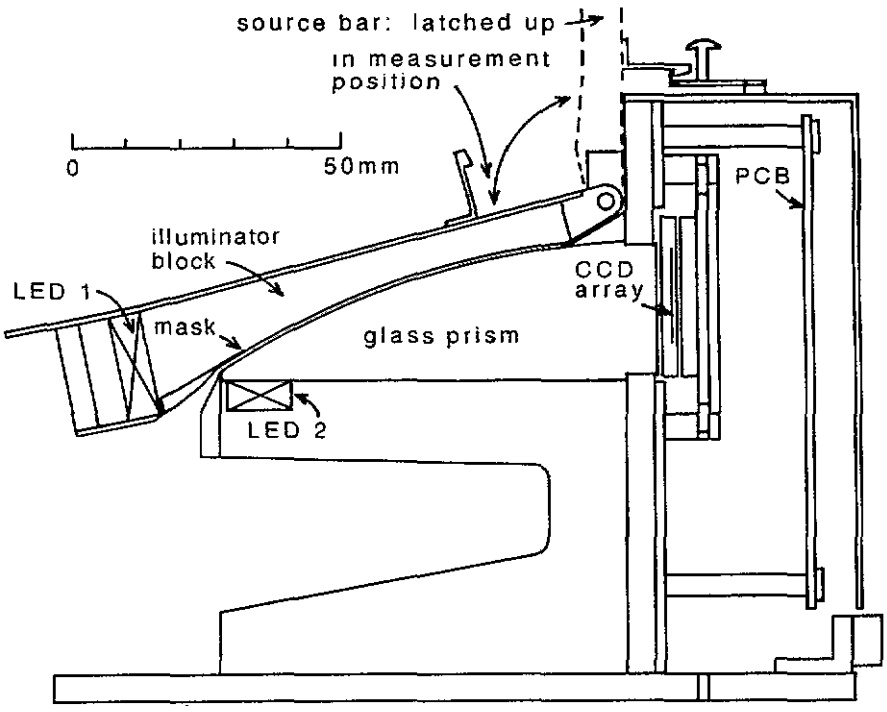

Figure 4. Construction of refractometer.

slope of the intensity profile. This small residual difference between modes is in any case removed by the auto-calibration process described below, as this is carried out for each mode separately; this is why the refractive index values for the two modes as shown in figure 3 are identical. For milky liquids, the peak positions in the two modes may differ, and this, together with the shapes of the peaks, may contain information about the liquid.

It is perhaps surprising, from the appearance of these intensity profiles, that they do each contain such a sharp gradient peak, the position of which is found to be reproducible to within one pixel, or 0.0001 in refractive index, i.e. one hundredth of a division in figure 3. In order to achieve gradient peaks as sharp as these it is necessary in the design to take great care with masking to reduce internal stray light, as described later. It is also important to keep the prism clean. While peak sharpness has only a minor effect on the measured value of the refractive index, it does affect the uncertainty. Furthermore, if the shape of the peak for a complex liquid is to be interpreted in terms of its properties, it is then essential for the peak shape for a clear liquid to be as sharp as possible. The fact that this instrument is linear in refractive index also simplifies the interpretation.

3. Optical and mechanical construction

The construction of the instrument is shown in figure 4, and the main structure is of Dural. The prism is of borosilicate crown glass of refractive index 1.5172 (at 589.3 nm and 20 °C), and it was made for us by SIRA Precision Ltd.

The detector is a linear CCD array, mounted in a vertically adjustable slide just clear of the vertical end face of the prism. The array has 1728 elements at 10 μm centres. The prism radius determines the refractive index scale factor, and this is chosen so as to make each element of the detector correspond to a refractive index increment of 0.0001; 1700 of the elements are used to cover the nominal refractive index range of 1.3000 to 1.4700. Vertical adjustment of the array position by ± 1 mm permits this range to be shifted by ± 0.01 in refractive index. The array is attached to a vertical printed circuit board which carries the array control and scanning electronics. A single 11-way cable leads to an external power unit and to a desk-top computer, where all the signal processing is carried out by specially prepared software, as described in section 4.

3.1. Illumination modes

There are two alternative operating modes: the transmission mode uses a light source external to the cylindrical active face of the prism, and the reflection mode uses a separate light source to illuminate the active face from inside.

In the transmission mode with external illumination, light at 635 nm is provided by an extended light emitting diode (LED 1 in figure 4) which is attached to the end face of a hinged transparent plastic illuminator block, which is shaped to fit against the cylindrical upper face of the glass prism. This source bar may be latched out of the way in a vertical position, or allowed to rest on the prism so as to trap a thin film of the liquid sample, which is so thin that it is thus possible to make measurements in transmission mode even with opaque

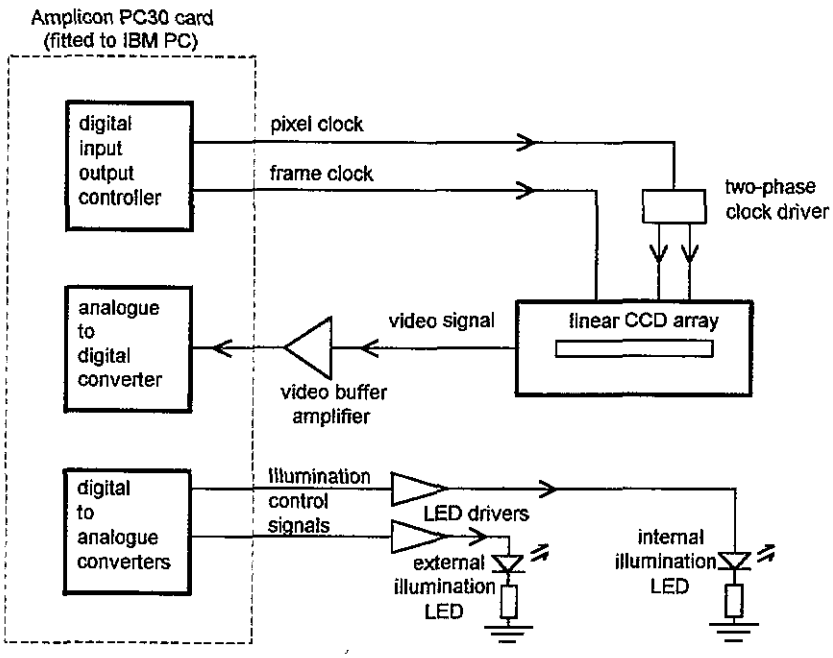

Figure 5. Electronic system.

liquids. The measurement is initiated from the computer keyboard, following an on-screen menu. The intensity and differentiated profiles, and the refractive index value, duly appear on the screen, and may be printed by a screen-dump routine.

In the reflection mode, with internal illumination, light from LED 2, placed below the tip of the prism, illuminates the active face from inside. In this mode, the sample may either be placed between the illuminator block and the prism, as before, or alternatively, the prism may be dipped in the liquid. For this purpose, two detachable supporting legs are provided which allow the instrument to be placed with its prism vertical and immersed in the liquid in a beaker. The source bar is then unused, and must be parked in its latched position. Stray room light is reduced by surrounding the beaker with an opaque cylindrical light shield.

As indicated earlier, careful masking is needed to reduce internal stray light. Uniform scattered light does not matter much—it reduces the image contrast, but has little effect on the differentiated profile. This is indeed one of the advantages of using differentiation, as it also makes the instrument relatively insensitive to external interference.

The main problem arises with stray light that is strong and non-uniform, such as unwanted reflected rays. The most serious case occurs in the external illumination mode: it is possible for rays from the external LED to be refracted into the prism, and then reflected and scattered towards the detector from the front face of the (unlit) internal LED, and from the prism face above it. This is the only part of the lower prism face that cannot be blacked out, as it must be left clear to act as a window above the internal LED; the only solution is therefore to prevent these rays from reaching this area. This is achieved by the mask shown in figure 4, which extends just far enough to block these rays, while passing the rays required for external illumination at the lower end of the refractive index range. Without this mask, the instrument is unusable in the external illumination mode.

In the internal illumination mode, a source of unwanted light is that which may be internally reflected from the prism face near to its tip, and also scattered from any deposit on its face in this area. This is prevented by painting the prism surface black as far as the edge of the mask on the illuminator block. Epoxy resin paint is used, which is durable enough to withstand thorough cleaning of the prism.

Another potential source of scattered light with a clear sample is light from the internal LED that may be refracted out of the prism and then scattered back in again from the rough upper face of the illuminator block. This has only a minor effect, as it is nearly uniform, but it is nevertheless minimized by painting this face matt black.

4. Electronic system and software

The electronic system is shown schematically in figure 5. The detector is a Thompson type TH7803 CCD array. It consists of a single row of 1728 silicon photodiodes at 10 μm pitch and of width 13 μm. The array elements are scanned in sequence, and the readout is controlled by two clock signals—the pixel clock and the frame clock. Scanning is initiated by a high logic level on the frame clock, and the signal level for each successive pixel is then obtained from the array by toggling the pixel clock.

The controlling clock signals are software generated, and are transmitted to the array via an Amplicon PC30 interface card; this also provides the required analogue-to-digital and digital-to-analogue conversion facilities.

The signal levels are digitized with 12-bit resolution, with a conversion time of 15 μs.

4.1. Software features

The software is implemented on an IBM PC compatible desk-top computer, and is written in Borland Turbo Pascal version 6. It performs the following processes.

4.1.1. Refractive index measurement. The refractive index is determined from the position of the cut-off edge in the intensity profile, which is the point of maximum spatial gradient. This operation is performed numerically on the digitized intensity profile. The following processes maximize the accuracy and reliability of the determination.

4.1.2. Illumination control. The illumination levels in both internal and external illumination modes are under software control. In order to minimize the effects of dark current leakage and quantization errors, the illumination level is adjusted until the maximum array signal is between 80% and 90% of the saturation level.

4.1.3. Dark leakage correction. Immediately prior to each scan with the illumination on, a dark reference scan is performed. This has the same timing characteristics as the illuminated scan, but is carried out with both LEDs off. This gives a zero reference level for each pixel, which is stored and subtracted from the signal for that pixel during the illuminated scan. It compensates for differences between the elements in both dark leakage and external stray light.

4.1.4. Sensitivity compensation. In practice, the detector elements do not have exactly equal sensitivities, and the effect of differentiation is to magnify these small differences greatly, giving an unacceptable noise level. In the internal illumination mode, compensation may be achieved by carrying out a 'dry' scan, with no sample in place. In the absence of a sample, the image field should ideally be uniformly illuminated: signal variations from element to element, after dark correction, are therefore due to sensitivity differences, combined with any non-uniformity of illumination. The signal value for each element, after subtraction of its dark value, is therefore stored, and these values are used as gain-correction factors for subsequent scans with a sample in place. The resulting corrected intensity profile is then relatively clean, and almost uniform to the right of the cut-off edge, as shown in figure 3.

In the external illumination mode, the 'dry' scan cannot be used for compensation. Although the inter-element sensitivity differences will be the same, as the same array is used, the non-uniformity of the illumination will not be the same, as this mode uses a different LED and different ray geometry. In this case too, a compensation scan is needed for which the whole image field is illuminated, but in this mode it must be carried out with a sample liquid in place, with a refractive index higher than the top of the range of the instrument. Convenient and innocuous liquids are glycerol (μ = 1.473) or olive oil (1.480). This compensating scan is stored, and used as before.

These compensating scans are retained in memory, even when the instrument and the computer are switched off, and they are used automatically for all subsequent measurement scans, until they are next updated. This can be done infrequently, as the instrument is very stable, and it is probably only necessary after mechanical disturbance.

4.1.5. Refractive index calibration. Calibration is a simple process because the instrument is linear in refractive index, so any correction factor needed is purely additive. At the start of each measurement session, the operator is prompted to use a test liquid of known refractive index as a sample, and to key in this value. The default option is with distilled water as the calibration liquid, and its refractive index is already stored as 1.3330. The operating program then calculates any correcting factor required. This is stored, and applied to all subsequent measurements, until the next calibration check—even if the instrument and the computer are turned off between measurements. This calibration is carried out separately for internal and external illumination modes, although the difference between the two modes is very small, as noted earlier.

5. Accuracy

The accuracy of the refractive index measurement, as distinct from its reproducibility, is established by the auto-calibration process. After the refractive index of the calibration liquid, usually distilled water, has been measured and its known value entered, all subsequent measurements use this as a datum. The accuracy at other points on the scale then depends on the linearity, which is an inherent property of the instrument, on the constancy of any off-set of the differentiated peak from the true cut-off edge, and on the distance of the measured refractive index from that of the calibration liquid, together with the scale factor. The scale factor in turn depends on the accuracy of the radius of curvature of the prism, in relation to the refractive index of the prism material. Tests in comparison with a conventional Abbe refractometer show that the error for this prototype varies from nil for a refractive index near to that of the calibration liquid, to about $\pm$0.0002 when they are almost the full range apart, and this probably indicates the size of the error in the scale factor. Even this residual error could, of course, be removed by a correction factor stored in the software. To increase the accuracy in the upper part of the range, calibration liquids of higher refractive index may be used, such as isopropyl alcohol (μ = 1.3700) and carbon tetrachloride (μ = 1.4607).

In measuring the refractive index to this accuracy, it is of course necessary to take account of the temperature. In this prototype instrument there is no provision for

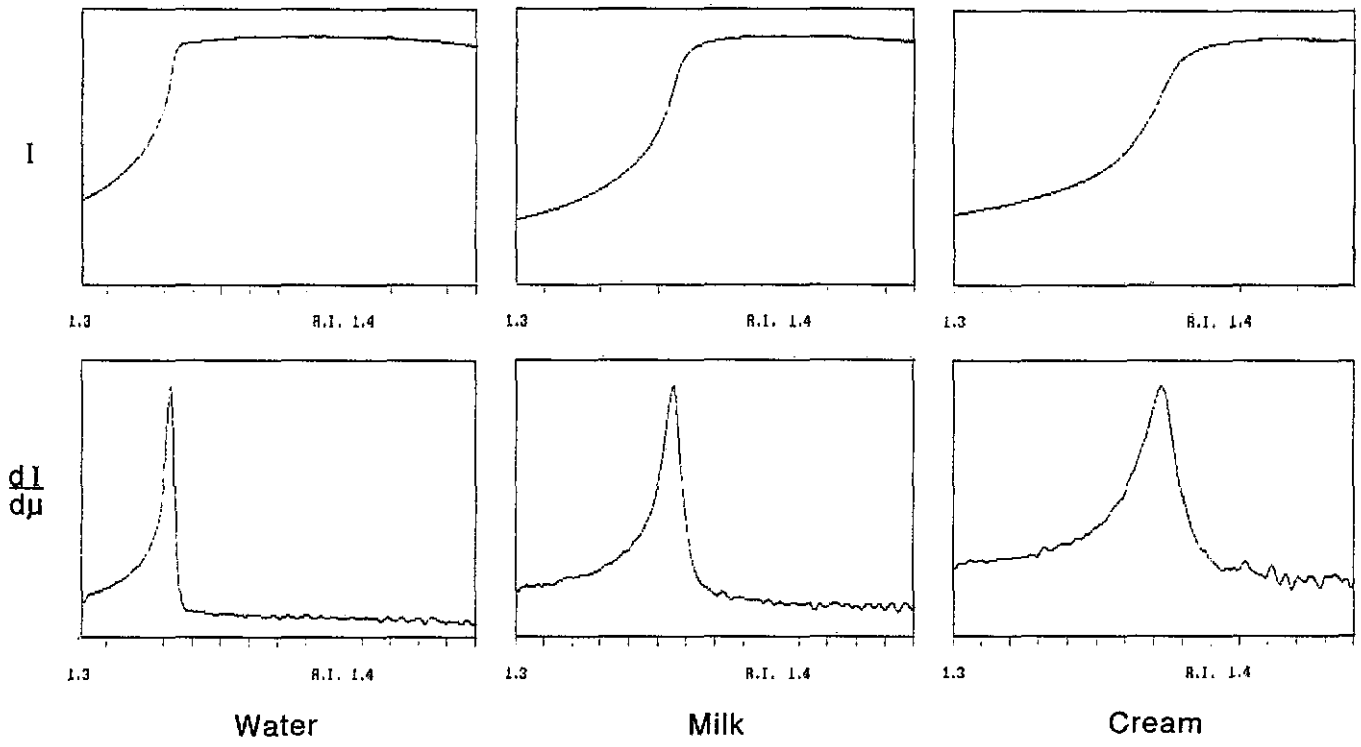

Figure 6. Computer printouts of the image intensity profile and its first differential, in the internal illumination mode, for water, milk and cream (see table 1).

controlling the temperature, and for our present purposes it is sufficient to measure the ambient temperature at the instrument. As the sample is a thin film, it rapidly attains the prism temperature without changing it significantly. Typically, a temperature change of a few tenths of a degree *celcius* changes the refractive index of a liquid by 0.0001, which is equal to the tolerance of the instrument. However, if the instrument is calibrated with, say, water, it is only the difference between the temperature coefficient for water and that for the sample liquid that applies.

Another factor to consider is the wavelength at which the measurements are made. The LEDs used have a peak output at 635 nm and a half-intensity width of 40 nm; for most clear liquids, the difference from measurements conventionally made at the NaD wavelength of 589.3 nm is insignificant to the fourth decimal place. In any case, it is only the difference between the dispersion for water as the calibration liquid, and that for the sample liquid, that applies. For particulate liquids, the wavelength effect is more significant than it is for clear liquids, as the particle size in relation to the wavelength is an important parameter affecting the refractive index. Indeed, a proposed development of this instrument is to replace the LEDs by light from a monochromator, enabling the wavelength to be varied over a wide range.

6. Operation

The instrument may be used with the illumination external or internal to the prism face, depending on which LED is activated, and this choice is offered on the menu. At the start of each measurement session, the surfaces of the prism and the illuminator block should be cleaned, and the calibration procedure described in the last section should be carried out for each mode. The measurement is then initiated by the following menu.

6.1. External illumination

In transmission mode, with external illumination, the source bar is raised to the vertical position and latched, and a few drops of liquid are placed on the prism face. The source bar is then lowered and allowed to rest on the prism, so as to spread the liquid out into a film covering the prism face. The operator then follows the menu, to take the reading, to display the intensity and differentiated profiles and the refractive index value on the screen, to store these results, and to print them. The source bar and prism faces should be cleaned between samples, with detergent solution or isopropyl alcohol.

6.2. Internal illumination

In reflection mode, with internal illumination, the sample may be inserted as above, and the appropriate menu sequence followed. Alternatively, the instrument may be dipped in the liquid in a beaker. In this mode, the source bar is raised and latched, and the two supporting legs are removed from their parking places and screwed into the holes provided. The instrument is then turned on its end and placed with the prism vertical and immersed in the liquid in a beaker. The beaker is surrounded by a cylindrical screen to shield it from ambient light.

Table 1. Comparison of refractometers: refractive index measurement of milky liquids.

Liquid	Refractometer		
	Abbe[1] visual	Index[2] electronic	Our instrument electronic differentiating
Distilled water	1.333	1.3330	(1.3330)[3]
UHT full fat milk homogenised (Country Range)	1.356–8[4]	1.3556 ± 0.0001	1.3560 ± 0.000 05
UHT cream homogenised (Cuisine)	no discernible cut-off edge	'unable to read'[5]	1.3703 ± 0.000 05

[1] Hilger and Watts Ltd (using white light, corrected to NaD).
[2] Index Instrument Automatic Refractometer model GPR 11-37 (using NaD light).
[3] As set during calibration with distilled water.
[4] Difficult to read because of the diffuse cut-off edge.
[5] *The response when no cut-off edge can be detected.*

6.3. Choice of modes

When a simple measurement of refractive index is required, either the internal or the external illumination mode may be used as described above, and only a few drops of sample are needed. The internal illumination mode must be used if it is required to dip the instrument into a body of liquid. For a simple measurement there is also no need to display and print the intensity and differentiated profiles, although they may be useful in explaining anomalous results.

With complex liquids, such as suspensions and emulsions, and where more than just the simple refractive index value is required, it is necessary to display the intensity and differentiated profiles. Again, either illumination mode may be used, but at present we are obtaining better results with internal illumination, for reasons that we are currently investigating. The reason why both illumination modes are provided in this prototype instrument is so that its properties can be explored, and because we have some evidence that with complex liquids the differential peak shape is slightly different in the two modes. We are not yet sure whether this is an instrumental artifact, or whether it is giving additional information about the liquid—this is one of the subjects of our continuing study.

7. Results for milky liquids

Examples of the output profiles obtained with milky liquids are shown in figure 6. The difference in the width of the first differential peak between water, milk and cream can be clearly seen, and the interpretation of this is the subject of our continued study. The display and interpretation of the peak shape are greatly simplified by the fact that this instrument has a linear scale of refractive index.

Table 1 lists the refractive index values obtained from these profiles, in comparison with those measured on two commercial refractometers—one a visual Abbe instrument, and the other an electronic refractometer. All three instruments can make measurements with milk, although it is difficult with the Abbe visual refractometer, and the precision is low. However, for cream, with its high content of fat globules, our instrument is the only one that can make a measurement. The Abbe visual instrument shows no discernible cut-off edge, and the other electronic instrument, which does not use differentiation, gives the response 'unable to read', which means that it too cannot detect a cut-off edge. The fact that our instrument can make a measurement shows the power of the differentiation technique.

Each of the values shown is the mean of ten readings with the same sample, and the standard deviation is given in each case. With our instrument, the calculated standard deviation in the mean for ten readings with the same sample was ±0.000 04 for both milk and cream; we have rounded this up to ±0.000 05, i.e. to the nearest pixel, or 0.0001 in refractive index. This very small spread with the same sample, even for milk and cream, is a measure of the stability of the data processing operation. However, bigger differences may occur between different samples of the same liquid. This is another matter that we are currently investigating—to find out whether these differences are due to the way the sample is loaded, or to inherent variations in an inhomogeneous liquid. The differences between the values for milk for the two electronic instruments may be partly due to the different instrumental criteria used to locate the cut-off edge; in our view the position of the first differential peak is the most valid.

8. Conclusions and further study

We conclude that the refractometer described here in prototype form is capable of routine measurements of refractive index, to an accuracy of about ±0.0001. It requires only a few drops of sample, is simple and rugged, relatively insensitive to outside interference and, given an existing PC, the refractometer itself is very

compact; with its software on disk, it can be attached to any PC that is fitted with a suitable analogue-to-digital conversion card. In addition, for complex liquids such as emulsions and mixtures, further information, yet to be interpreted, is given by the shape of the first differential peak. It is capable of measuring liquids such as cream, which visual refractometers and electronic instruments not using differentiation are unable to measure. To make the present prototype into a fully operational instrument, some form of temperature control would be necessary.

Several aspects of the performance of the instrument and of the interpretation of the results are the subjects of our continuing study, and of a further paper in preparation (Mohammadi *et al* 1994). These include the interpretation of the differential peak shape for complex liquids and dispersions, and whether there are differences in shape, as distinct from width; also, whether any difference in the shape for the two illumination modes is really giving further information about the liquid, or whether it is just an instrumental artifact. The question as to whether differences between the refractive index values for different samples of the same liquid are due entirely to real inhomogeneities in the liquid, or whether they are partly due to differences in the loading of the sample, is also being investigated.

Acknowledgments

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