

**PRACTICAL APPLICATION
FOR
MEASURING GEMSTONE DISPERSION ON THE REFRACTOMETER
Using the C - F solar spectral interval**

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EXTENDED ABSTRACT

This paper will discuss techniques developed while researching practical aspects for determining the apparent and true dispersion of gemstones using a gemmological refractometer. Each gemstone has a distinct dispersion, since dispersion is a property related to a variation in refractive index with a change in wavelength.

Low-dispersion barium glass yields a colourless refractometer glass that allows measurement of refractive index in deep blue light below 500 nm when used in association with the hemisphere or hemicylinder prism refractometer to which the wide field eyepiece of the Eickhorst SR/XS refractometer has been attached. The Eickhorst refractometer, with a visually expanded scale, is the preferred instrument for measuring dispersion because apparent refractive index can be measured at wavelengths other than that of the standard sodium emission light source at 589.3 nm. Accuracy, not available on sixty-degree exit prism refractometers, is available for refractive index determinations at many wavelengths not previously available on refractometers.

The choice of lighting techniques can improve the accuracy of refractive index determinations when used in association with appropriate sources of narrow bandwidth blue 486 nm and red 656 nm wavelengths. These measuring techniques, when combined with extrapolation of a RI-wavelength dispersion curve using Sellmeier's linear conversion, permits the extrapolation of refractive indices at B (686.7 nm) and G (430.7 nm) wavelengths and allows comparisons of these data with values previously published in the gemmological literature

This research suggests that existing B to G lists for the dispersions of gemstones leave much to be desired with respect to their accuracy. Dispersion at B-G interval was rarely measured. It was extrapolated by various techniques that provide conflicting data. The B-G interval for the measurement of dispersion that was adopted by gemmology produced a larger value, but this is of no practical use to gemmologists.

A new list of values for the dispersions of gemstones, measured at the C-F (656.3 - 486.1 nm) interval with the assistance of the gem refractometer, is presented in table 3 of this paper.

Measurements of dispersion, with the gemmologist's refractometer, produces apparent dispersion. However, a means of converting this to true dispersion, after extrapolation, can be achieved by Suhner's technique of subtracting apparent dispersion from the sum of true plus apparent dispersions.

INTRODUCTION

(A summary of two previously published papers)

D.B.Hoover and T. Linton published a paper titled 'Dispersion measurement with a gemmologist's refractometer' in two parts in *The Australian Gemmologist*, volume 20, number 12 (2000), and volume 21, number 4 (2001).

In this paper the author's reviewed the available literature and described development of a technique that can be used to measure dispersion over the C to F interval which then can be extrapolated to B to G interval.

SUMMARY OF HOOVER & LINTON DISPERSION PAPER

This brief summary of the Hoover & Linton papers of 2000 and 2001 paper will give the basis for research that is subsequently reported in this paper.

In their paper, the authors explained the operational principles of and how construction of the two main types of gemmological refractometers limited their use to a single type for measuring dispersion with the refractometer. Furthermore, the authors showed that the popular 60 degree prism type of refractometer could not be used to measure true dispersion. Instead, only hemicylinder or hemispherical type instruments were shown to be suitable for measuring true dispersion.

Due to the increased visibility of the contrasting shadow edge and/or a bright line achieved at each critical angle, grazing incidence illumination at the refractometer glass- gemstone interface was shown to provide improved accuracy for determination of refractive index. The visibility of bright line images was controlled by positioning the head of the observer so as to achieve minimum line width and increased accuracy of visibility on the scale of the refractometer.

Measuring apparent refractive index (RI), at each selected wavelength, produced a curved line between 400 and 700 nm. As measurements were made between the C (656.3 nm) and F (486.1 nm) Fraunhofer lines, extrapolation of these data out to the B (586.9 nm) and G (430.7 nm) lines was unreliable unless this curve was linearised—that is converted into a straight line.

Measurements of dispersion with the gemmologist's refractometer requires prior knowledge of the dispersion of the refractometer glass. However, as refractometer manufacturers refuse to divulge the composition of the glasses used in their refractometers, an empirical calculation had to be made to determine the dispersive properties of the glass of both instruments used to determine refractive indices during this research. This involved using both the Eickhorst and GIA Duplex II refractometers to measure the dispersions of six gemstones at the C to F intervals, and then extrapolating this data to the B-G interval.

Comparisons with published lists of dispersions and data from available sources, which included Smith (1930, 1940), Payne (1935, 1939), Liddicoat (1969), Pschichholz (1976), Schumann (1977), Arem (1977, 1987), Berg & Morse (1981) and Webster (1994), revealed few values not available in Arem (1987). Since these authors did not reference the sources of their data, verification of their results by the authors of this paper was difficult. Indeed, agreement between authors was no guarantee of the ultimate accuracy of dispersions quoted in their publications.

The literature on garnets, in particular, provided so many variations in dispersion that the authors recommended that the values for the dispersions of garnets previously reported in the literature should be reassessed.

As a result of the authors' investigation it appeared that empirical calculations, for the purpose of calibrating the hemisphere-based refractometer, were suitable for those gemstones for which the authors did have accurate, reproducible dispersions.

DEFINING DISPERSION

Dispersion may be measured over any wavelength interval desired, but generally in the fields of physics and optics it is defined as the difference in refractive indices over the C-F interval. Gemmologists, on the other hand, have elected to calculate dispersion over the larger B-G interval, which is near the limits of human vision. This gives a value for dispersion that is about double that determined at the C-F interval.

The optical property of dispersion, as seen by gemmologists, is due to very strong absorptions in the UV and IR—and principally those in the UV where light interacts with the electrons of the constituent atoms of the gem material. Thus any atomic substitution or modification to the atomic structure of the gemstone, which changes the electrical field near the atom, may change its dispersion.

Because critical angle refractometers are calibrated at the wavelength of 589.3 nm (the D sodium line in the Fraunhofer spectrum) this defines the refractive index of the particular medium under measurement—if no other wavelength of calibration is specified. Therefore, the gemmologist's refractometer does not read correctly the refractive index at any other wavelengths. Thus, the refractive index determined at any other wavelength is termed an apparent refractive index—and this value must be corrected appropriately to obtain the true refractive index for a particular gemstone. When each set of values for refractive index are plotted, they should form a straight line on a plot of refractive index versus wavelength. Also, when determinations of refractive index are made near areas of strong absorption in the near UV or IR ranges, additional terms within the Sellmeier formula need to be used (Nassau, 1983). The reason for this modification is quite basic, for typically, within the visible range, the medium (gemstone) slows rays down as they shorten in wavelength, thus increasing the index of refraction.

PRESENT PROBLEMS ASSOCIATED WITH THE MEASUREMENT AND RECORDING OF DISPERSION WHEN DEFINED OVER THE B-G INTERVAL

Scientific and optical measurements of dispersion use C to F interval. It would appear that the decision to use B to G interval for gemmology is not justifiable, as gemmological instruments for measuring refractive index are not efficient at 430 nm or G line, for the following reasons:

1. At 430 nm wavelength the human eye is extremely insensitive.
2. Gemmologists and members of the gem and jewellery industry, who are not trained Scientists, may experience difficulty linearising the determinations of refractive index required to calculate dispersion taken at the B-G interval;
3. Difficulties associated with linearising refractive indices determined at the B-G interval make it difficult to compare dispersions determined at the C-F or other interval with values determined for dispersion at the B-G interval.
4. Gemmological tabulations of dispersion only give a single value, to two decimal places, for the dispersion of birefringent gemstones. This clearly shows that existing tables of dispersion have no real determinative value for gemmologists.
5. Questionable values for dispersion are frequently found in tables of dispersion used by Gemmologists.

While all gemmologists are aware of the term dispersion, the question has to be asked:

Do we really know anything about dispersion?

When gemmologists discuss dispersion, as a gemmological property, little can be said, for this property - when measured at the B-G interval - has little significance to techniques routinely used for gem testing. Factually, dispersion can not be measured easily by the practicing gemmologist with conventional gemmological instruments. Thus, this value cannot be effectively compared with and verified by those B-G values given in previously published standard mineralogical tables.

The listing of only a single value for the dispersion for birefringent gemstones, to two decimal places, is an error that has not been commonly recognized by gemmologists. This common error clearly shows that dispersion measured over the B-G interval has no real determinative value for gemmologists. Similarly, failing to indicate ranges in dispersion, caused by variations in gemstone's crystal chemistry, and its UV absorption, also is erroneous.

Values listed in existing tables of dispersion are also subject to questioning, as a consequence of the unspecified techniques of measurement and extrapolation that have been used to determine their published values. Indeed most of these published dispersions were not determined by direct measurement.

It is a fact that before Hoover & Linton papers of 2000 and 2001, no proven instructions for measuring dispersion, using a conventional critical angle refractometer, had been previously published in the gemmological literature.

Doubly refractive gemstones must, by definition, have at least two values for dispersion associated with each polarised ray that refracts within the gemstone. Thus uniaxial stones will have a discrete dispersion associated with the ordinary (ω) ray, and a variable dispersion associated with their extraordinary (ϵ) ray. A biaxial gemstone's dispersion also would provide values associated with all three of its principal refractive indices (α , β and γ); but these are only very rarely given. Refractive indices for some biaxial gemstones are provided in the International Critical Tables (ICT) of Washburn (1930). In this present investigation the C to F and B to G dispersions were calculated from these data in order to provide potentially reliable reference data with respect to dispersion. However, these indices may be questioned when compared with refractometer data, as the ICT data for refractive index was obtained from either use of the table spectrometer or by immersion techniques.

WAVELENGTHS REQUIRED FOR MEASURING DISPERSION

It is a now established fact that reliable measurements of dispersion only can be obtained by using three narrow bandwidth light sources. However, reliability will improve when more than three wavelengths are used. This fact will become apparent when the Sellmeier linearisation is discussed later in this paper.

Because the human eye has difficulty sensing changes at the extreme ends of the visible spectrum, the visibility of monochromatic wavelengths between 460 and 400 nm is poor. Therefore, it is best to use wavelengths where the eye is far more sensitive. Accurate determinations of refractive index then can be made so that these results can be extrapolated to the appropriate B-G or C-F values. This research used as reference wavelengths light sources that generated wavelengths of 640 nm, 589.3 nm (D Fraunhofer line), 486 nm (F Fraunhofer line) and 452 nm. When extrapolation to the B-G interval of dispersion is required, a 450 nm interference filter was included to increase accuracy of measurements at shorter wavelengths.

A small hand-held 640 nm laser pointer, modified to run on an adjustable voltage power supply of 2.2 to 4.5 volts, was selected to provide 640 nm wavelength illumination. Varying the voltage to this laser pointer changed the intensity of the power of its laser diode from weak to very bright.

This variability was necessary to prevent multiple reflections within the light path, and prevent flash blindness—after which the eye required considerable time to recover its dark-adapted sensitivity. It was important that the wavelength of the laser used was accurately known, for many laser pointers have no indication of the wavelength/s of their emission, and others only have a nominal wavelength that usually proved to be not correct when placed on a Sellmeier scale.

It is suggested that possible low readings from a laser light source may arise from a ‘bright line’ that appears at the critical angle shadow edge. The grazing incidence technique, which produces a bright line across the refractometer scale as mentioned by Anderson (1980) and Webster (1975), can be reduced to a thin line over the critical angle by appropriate positioning of the eye. Use of a diffusion plate, between a laser light source and refractometer, proved to be essential for the generation of a clear image on the scale.

A sodium lamp was the source of the 589.3 nm wavelength illumination. Use of sodium light is essential for verification of the gemstone’s known refractive indices.

The blue wavelength was provided by using a narrow band filter to isolate the Fraunhofer (F) line at 486 nm. This 12 nm pass bandwidth filter was used on short optical fibre paths associated with a 100-watt fibre optic light source. The optical fibre light source did provide suitable dimmable light control that set the level of illumination of the refractometer scale to that of maximum eye sensitivity for the blue filter. As bright scale illumination can prevent the observation of clear images of the critical angle on the scale of the refractometer, reducing the light intensity is often necessary in order to allow many determinations of refractive index with this light source. With practice, the 486 nm (F line) was easily read with the assistance of an intensity controlled light source.

A word of warning, however, for this author soon discovered that visually distracting bright lines may appear on the scale of the refractometer as a consequence of low intensity transitions below the critical angle when using any high intensity light source behind the refractometer.

THE REFRACTOMETER’S REVERSAL OF REFRACTIVE INDEX WITH WAVELENGTH

For most minerals, in the visible range of wavelengths the refractive index of the mineral increases with shorter wavelengths. However, refractometer measurements, using shorter wavelengths (e.g. blue wavelengths), usually yield reduced refractive indices; while longer wavelength illumination (e.g. red) increases the value of refractive indices. A mathematical explanation of this phenomenon is included in a section of Hoover & Linton (2000) that was published on pages 510-514 of *The Australian Gemmologist*, volume 20, number 4.

CHOSEN TECHNIQUE FOR MEASURING DISPERSION

Always choose a refractometer fitted with a colourless, hemispherical exit prism. Unfortunately some instruments have a yellow glass prism that absorbs blue light and severely reduces the effectiveness of the use of blue light as a measuring wavelength. Refractometers fitted with a wide-field eyepiece ocular have a distinct advantage for measuring dispersion as their wider field of view allows for accurate estimates of refractive index to three decimal places. Eickhorst's SR/XS standard refractometer has these advantages over the earlier Eickhorst and Shibuya refractometers. With respect to the GIA Duplex II refractometer, this has a large hemispherical prism, its scale is difficult to read to three decimal places, and also it has the yellow glass hemicylinder that absorbs blue light.

Always ensure that when using a refractometer, which has rear entry light source, ensure that the any yellow filter is removed. If the filter is fixed, use of grazing incidence illumination across the face of the instrument is the only alternative source of illumination that can be used when determining dispersion. As illustrated in figure 1, grazing incidence (Kerr 1959) can produce the Anderson 'bright line' method of measurement at critical angles when a higher intensity light source effectively refracts through the hemisphere (Anderson 1980).

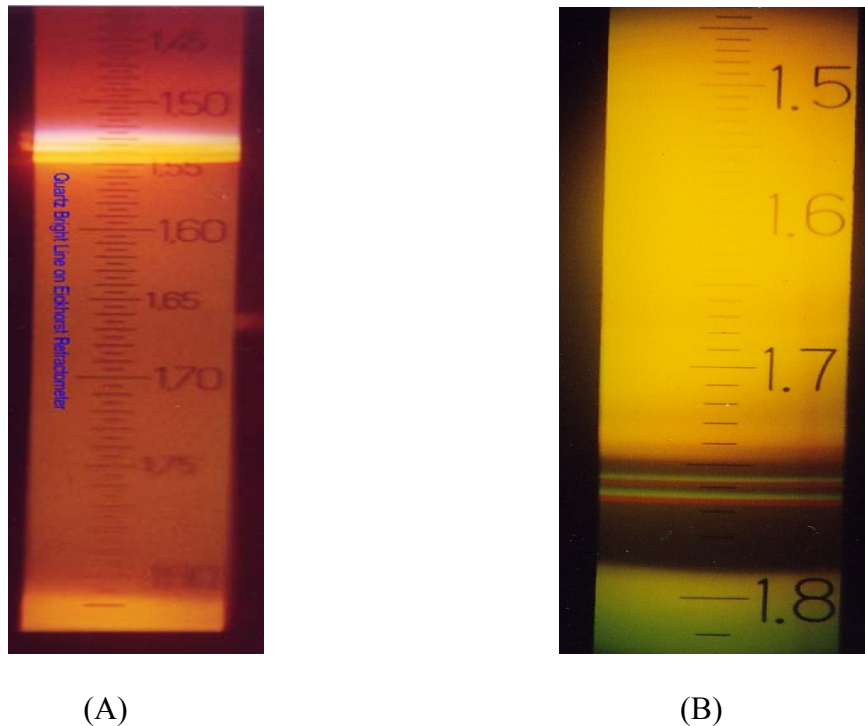


Fig. 1. Use of grazing incidence illumination on Eickhorst and Topcon refractometers
(A) Bright line birefringence of quartz as observed on the scale of the Eickhorst SRXS refractometer (B) Bright line birefringence of corundum as observed on the scale of a Topcon refractometer scale.

Sodium emission 589.3nm (D) light should be used to determine the standard refractive indices of any gemstone being tested. It is preferable to establish this standard refractive index first as a known reference. Then the birefringence can be set at its maximum for that particular gemstone. With respect to this, it is important that the gemstone be tested for dispersion on both sides of its maximum birefringence, for when determining refractive index at other wavelengths both the birefringence and dispersion can increase when determined at shorter wavelengths. Note the transition edges at the D wavelength, and then replace the light source with an F line source at 486.1 nm.

Use of a fibre optic light source will allow individual variation of the intensity of the light source to suit personal eye sensitivity. Eyepiece focus must be reset with the change to 486.1 nm illumination, as this reduced wavelength is defocused with respect to 589 nm wavelengths. Readings will indicate reduced refraction and give lower numerical refractive indices that are inverted with respect to standard table spectrometer measurements. Note the 486.1 nm readings. When a 452 nm filter is available, its use can assist the extrapolation of refractive indices to the B-G interval.

Varying the intensity of the light source does improve the visibility of the critical angle on the scale of the refractometer, and greatly assists in defining the accuracy of scale readings—particularly when deep blue coloured illumination is used. The same effect is noted when using the

red light source. A narrow band red filter, centred at the C line of 656.3nm, or a low power (1 Mw) laser pointer that emits a wavelength between 660 and 640nm, can be used as a suitable light source for red wavelengths.

Calibrating the refractometer

Because critical angle refractometers are calibrated at the sodium D line (589.3 nm), they do not read correctly at other wavelengths. Therefore, the determination of refractive index at an other wavelength is termed an apparent refractive index, and must be corrected appropriately to obtain a true refractive index. These calculations produce *apparent refractive indices*, and it is from these data that *apparent dispersion* is calculated. *True dispersion* is then found by subtracting apparent dispersion from a Suhner number developed by the summing the apparent and true dispersion of the particular gemstone over the range refractive indices available on the chosen instrument. However, the Suhner number is only accurate—if the dispersion data for the refractometer glass being used is known.

For the purpose of this investigation calibration was achieved by measuring the refractive indices of fluorite, gypsum, quartz, beryl, topaz, and gem corundum at three wavelengths corresponding to the C, D, and F Fraunhoffer lines. Dispersions, true plus apparent, for each of the determined gemstones, were then plotted on a Sellmeier graph, and the best fitted straight line through the group of data points was used to determine the appropriate Suhner Number for that particular gemstone.

Note that the Suhner line for C and F dispersion has been added to figure 2 , below.

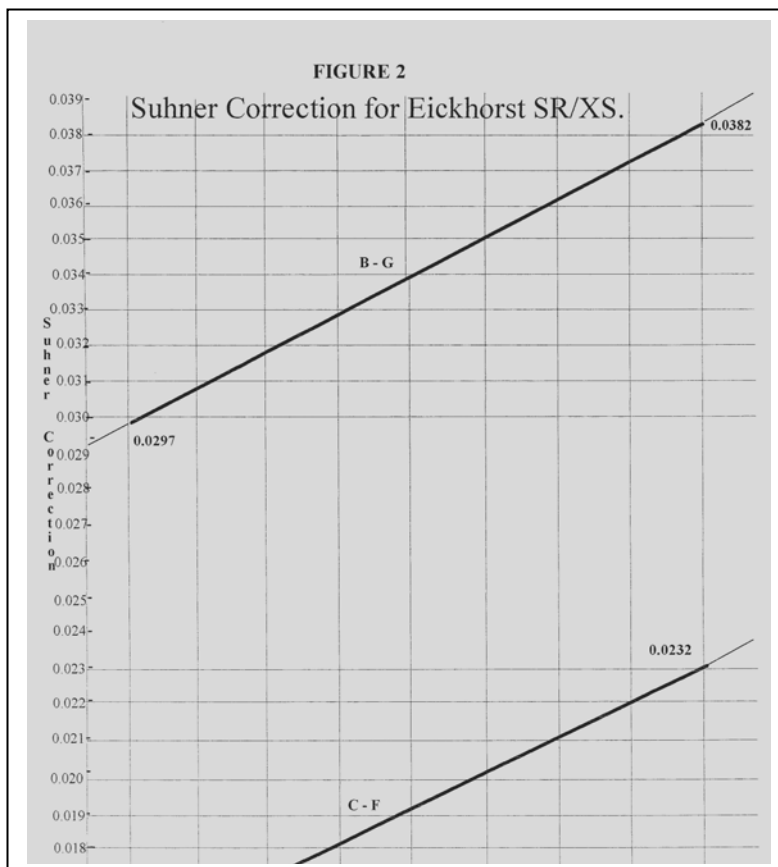


Fig. 2. Suhner B-G and C-F Correction graphs for the Eickhorst SR/XS refractometer.

Linearising wavelength-refractive index curve

A plot of wavelength on the horizontal x-axis against determined index of refraction on the y-axis reveals that a curved relationship exists between these two factors. The conversion of this curved line relationship into a straight line Sellmeier function is possible by converting determined values of refractive index with equation 1.

$$\frac{1}{n^2-1} \quad \text{Equation 1}$$

That is the data on refractive index recorded in the y-axis of the relationship is the reciprocal of the refractive index squared, minus 1.

This wavelength is then converted by formula 2

$$\frac{1}{\lambda^2} \times 10^6 = \text{the reciprocal of wavelength squared.} \quad \text{Equation 2}$$

When the function pairs (M and N), representing the data pairs of refractive index and wavelength, are plotted on a graph for three or more wavelengths, they will form a straight line if the data are accurate. The best line through the group of data points shows the dispersion for that particular gemstone. Being a straight line these data are very easy to interpolate or extrapolate to whatever wavelength one wants. To obtain any corresponding wavelength and refractive index, one merely inverts the numbers produced by equations 1 and 2 using equation 3.

$$\frac{1}{\sqrt{\text{Sellmeier No.} + 1}} \quad \text{Equation 3}$$

That is, 1 divided by the square root of Sellmeier number plus 1.

It is a fact that Sellmeier space graphs (Figs 3 & 4) are accurate and readily display 0.0005 differences in accuracy of refractive index. However, 'straight line' functions may require corrective mathematical weighting when all four points of measurement are not a straight line. It is important to remember that weighting must be highest at D and F, as these provide reliable readings. The wavelength 640 nm or C receives next priority, while 450 nm is the least accurate. Small variations to the angle of the Sellmeier line angle produce obvious differences to extrapolated B-G dispersion results.

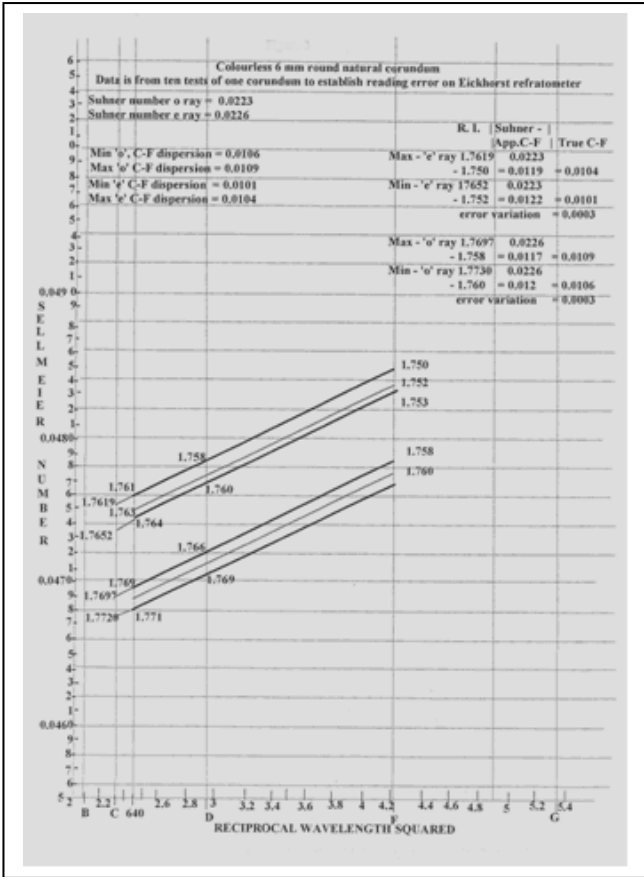


Fig. 3. Sellmeier graph for C-F dispersion of corundum that represents the best fit attained following ten replicated determinations of refractive index at the C-F interval.

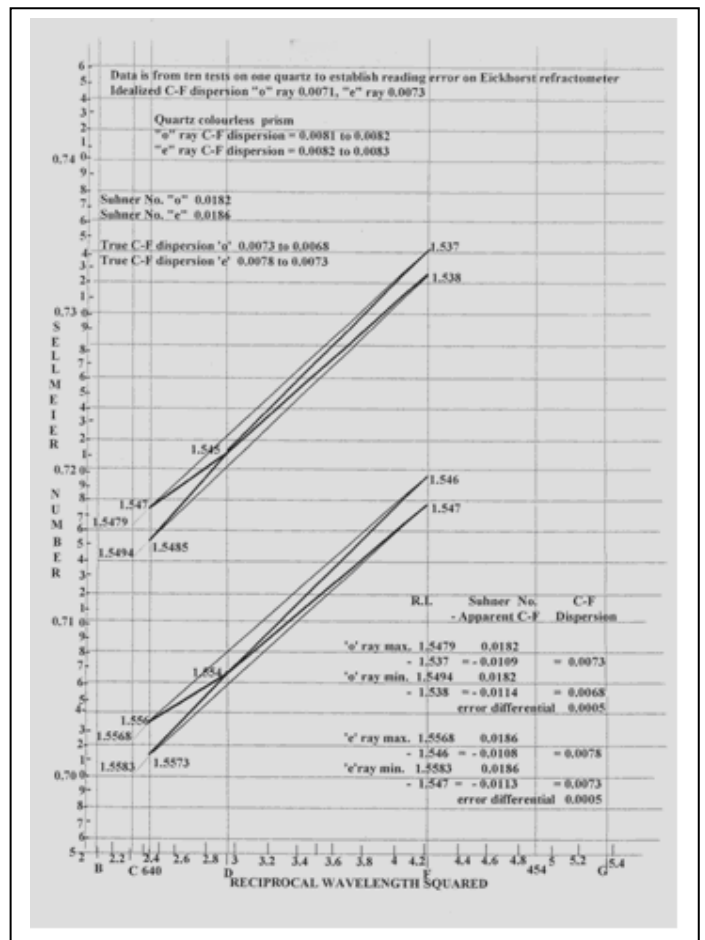


Fig. 4. Sellmeier graph for C-F dispersion of quartz that represents the best fit attained following ten replicated determinations of refractive index at the C-F interval.

It is important to remember that C to F dispersion is determined directly from numerical refractive indices without extrapolation

Technique for determining dispersion using the C and F lines

Although measurement, linearisation and extrapolation of refractive index data can be accomplished by the practicing gemmologist using the method described above, in order to obtain a measure of dispersion, this method is clearly cumbersome and not apt to be much used. Therefore, the author proposes that refractive index data be taken over the C-F interval and that these data be used as a measure of dispersion as used in other scientific disciplines. This short cut eliminates the need for linearisation and only involves the determination of three or four refractive indices— that can be accomplished fairly quickly.

When measuring refractive indices, ensure the refractometer's contact surface is clean and polished. This will maximize the dark shadow representing the critical angle edge. As excess contact fluid allows the shadow edge to move as the head is moved, excess fluid must be removed, or prism must be cleaned of excess fluid, in order to achieve the necessary small spot of contact fluid and so ensure an accurate refractive index.

To produce accurate measurements of dispersion, which can then be calculated to whatever many decimal places one wants, gemstones must be correctly oriented on the refractometer's hemisphere/hemicylinder to achieve maximum birefringence and also so separate refractive indices determined at the extreme limits of both the alpha and gamma rays in biaxial gemstones.

Figure 3 from Hoover & Linton's Part 2, 2001 paper, is required to facilitate this simple technique. This relationship, which is presented as figure 2 in this paper, requires an additional Suhner line that measures the sum of true and apparent C-F dispersions for the refractometer used. For the Eickhorst SR/XS the line commences at 0.0153 at refractive index 1.40 and rises to 0.0232 for the refractive index at 1.80. This line represents the Eickhorst-Suhner correction to be used for determining the D refractive index for the gemstone under investigation. When measuring birefringent gem materials the lower and higher refractive indices provide the appropriate Suhner number for each end of the C-F birefringence dispersion.

A 656 nm laser pointer can provide accurate C line refractive indices when determined on the Eickhorst SR/XS refractometer. However, when using a 640 nm laser pointer, determine the refractive index and then add 0.001 to get the correct C line value. Next determine the D line refractive index. Then using a 12 nm wide F line filter, finally determine the refractive index for that wavelength.

In summary,

- ... First, determine the lower and upper refractive indices with the laser (640 nm), D (589.3 nm) and F (486.1 nm) wavelengths.
- ... Second, subtract the F refractive index from the C refractive index to calculate apparent dispersion.
- ... Third, subtract this apparent dispersion from the C-F - Suhner correction number to find the true C-F dispersion at both birefringent points of the gemstone using the C-F Suhner relationship illustrated in figure 2.

However, it is important to remember that Sellmeier linearisation and extrapolation out to B and G is the only method of reliably converting any C - F readings to find B - G dispersion.

A reliable listing of increasing C-F dispersions may be found in Winchell (1937) and in table 1 of this paper.

ERRORS (VARIATIONS) IN PUBLISHED DISPERSIONS

Few lists of actual refractive indices, at specified wavelengths, which may be used as reference information for determining dispersions, exist in the literature. Detailed review of the content of these detailed listings can cause confusion, with conflicting information being provided by different sources. This is evident when ICT tabulation of Washburn *et al.* (1930) is compared with relatively new information available from the spectrometer measurements made by Hoover in Hoover & Linton (2001).

Errors are obvious in many commonly used tabulations of the dispersion of gemstones. Some of these errors have been mentioned in Hoover & Linton (2001). For example, tanzanite is given a dispersion of 0.030. Hoover measured the dispersion of tanzanite on a table spectrometer and found this to be 0.0177 for the low index ray and 0.0196 for the high index ray. This result was subsequently confirmed by Linton, using the Eickhorst SR/XS refractometer, as 0.018 for the α ray and 0.019 for the γ ray.

Data from Sinkankas (1981) gives the refractive indices for diamonds at four wavelengths that convert, through Sellmeier numbers, to B-G = 0.0446 and C-F = 0.021. In contrast Payne (1935) provided three test series, for measurements of refractive index at Li, D and Cy, producing dispersions of diamond of 0.0453, 0.0450, and 0.0452. In this paper Payne commented that "0.0452 is the most accurate value": Payne also gave B. Walters' figure of 0.0438 as B-G dispersion of diamond. Both Smith and Winchel gave the C-F dispersion of diamond as 0.025.

In this paper, table 2 gives the determined measurements of dispersion over both the B-G and C-F intervals for a variety of gemstones—using the refractometer methods described above. For example:

- Corundum, which has published dispersions of ϵ ray = 0.0162 and ω ray = 0.020 (ϵ = 0.0162, ω = 0.020), also given dispersions of 0.0184 and 0.0186, ranged from 0.0172 to 0.022 in dispersions determined by the method used in this investigation.
- Epidote with a published dispersion of 0.03 gave dispersions of 0.023 to 0.024.
- Feldspars, with a published dispersion of 0.012, ranged from 0.0145 to 0.018.
- Gypsum var. selenite (0.03) ranged from 0.0149 to 0.0152.
- Garnets provided the following new data with respect to their dispersions: almandine (0.0222 to 0.0241), grossular (0.0218 to 0.0238), hessonite (0.022 to 0.038), tsavorite 0.0182, malaya (0.022 to 0.038), pyrope (0.0216 to 0.0238), and spessartine 0.0267.
- Rhodolite garnet ranged from 0.020 to 0.0234.
- Peridot (0.020) ranged from 0.0181 to 0.0242.
- Tourmaline (0.017) ranged widely from 0.0153 to 0.0201.

Payne (1939), page 33, did indicate the variability in his determined dispersions by commenting "The refractive indices for various wavelengths are the mean of three readings" for kornerupine, scapolite and danburite.

Gunter and Bloss (1982) stated that the effect of Fe^{3+} in andalusite caused a greater increase in refractive indices than Mn^{3+} and that "The indices for crystals containing high amounts of Fe^{3+} will

likely plot above the curves in Figure 3". His table 5 demonstrated that ten andalusites yielded refractive indices with a differential of 0.01.

As Fe^{3+} is a common colour-causing element that is included in the chemical compositions of many gemstones, it is not unreasonable to expect significant variations in the refractive indices of those gemstones that containing this and other colour causing ions. It must be emphasised that variations in dispersion of gemstones must occur as a consequence of the inclusion of various amounts of ions such as Fe^{3+} in their chemical compositions.

Payne (1935), Webster (1944) and Hoover & Linton (2001), all expressed concern over problems associated with using a table spectrometer to measure refractive indices. Although they also recognize that this is the instrument to use when accuracy is necessary, results are often not identical between authors who using the minimum deviation technique for determining refractive index and dispersion.. Webster described the problems accurately while Hoover & Linton (2000.2001) suggested that finding the position of minimum deviation is difficult, for the minimum position is so broad as to be at times almost interminable.

Hoover & Linton also commented problems associated with the measurement of dispersion on standard faceted gemstones that have non-optically flat facets that disturb the refracted spectrum in the auto-collimating telescope of the table spectrometer. In addition, Webster listed the following observations with respect to use of the table spectrometer:

1. The faceted gemstone must be set for minimum deviation at every wavelength for which refractive index must be measured.
2. Very few gemstones are faceted well enough to produce good spectral images from larger, flat facet surfaces.
3. Even well polished table facets are rarely polished flat enough to act as a prism refracting face.
4. Webster also cited two examples of refractive indices for diamond and tourmaline from Payne. Webster concluded that diamond had a refractive index of 2.4183, while Payne gave the refractive indices for diamond at D as 2.4177, 2.4171 and 2.4174. Sinkankas and Walter suggested a refractive index of 2.4175, while Dana quoted 2.4195. The Payne value for the B-G dispersion has quoted previously at being 0.0453, 0.0450 and 0.0452.

RESULTS OF THIS STUDY

This paper has demonstrated that the combination of new type gemmological refractometers, which are fitted with either a hemispherical or hemicylindrical glass prisms and use of improved techniques for visualising and reading the scale of the refractometer, can be used to measure the dispersion of gemstones with sufficient accuracy to be useful with respect to their identification.

Gemmologists can use dispersion as a useful tool in determinative gemmology, however, an accurate list or tabulation of universally accepted values of C to F interval dispersion is essential. These data should be as complete as possible and contain values for birefringent gemstones with their orientation along fastest and slowest directions clearly specified. This list must also contain the range to dispersions that can be expected as a consequence in likely variations in the gemstone's crystal chemistry.

Unfortunately, in this regard, all previous sources of gemological information are completely inadequate; for their data is based on measurements from 70 to 100 years ago. These data provide only one value for the dispersion of a gemstone and do not generally indicate in what orientation dispersion was measured on birefringent gemstones. Further, many compilations of dispersion data were, for the most part, simply copied from the data of prior author, usually without attribution.

This information does not guarantee the quoted dispersion to be the correct value for B to G dispersion. Rarely does one find, in gemmological literature, details of the essential refractive index-wavelength data from which dispersion values have been derived.

Clearly a modern tabulation of dispersion values is needed for use by the practicing gemmologist. It is hoped that this paper offers a beginning for such a listing.

Table 1, below, also provides a condensed summary of the principal investigation conducted by the author of this paper. The results indicate the dispersions obtained for forty-eight (48) gemstones and seventy (70) varieties of gemstones that totalled 217 gemstones. Data given in table 2 was measured by the author for both singly refractive and doubly refractive (ω , ε and α , γ) rays in the individual gemstone's most birefringent orientation. To make the necessary measurements, three wavelengths of incident light were used in association with an Eickhorst SR/XS refractometer. It is important to remember that measurements recorded in table 2, which were not made at the wavelength of the sodium emission D (Fraunhofer) line are not true refractive indices, but only represent apparent refractive indices. To evaluate the quality of the data, Sellmeier linearisation was used to test the linearity of each data set. Results indicated that data were sufficiently linear and were then used to interpolate or extrapolate to the B and G values of apparent refractive index.

The criterion used for inclusion of measurements into table 2 was that following conversion and plotting the data had to present as a straight line on the Sellmeier plot. Unfortunately, not all measurements taken fitted that criterion.

From the results presented in table 3, it is apparent that many gemstones of the same variety produce differing dispersions when these are determined on the refractometer. These variations are not limited only to measurements made on a critical angle refractometer. Payne indicated variations occurred in his 1934 paper by saying, "mean readings are listed providing an appropriate number". Some of this variation must be due to variations in the crystal chemistry of individual gemstones—as may be expected. However, some variation is certainly due to measurement error that is difficult to evaluate without further measurements.

However, the author believes that table 3 does provide an 'interim' reference table of dispersion data for gemmologists, for it provides details of both the B to G and C to F dispersion of the gemstones investigated. However, additional testing of other gemstones must be completed before a permanent tabulation will be available.

Gemstones and gem materials that have a complex chemistry are difficult for gemmologists to understand and describe accurately, particularly when a continuum exists between members of a group. Particular examples of these problem gemstones include the feldspars, garnets, peridots etc. These gem minerals will require further studies into their chemistry and crystal structure before accurate detail with respect to their dispersions can be obtained...

RECOMMENDATIONS BASED ON THE RESULTS OF THIS STUDY

A simple technique for measuring dispersion with a refractometer, using C and F wavelengths, is available to any gemmologist who wishes to measure dispersion on a gemstone with refractive indices below 1.79. This simple technique can be completed in a few minutes, compared with a factor of fifteen times that when extrapolating calculations out to B and G interval dispersion numbers.

C to F dispersion alone may not be a universally defining parameter for a gemstone. However, when added to other gemmological information it can be used to effectively confirm the identity a gemstone.

Please remember that gemstones that have refractive indices above 1.79 require further investigation with respect to their oft-stated numerical dispersions. While the dispersions of some high refractive index gemstones have been calculated in table 1, from Washburn (Merwin 1930), this is yet another area that requires further evaluation.

CONCLUSIONS

This author would like to put the proposition that gemmologists cannot use current single B to G numerical dispersions for identification purposes. Unfortunately, these data have no value as determinative factors for measuring the dispersion of either isotropic or birefringent gem materials. Based on this investigation it is inconceivable that dispersion can be adequately expressed as a single number for birefringent gemstones such as the garnets, beryls, feldspars, corundum, topazes or tourmalines.

Extrapolation of apparent dispersion values out to B and G wavelengths is a complex and time consuming process that offers little chance of arriving at single three decimal place numbers that approximate a gemstone's dispersion. In practice a single number cannot represent the dispersion of a birefringent gemstone.

Dispersion is not presently considered to be part of a viable gemmological test procedure, owing to the complex and impractical possibility of obtaining accurate and reproducible B to G data with respect to refractive index. This author has demonstrated a simple and practical technique, using simple instruments and equipments, to determine C to F interval dispersion. Table 1 lists data from his assessment of 56 gemstones.

Data in table 3 should be considered to be a believable, and possibly a basis for the future use of dispersion as an adjunct to gem identification. Although data in table 3 revises previous data, it is only part of a system for the accurate measurement of dispersion at the C line (656.3 nm) to F line (486.1 nm) interval.

Investigations into adapting new electronic narrow bandwidth, high intensity LED light sources for dispersion measurements are progressing. It is now well established that the larger number of refractive indices, measured at known wavelengths, improves accuracy of dispersion measurements. These LEDs have a distinct potential for increasing the accuracy of measurements of dispersion.

While further investigations into the measurement of C to F dispersion are essential, this author can definitely see considerable benefits for the determinative use of dispersion by gemmologists—particularly when accurate measurements are available on a gemmological refractometer.

Acknowledgement

The author wishes to thank Dr. Donald B. Hoover for his time and effort in assisting with the direction and development required for presentation the Research Diploma in Gemmology thesis upon which this paper has been based. The author appreciates his experience, assistance and advice with respect to the generation and analysis of the dispersion data produced by this project.

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Errata

Three numerical typographical errors occurred in ‘Dispersion measurements with a gemmologists refractometer’, Part 1, that was published in *The Australian Gemmologist* volume 20, number 12.

On p. 510, second last line RHA ... formula 3 should read ‘ $\sin i_c = 1.5544/1.9462 = 0.79858$ ’.

On p. 512, line 23 LHS ... apparent dispersion then is $1.5092 - 1.5537 = 0.0445$

On p, 512, line 10 LHS ... after formula 10 – ‘ $n_G = 1.4563$ ’

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Attachments

Table 1 .

Table 2

Table 3

Mineral	Ray	Linton		Linton		Winchel
		Arem (B-G)	Other	Extrapolated (B-G)	Extrapolated (C-F)	
Anatase	ω ray	0.213				
-	e ray	0.259				
Andalusite	ω		0.016	0.0156	0.0093	
-	e			0.0191	0.0113	
Apatite	e	0.013		0.0166-0.0167	0.0097	0.0097
-	ω			0.0169	0.0097	
Apophyllite	ω			0.0170	0.0090	
-	e			0.0175	0.0094	
Aragonite	a			0.019	0.0114	0.0123
-	b			0.0220	0.0127	
-	g			0.0226	0.0131	
Barite	a	0.016		0.0159	0.009	0.009
-	g			0.0165	0.0095	
Benitoite	ω	0.039	0.0395	0.035	0.0227	
-	e	0.046		0.0506	0.0329	
Beryl	ω	0.014		0.0140	0.0084	0.009
-	e			0.0149	0.0089	0.0127
Beryllonite		0.010				
Brazilianite		0.014				
Brookite		0.0131				
Calcite	ω		0.02			
-	e					
Cassiterite	ω	0.071		0.071		0.049
-	e			0.064		
Chrysoberyl	a	0.015		0.0149	0.0086	0.011
-	e			0.0211	0.0122	
Cordierite	a	0.017		0.0175	0.0085	0.0084
-	g			0.0172	0.0084	
Corundum	ω	0.018		0.0184	0.0097	0.0106
-	e			0.0186	0.0109	
Danburite	a	0.017		0.0174	0.0101	0.01
-	g			0.0185	0.0106	
Datolite		0.016		0.0165	0.013	
Diamond		0.044		0.0446	0.021	0.025
Epidote			0.03	0.0227		0.016
				0.0227		
Euclase	a	0.016		0.0192	0.0114	
-	g			0.0202	0.0117	
Feldspar						
Potassium feldspar						
Adularia			0.014			
Microcline			0.018			0.011
Orthoclase	a	0.012	0.0145	0.0133	0.0074	0.0083
-	g			0.0133	0.0075	
Plagioclase feldspar						
Albite	a		0.0137	0.0169	0.0093	
-	g			0.0184	0.0108	
Andersine			0.0086			
Anorthite	a	0.0172		0.0169	0.0101	
-	g			0.0185	0.0109	
Anorthoclase						0.009
Bytownite	a					0.0093
-	g					0.0134-0.0136
Labradorite	a		0.0149			0.009
-	g					
Oligoclase			0.0147			
Fluorite		0.007		0.0076	0.0045	0.0045
Forsterite	a	0.02		0.0174 - 0.0181	0.0107	0.013
-	g			0.0186 - 0.0192	0.0114	

Gypsum	a	0.033	0.0132	0.0078	0.0079
-	g		0.0132	0.0078	
Garnet					
Almandine		0.027			0.015
Andradite		0.057			0.04
Grossular		0.027			0.013-0.017
Pyrope		0.022			0.01 - 0.0125
Rhodolite		0.026	0.0217	0.0126	
Spessartine		0.027			0.015
Hambergite	a	0.015	0.0142	0.0077	0.009
-	g		0.0142	0.0076	
Idocrase		0.019	0.019	0.0127	
Kornerupine	a	0.018	0.019	0.0112	
-	g				
Moissanite	ω		0.112	0.111	0.0635
-	e		0.123	0.1254	0.0708
Peridot	a	0.02	0.0196	0.0117	
-	g		0.0213	0.0127	
Petalite					0.010
Phenakite	a	0.005?(0.015)	0.0164	0.0087	0.009
-	g		0.0169	0.0087	
Quartz	ω	0.013	0.0131	0.0079	0.0078
-	e		0.0135	0.0082	
Rhodozite		0.026			
Rutile	ω ray	0.28	0.2755	0.1497	0.158
-	e ray		0.368	0.1947	
Scapolite	ω	0.017	0.017	0.0095	0.009
-	e		0.0178	0.0095	
Sillimanite	a	0.015	0.0184	0.0108	0.01
-	g		0.0186	0.0108	
Smithsonite	a	0.037	0.0164	0.0085	0.01
-	g		0.0217	0.00126	
Sphene	a	0.051	0.0577	0.0313	
-	g		0.0932	0.0513	
Spinel		0.020	0.0206	0.0119	0.012
Spodumene	a	0.017	0.0171	0.0094	0.01
-	g		0.0175	0.0107	
Topaz	b	0.014	0.0130	0.0074	0.0078
Tourmaline	ω	0.017	0.0148		0.009
-	e		0.0155		
Zircon	ω ray	0.039	0.0382	0.0219	0.023
-	e ray		0.0391	0.0225	
Zoisite Var.	a	0.012			
Tanzanite	g				

Note: Linton's data are extrapolated data calculated from the Washburn (1930) ICT wavelength/ refractive index tables.

Table 1 Comparison of data on dispersion from previously published sources, from left to right: Arem; Other unspecified; Linton's extrapolated Sellmeier B to G dispersion data from wavelength-R.I. data listed by Dana, Payne and Washburn; Linton's C to F dispersion that has been derived from extrapolation of the B-G data in column 2; Winchel.

GEMSTONE		Listed B-G	Sellmeier/Suhner calculated B-G variations	Listed C-F	Sellmeier/Suhner calculated C-F variations
Fluorite		0.007	0.0082	0.0045	0.0045
Natrolite	- α	-	0.0134	0.009	0.0052
	- γ	-	0.0118	-	0.0052
Quartz	- ω	0.0131	0.0125 – 0.0145		0.0062 – 0.0084
-	- ϵ	0.0135	0.0132 – 0.0163		0.0071 – 0.0089
Montebaisite	- ϵ	-	0.0125	-	0.0064
	- ω	-	0.0117	-	0.0064
Petalite	- α	0.0141	0.0121 – 0.0141	0.010	0.0073 – 0.0085
Aragonite	- α	-	0.0147	-	0.0068
	- γ	-	0.0233	-	0.0133
Topaz	- α	0.014	0.0133- 0.0153	0.0078	0.0070 – 0.0100
-	- γ		0.0124 – 0.0162		0.0064 – 0.0110
Beryl	- ϵ	0.0140	0.0139 – 0.0174	0.009-0.0127	0.0077 – 0.0077
-	- ω	0.0149	0.0140 – 0.0171	0.009	0.0073 – 0.010
Gypsum	- α	0.033	0.0136	0.0079	0.0081
-	- γ		0.0149		0.0085
Heliolite	- ϵ	-	0.0171	-	0.0085
	- ω	-	0.0167	-	0.0099
Lazulite	- α	None	0.014	-	0.0083
-	- γ		0.0141		0.0086
Diaspore	- α	-	0.0144	-	0.0088
	- γ	-	0.0164	0.010	0.0098
Scapolite	- ϵ	0.017	0.0151 – 0.0178	0.007	0.0082 – 0.0106
-	- ω	0.0178	0.0150 – 0.0176	0.009	0.0084 – 0.0109
Feldspar (all)	- α	0.012	0.0145 – 0.0177		0.0088-0.0093
-	- γ		0.0151 – 0.0184		0.0075-0.0100
Barite	- α	0.016	0.015	0.009	0.0088
	- γ		0.0169		0.0099
Apatite	- ϵ	0.016	0.0152 – 0.018	0.01	0.0083-0.0103
-	- ω		0.0147 – 0.018	0.01	0.0084- 0.0095
Phenakite	- α	0.015	0.0156 – 0.0174	0.007	0.0089-0.0104
-	- γ		0.0178 – 0.0183		0.0102-0.0104
Tourmaline	- ϵ	0.0155	0.0147 – 0.0185	0.009-0.012	0.0081-0.0111
-	- ω	0.017	0.0147 – 0.0197		0.0093 – 0.0125
Zoisite	- α	0.0177	0.0162 – 0.0203	0.0103	0.0093 – 0.0119
-Var. Tanzanite	- γ	0.0196	0.0185 – 0.0203		0.0111 – 0.0122
Clinohumite	- α	-	0.0210	-	0.0091
	- γ	-	0.0218	-	0.0120
Andalusite	- α	0.0156	0.0153 – 0.0182	-	0.0091 – 0.0103
-	- γ	0.0191	0.0160 – 0.0201		0.0094 – 0.0103
Iolite	- α	0.017	0.0174 – 0.0177	0.0084	0.0096 – 0.0103
-	- γ		0.0173 – 0.0179	0.009	0.0100 – 0.0109
Hambergite	- α	0.015	0.016	0.009	0.0098
-	- γ		0.0146		0.0104
Datolite	- α	0.016	0.0173		0.0098 – 0.0103
-	- γ		0.0171-0.0192		0.0096 – 0.0114
Sinhalite	- α	0.018	0.0171 – 0.0187		0.0092 - .0106
-	- γ		0.0158 – 0.0196		0.0083 - 0.0103
Kornerupine	- α	0.018	0.0168 – 0.0192		0.0099 - 0.0124
-	- γ		0.0168 – 0.0213		0.0097 - 0.0139
Euclase	- α	0.016	0.0158 – 0.016	0.009	0.0099 - 0.0104
-	- γ		0.0150 – 0.0182		0.0097 - 0.0101
Spodumene	- α	0.0171	0.0154 – 0.0205	0.01	0.0083 – 0.0122
-	- γ	0.0173	0.0190 – 0.0195		0.0092 – 0.0122

Amblygonite	- α	None	0.0179- 0.0186	-	0.0094
-	- γ		0.0177- 0.0189	-	0.0100
Smithsonite	- α	0.014	0.0175	0.017	0.0193
-	- γ				
Brazilianite	- α	0.014	0.0168	-	0.0100
-	- γ		0.0179		0.0103
Danburite	- α	0.017	0.0167	0.010	0.0094
-	- γ		0.0164		0.0097
Corundum	- ϵ	0.018	0.0169 – 0.0203	0.0106	0.0097 – 0.0118
-	- ω		0.0141 – 0.0211		0.0097 – 0.0123
Lithophylite (brown)- ϵ	-		0.0175	-	0.0100
(Triphylite ,blue) - ω	-		0.0184	-	0.0109
Kyanite	- α	0.02	0.0181-0.0189	0.0114	0.0109 - 0.0124
-	- γ		0.0181-0.0183		0.0103 - 0.0112
Celestite	- ω	-	0.0 177	-	0.0103
-	- ϵ	-	0.0179	-	0.0104
Peridot	- α	0.0196	0.0181 – 0.0220	0.0124	0.0101 – 0.0134
-	- γ	0.0213	0.020 – 0.0242	0.0132	0.0110 – 0.0136
Forsterite	- α	0.0182	0.0182	0.01	0.0108
-	- γ	0.0192	0.0179		0.0107
Chrysoberyl	- α	0.0149	0.0163 – 0.0204	0.011	0.0107 - 0.0115
-	- γ	0.0211	0.0171-0.0207		0.0108 - 0.0117
Enstatite	- α	-	0.0204-0.0223	-	0.0111-0.0129
-	- γ		0.0197-0.0223		0.0108-0.0129
Sappherine	- α	None	0.0191	-	0.0115
-	- γ		0.019		0.0109
Spinel		0.020	0.0201 – 0.021	0.012	0.0112 – 0.0141
Sillimanite	- α	0.0186	0.0185	0.009	0.0117
-	- γ	0.0184	0.0182	0.01	0.0110
Taaffeite	- α	-	0.0201	-	0.0093
-	- γ		0.0210		0.0122
Diopside	- α	-	0.0196 – 0.022	0.0106	0.0119 – 0.0141
- (Chrome)	- γ		0.0202 – 0.0221		0.0120 – 0.0139
Epidote	- α	0.03	0.0217 – 0.0238	0.012	0.0120 – 0.0139
-	- γ		0.0231 – 0.0245	(.016-.018)	0.0137 – 0.0143
Prehnite	- α	-	0.0203	0.009^	0.0110
-	- γ		0.0239		0.0146
Garnet Almandine		0.024	0.0222 – 0.0238	0.017	0.0130 - 0.016
Garnet Grossularite		0.028	0.0182 – 0.0239	0.018	0.0133 - 0.0139
Garnet Hessonite		0.028	0.022 – 0.0238		0.0130 – 0.0141
Garnet Tavorite		0.028	0.0182 – 0.023		0.0114 – 0.0128
Garnet Malaya	-	0.0222	– 0.024		0.0121 – 0.0140
Garnet Pyrope		0.022	0.0203 – 0.0248	0.014	0.0133 – 0.0158
Rhodolite		0.023	0.0206 – 0.0228		0.0133 – 0.0139
Spessartine		0.027	0.0267	0.011-0.019	0.0165
Zircon	ω ray	0.039	0.0382	0.0219	0.023
-	e ray		0.0391	0.0225	
Diamond		0.044	0.0446	0.021	0.025
Moissanite	ω	0.112	0.111	0.0635	0.073
-	e	0.123	0.1254	0.0708	

Table 3 Variations in measurements of dispersion calculated from measurements using the Eickhorst SR/XS refractometer and listed in increasing order of C-F dispersion. Also listed are pervious B-G and C-F data from Arem, Smith, Payen and Winchel.