Invited Paper

Designing apochromatic telescope objectives with liquid lenses.

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ABSTRACT

The traditional approach to designing a high performance, apochromatic, telescope objective has always required the incorporation of an abnormal dispersion glass or crystal. These materials are notorious for their high cost and poor mechanical properties. Recently, some optical liquids have been found that have dispersion properties unequaled by any known glass or crystal. This has opened the way to lower-cost apochromatic objectives. While many of the problems associated with the use of traditional abnormal dispersion materials can be avoided, the incorporation of an abnormal dispersion liquid 'element' in combination with common (normal dispersion) glasses in a telescope objective design creates some unique design considerations.

In this paper a comparison of the dispersion characteristics of glasses and liquids are presented. Also presented are specific design examples which illustrate the performance improvements possible with glass-liquid combinations. The problems associated with obtaining high precision refractive index measurements on liquids and a comparison of liquid catalog and measured indices are discussed. Finally, some design issues unique to liquid lenses such as athermalization, sealing, volumetric expansion accommodation, freezing and long term stability are addressed.

1. INTRODUCTION

It is well known that achieving apochromatic color correction requires the use of refractive materials that possess abnormal dispersion. Calcium fluoride has been used for a hundred or more years and in the last few decades abnormal dispersion glasses have become available. However, it is also well know that there are problems associated with all traditional abnormal dispersion materials; they have poor mechanical properties, are expensive and are frequently limited in their availability and optical quality. Thus, the goal of a low-cost apochromatic telescope objective has been elusive.

The fact that a liquid and one or more normal dispersion glasses can be combined to achieve an achromatic optical system has been known for a very long time. The realization that some liquids have abnormal dispersion and that these liquids can be used in combination with common, normal dispersion glass to achieve apochromatic color correction is a much more recent development. With this combination of materials, the low-cost apochromat is now a possible.

2. THE DISPERSION PROPERTIES OF CARGILLE LIQUIDS

The most common representation of dispersion is the Abbe vs. N_d diagram like Fig.1 which shows the properties of many Schott glasses and Cargille liquids. The R.P. Cargille Corp. is by far the world's largest manufacture of optical liquids[1]. The Abbe diagram represents the linear component of a material's dispersion (i.e. the slope of the index of refraction over a spectral bandwidth) and therefore can not be used to find materials with abnormal dispersion. However, even looking at the linear dispersion component, Fig. 1 shows that most liquids are quite unusual. Abnormal dispersion is most often identified with partial dispersion plots such as that included with every glass makers catalog. On such a plot, a material with abnormal dispersion will be located well off a straight line connecting common glasses such as BK7 and F2. This line is referred to as the normal line for glasses. One disadvantage of the partial dispersion representation is that it is tied to several specific wavelengths and it takes several plots to characterize the true nature of a material's dispersion. A Buchdahl dispersion plot[2] is not tied to any specific wavelength set and can represent the dispersion of a material over an entire range of wavelengths (i.e., the visible spectrum).

In the Buchdahl equation, the refractive index as a function of wavelength is given by:

$$N(\omega) = N_0 + \nu_1\omega + \nu_2\omega^2 + \dots\dots\dots + \nu_i\omega^i \qquad (1)$$

where N_0 is the index at the base wavelength and the quantities ν_1, ν_2, etc. characterize the dispersion of the material. The chromatic coordinate ω, is defined as:

$$\omega = \frac{\lambda - \lambda_0}{1 + 5/2\ (\lambda - \lambda_0)} \qquad (2)$$

where λ_0 is the base wavelength. A good choice for the base wavelength when using a quadratic dispersion model over the visible spectrum has been found to be 0.574μm[3]. The Buchdahl equation was used to fit to index data at four wavelengths supplied by Cargille. The quadratic Buchdahl equation is used only for the material selection process and once promising materials are found, all lens design optimization and analysis should be performed with a more accurate representation such as the 6-term Schott equation[4] (which has been based upon index measurements at more than 6 well spaced wavelengths, preferably as many as 10).

The dispersive power of a material using the Buchdahl model is defined as:

$$D(\lambda) = \frac{\delta N(\lambda)}{(N_0 - 1)} = \sum_{i=1}^{n} \eta_i \, \omega^i \qquad (3)$$

where $\eta_i = \nu_i/(N_0 - 1)$ and n is the order of the dispersion equation. With a quadratic representation, the quantities η_1 and η_2 are called the primary and secondary dispersive coefficients.

The dispersion coefficients for Cargille liquids and Schott glasses are plotted in Fig. 2. Also shown on this plot is the normal line for glasses. It is immediately obvious that some Cargille liquids are much more abnormal than any glass. Abnormal dispersion in liquids appears to be relatively common. Surprising little research has been published on the chemical-physical nature of abnormal dispersion in liquids. An exception to this are investigations currently being done in the Soviet Union[5].

A unique feature of Cargille liquids is their grouping into straight line segments on the dispersion map. These segments are characteristic of a series of liquids in which the series members are mixtures of the several components in different ratios. A few of the more interesting series are noted. It should be remembered that all the liquids shown on this plot are based on index measurements made by Cargille at only four wavelengths (.4799, .54607, .5893, and .64385 µm). Any promising liquid will require more extensive dispersion measurements before it can be incorporated into a high-performance lens design.

3. DESIGN EXAMPLES

The procedure for finding apochromatic combinations of two materials with a Buchdahl dispersion map like Fig. 2 is very simple. The materials must be on or very near (within a few degrees) a radial line drawn from the origin of the plot[2]. The farther apart the materials are on this radial line, the better the power distribution. When three or more materials are used, the technique is only sightly more complicated but will not be detailed here as it has been described previously[6].

In order to evaluate the performance potential of glass-liquid apochromat designs, it is helpful to examine the performance of all-glass designs which have the same scale and f/number. For comparison, the performance of representative all-glass achromatic and apochromatic objectives are shown in Fig. 3. Note that the approximate raw material cost is also indicated and that the material cost for the all-glass apochromat design is very high.

Two single-liquid apochromat examples are shown in Fig. 4. In the example which uses only one glass type, the liquid has substantial optical power and this can lead to increased thermo-optical sensitivity as will be discussed below. The other example, two glass types are used that are a good achromatic combination by themselves and therefore, the liquid need have only a small optical power to yield an apochromat. When the optical power of the liquid element is small, the element can be very thin compared to the glass elements and very little liquid is required. In fact, this example is nearly a cemented doublet. Correcting coma in addition to color and spherical aberration in glass-liquid apochromats requires careful selection of the surrounding glasses. Glass-liquid apochromats are similar to cemented doublets, in that there are no air-spaces that can be varied to reduce coma and spherochromatism. The optical performance of the two single-liquid objectives is shown in Fig.5. It is evident that the liquid has been very effective in reducing both the secondary spectrum and spheroachromatism in each case. Note that the cost of materials is only about 6% of that required for the all-glass apochromat objective.

4. THERMO-OPTICAL CONSIDERATIONS

All liquids have large changes in index with temperature. Typical value of dn/dt for liquids are -4×10^{-4} /K° (about a 100 times greater than a typical glass). Therefore, a glass-liquid apochromat can be expected to experience a larger change in focal length than would a comparable all-glass designs when subjected to temperature changes.

The defocus as a function of soak temperature for the two single-liquid designs are shown in Fig. 6. In those cases where it is possible to refocus the objective periodically, the thermally induced defocus is usually not a serious problem (unless the temperature changes are larger than about ± 15° C). However, in those design which have thick liquid elements (i.e. they have significant optical power), rapid changes in ambient temperature may generate localized thermal gradients within the liquid that can result in convection currents and striae-like filamentation as well as significant changes in focal length.

If the surrounding glass elements constitute an achromatic combination, they will contain most of the optical power of the objective and the liquid element will need to have only a small optical power to correct the residual secondary spectrum. In this case, the liquid element can be quite thin. It has been observed that thin liquid elements are more easily dominated by the thermal mass of the surrounding glass and are therefore much less likely to develop filamentation during temperature changes. A second benefit of keeping the optical power of the liquid element small is that the defocus due to changes in soak temperature is reduced. For these reasons, the SK15/550206/F5 objective is superior to the BK7/54633/BK7 objective.

No known glass has a large enough dn/dt to thermally compensate a liquid in a manner that would yield an optically athermal objective (but some plastics or crystals might make this possible), so if athermalization is necessary, a second liquid element is needed and at least three glass elements are required (see ref. 6 for a discussion of designing athermal glass-liquid apochromats). The glass elements could be all of the same type, but the optical power of the liquid elements will be minimized if the glasses themselves form an achromat. In a two-liquid apochromat, both liquids need not be abnormal in dispersion, but it does not complicate the design much if both are and even better color correction can be obtained. An example of this type of athermal glass-liquid apochromat using the combination BAK2/400513/SF2/550206/BAK2 is shown in Fig. 7 and its optical performance is shown in Fig. 8. This objective, in addition to being athermal, is also corrected for spherical aberration, coma and has color correction at four wavelengths (i.e. it is really a superachromat). The defocus with temperature for this objective is not shown here, but an a similar example has been fabricated and was found to be comparable to an air-spaced BK7/F2 achromat over typical operating environments (25 ±15C°)[6].

Another thermal consideration with glass-liquid apochromats is the possibility of the liquid freezing or boiling in extremely severe environments. Boiling is not really a problem as the boiling points of all liquids shown in Figs. 1 and 2 are 135C° or greater. Freezing can be be more of a problem. Liquid 400513 freezes at -70C° (about the lowest freezing point of the Cargille liquids) while 550206 freezes at 7C° (about the highest freezing point of the Cargille liquids with good visible spectrum transmission). When a liquid freezes, it typically becomes opaque and imaging is impossible. However, even repeated freeze/thaw cycling does not appear to affect the optical characteristics of glass-liquid apochromat provided the sealing mechanism is properly designed.

4. REFRACTIVE INDEX MEASUREMENTS

Central to the design of any high performance apochromat are good refractive index measurements at numerous wavelengths across the intended spectrum of operation. The data shown in Figs. 1 and 2 represents the average or typical dispersion properties of nearly all the liquids produced by Cargille (based on their measurements of refractive index at four wavelengths over several lots). The accuracy of Cargille's refractive index measurements is about ±0.0004. Very careful control of the temperature during index measurements is essential because of the large thermal sensitivity of liquids. Cargille monitors the temperature during their measurements to ±0.01C°.

Cargille controls the nominal refractive index (N_d) of each liquid it produces to match the catalog value to within ±0.0002. In order to evaluate how much dispersion variations could be expected between individual liquid lots (the equivalent glass melts) and their catalog value, eight liquids with promising dispersion were obtained. Refractive index measurements were made on these liquids at 0.4799, .54607, .58929, and .64385μm with an accuracy of approximately ±0.0001 by Cargille. These data were fitted to a quadratic Buchdahl dispersion model and the resulting dispersion coefficients along with the catalog dispersion coefficients are plotted in Fig. 9. A slightly disturbing trend is apparent in this plot. Many of the measured dispersions were closer to the normal line than were the catalog values. However, compared with glasses, these liquids are still quite abnormal. The magnitude of the difference between lot and catalog dispersions shown in Fig. 9 is not much different from that found with optical glasses.

Two of the most promising liquids, 400513 and 550206, differed only slightly from their catalog values. Liquid 550206 is produced frequently and sold in large volume and as a result, Cargille had a good data base of index measurements from previous lots. As this kind of data gives a good indication of the variation in properties from lot-to-lot, the measured indices from twelve different lots were obtained from Cargille and are presented in Fig. 10. Several interesting things can be seen in this plot. First, the lot data is remarkably consistent, considering that nearly all the data spread is contained within the measurement error bars. This is probably as consistent as most optical glasses. The second observation is that the catalog data is not very representative of the average dispersion. Note that there is a strong linear component to the difference between the catalog data the average of the lot data. This linear component (which is similar to a change in Abbe number) is also reflected in the vertical component of the catalog-to-lot change vector shown in Fig. 9.

From the limited number of Cargille liquids evaluated by the author, it would appear that basing optical designs on catalog index data alone would be quite risky. As is always the case in apochromatic designs, accurate index measurements at many wavelengths, should be made on all liquid lots and glass melts used in a design. It is routine to obtain precision index measurements of glasses with an accuracy of ±0.000005. Unfortunately, obtaining similar accuracy with liquids is not available from Cargille or anywhere else for that matter. On lots of the liquids 400513 and 550206 supplied to the author, Cargille performed measurements at 10 wavelengths across the visible with an stated accuracy of about ±0.0001. Since then, glass-liquid apochromats have been fabricated and tested which used the Cargille measured liquids and precision measured glasses from Schott[6]. It is therefore possible to infer the true index of the liquids (or at least a more accurate estimate of it) through a backwards calculation of the index of refraction from the measured performance data. The difference between the index given by a model based on the Cargille measurements and that inferred from the measurements of the lens assembly is shown in Fig. 11. It is noted that Cargille's measurement error is everywhere smaller than their stated tolerance of ±0.0001 and very much smaller than this outside of the blue end of the spectrum.

5. MECHANICAL CONSIDERATIONS

The glass-liquid apochromat presents some new challenges in opto-mechanical design. The most significant is to join the rims of the glass elements together to form a leak-free volume without distorting the optical surfaces of the glass. Shown in Fig. 12 are several sealing arrangement possibilities. It has been the author's experience that a seal on the edge of a lens is superior to a seal on its face of a lens (i.e. the optical surface). This is because adhesives always have some amount of shrinkage during there cure and this can introduce distortion in the lens surfaces. For similar reasons, flexible adhesives are better than rigid ones (i.e. epoxies). Adhesives that air-dry or require atmospheric moisture to cure (e.g. RTV's) seem to have more outgasing products and this can contaminate optical surfaces and liquids more than would adhesives which cure with a catalyst (e.g. two-part cure systems like epoxies) or UV radiation. Two-part curing systems are also much more reliable in achieving a complete cure (and therefore good sealing) in deep pockets and recesses and with thick bond lines. Using the proper primer on all bond surfaces is also very important in achieving good adhesion and sealing. Many optical liquids are very penetrating and poor bonds will surely result in leaks.

Dow-Corning has a new fluorosilicone sealant, X5-8738, that appears to be ideal for glass-liquid apochromats[7]. It is a two-part, slow-flowing sealant that cures to a tough rubbery elastomer. It does not require moisture to cure and will cure in deep sections with no by-products produced. It is resistant to nearly all optical liquids (also gasoline, motor oil, and many solvents). It remains flexible over a wide range of temperature (-57° to 260°C) and is not effected by weathering, vibration, moisture, or ozone. An effective primer for good adhesion to metals (aluminum,steel, stainless steel, brass, etc.) is Dow Corning A-4040 prime coat.

The cross-section view of a two-liquid, three-glass element lens which shows the edge sealing details and the filling ports is given in Fig. 13. Rather than have an integral expansion volume (for the liquid expansion/contraction during temperature changes), this lens takes advantage of the flexible nature of the fluorosilicone edge seals which can accommodate small volumetric changes of the liquids without inducing wavefront disturbing stresses.

Long term stability data on optical liquids is still rather limited. However the author has glass-liquid apochromats based upon the liquids 400513 (a siloxane) and 550206 (triacetin and ethyl cinnamate) that have been measured periodically over a period of three years and to date, no measurable changes have occurred.

The author is grateful to Robert Sacher of Cargille Labs for access to data on lot dispersion properties.

6. SUMMARY

The incorporation of abnormal dispersion liquids can yield optical designs which are exceedingly well color corrected and yet economical. To date, only a few optical liquids have been characterized to the level required in high performance apochromats but the results from those have been most encouraging.

7. REFERENCES

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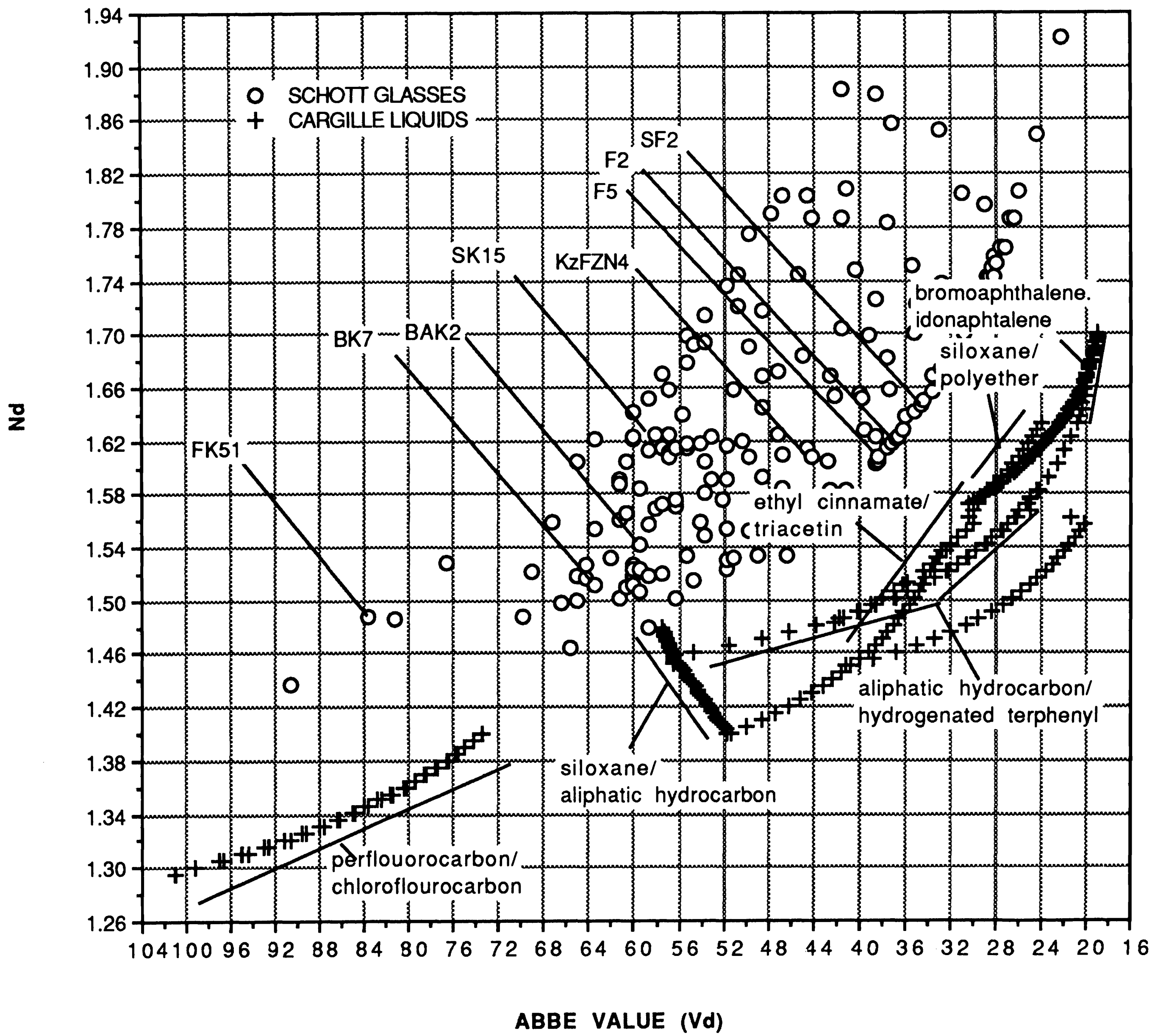


Fig. 1 Plot of Nd vs. Abbe number for Schott glasses and Cargille liquids.

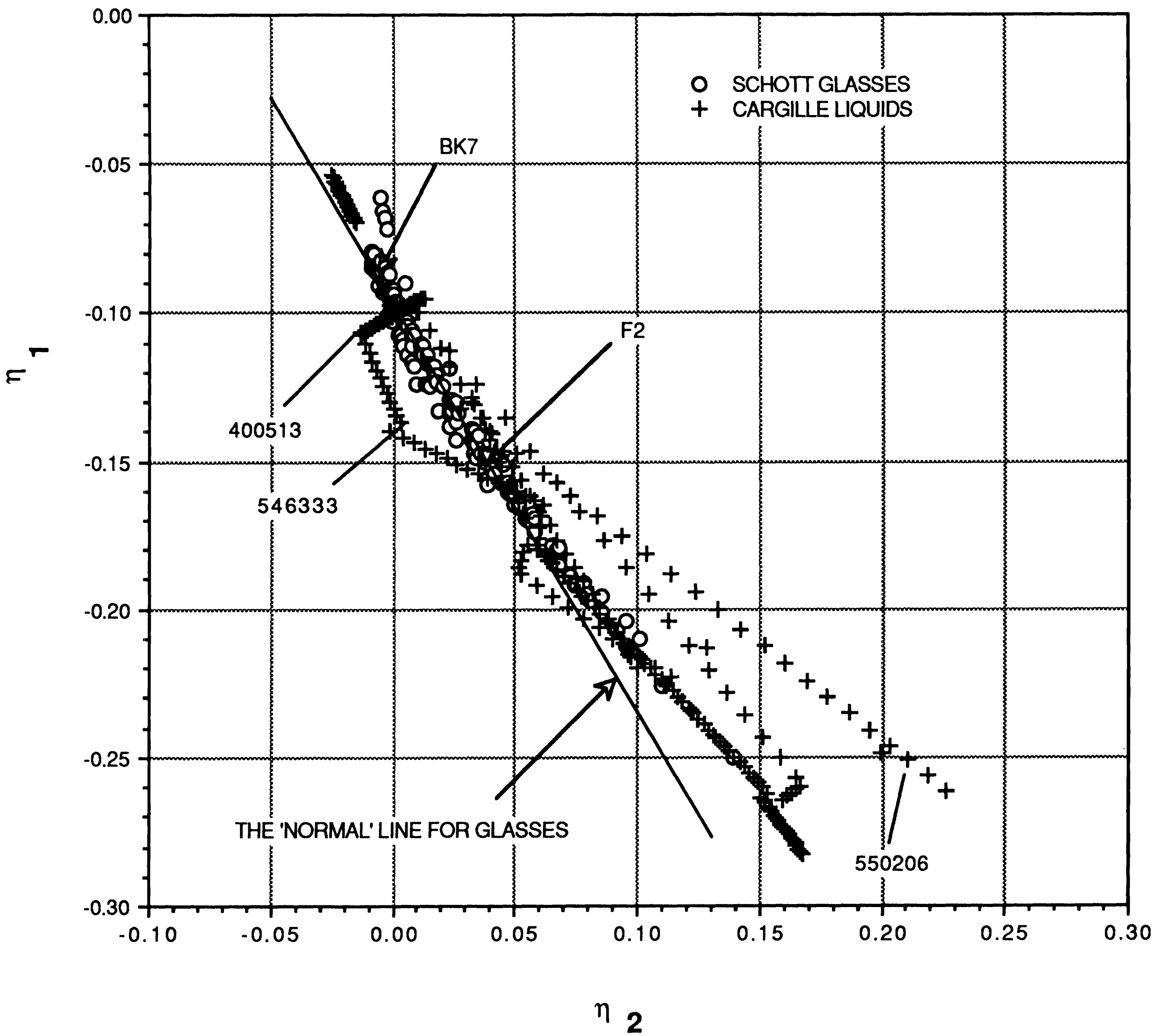


Fig. 2 Buchdahl dispersion map for Schott glasses and Cargille liquids.

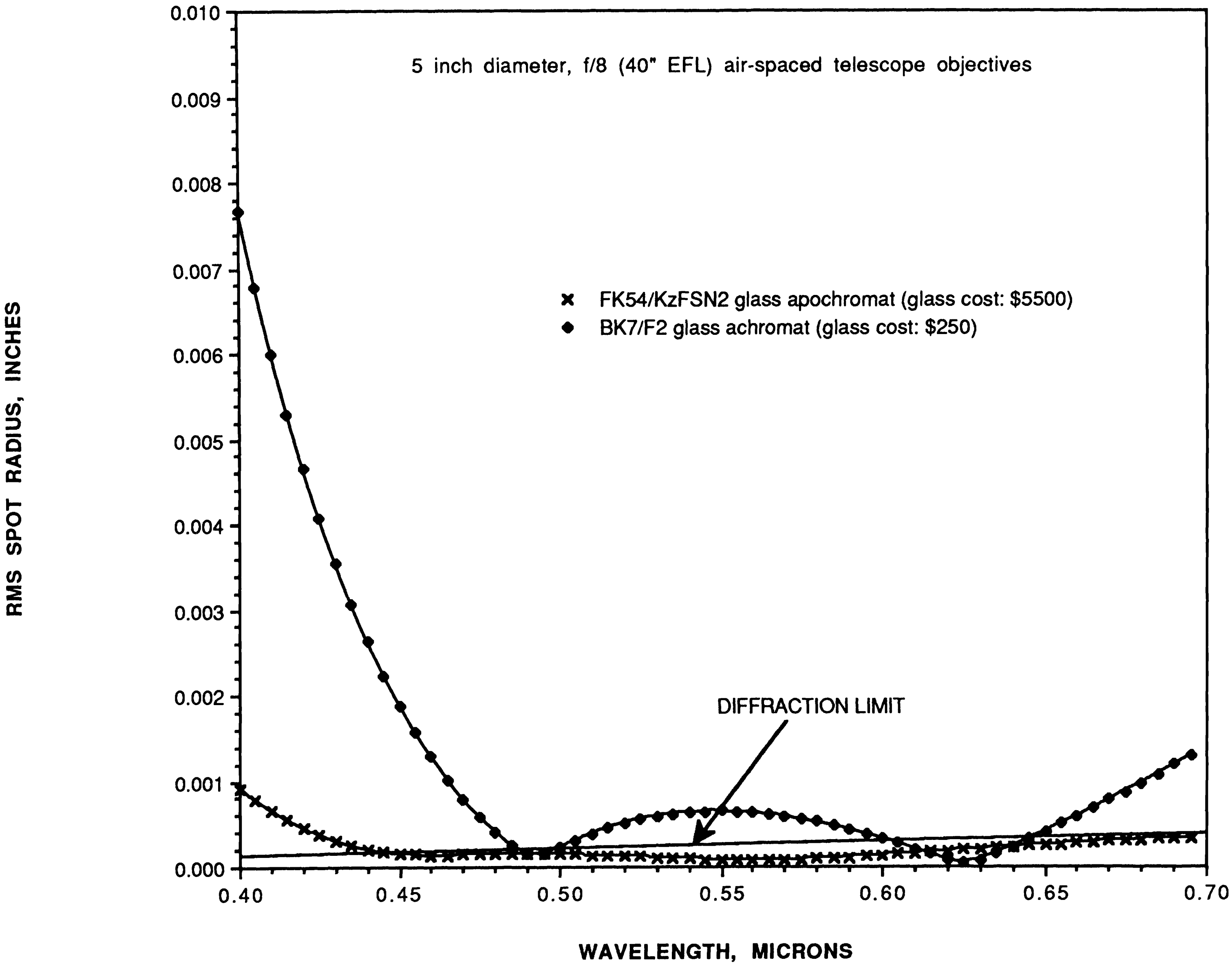
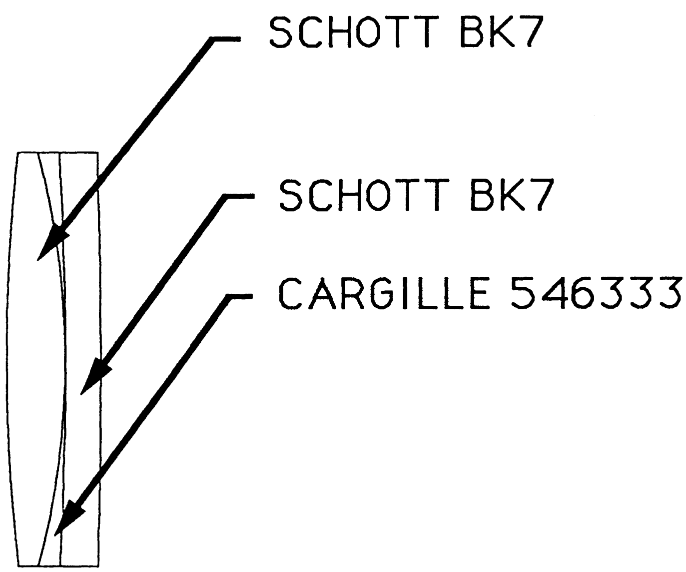
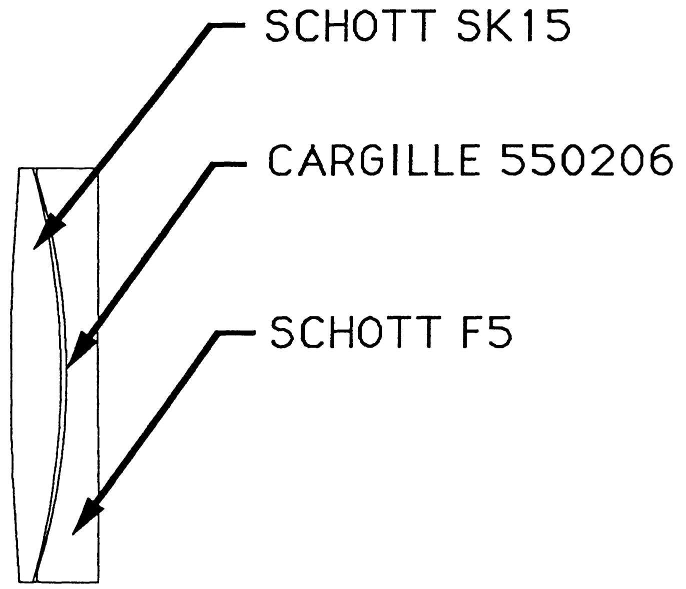


Fig. 3 RMS Spot radius vs. wavelength for two all-glass objective designs.

5 INCH DIAMETER, F/8 TELESCOPE OBJECTIVES.



A ONE GLASS, ONE LIQUID EXAMPLE.



A TWO GLASS, ONE LIQUID EXAMPLE.

Fig. 4 One and two-glass, one-liquid apochromat designs which use common glasses and an abnormal dispersion liquid. These designs are corrected for spherical aberration, coma, and are color corrected at three wavelengths.

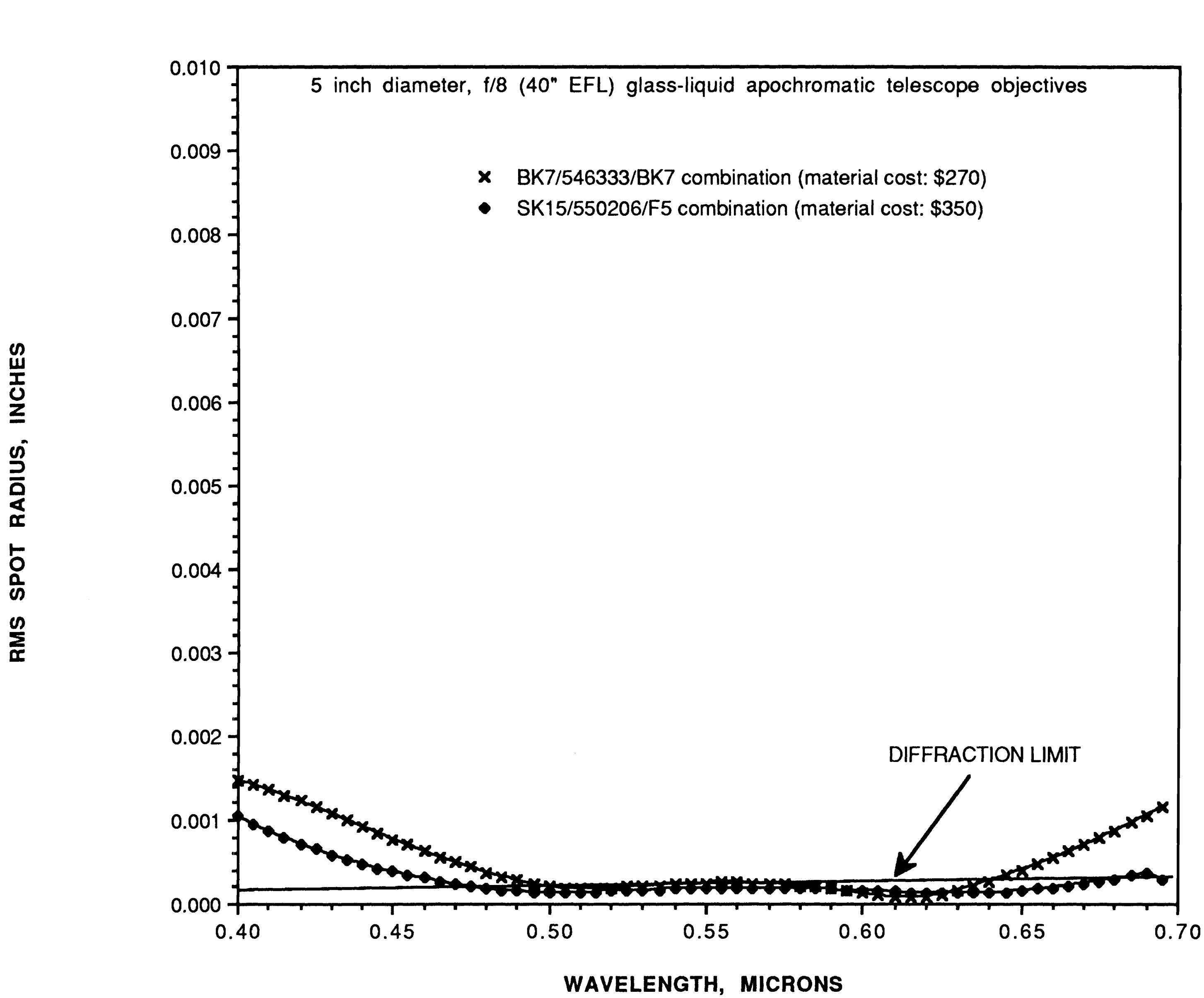


Fig. 5 RMS Spot radius vs. wavelength for apochromats with common glasses and one liquid.

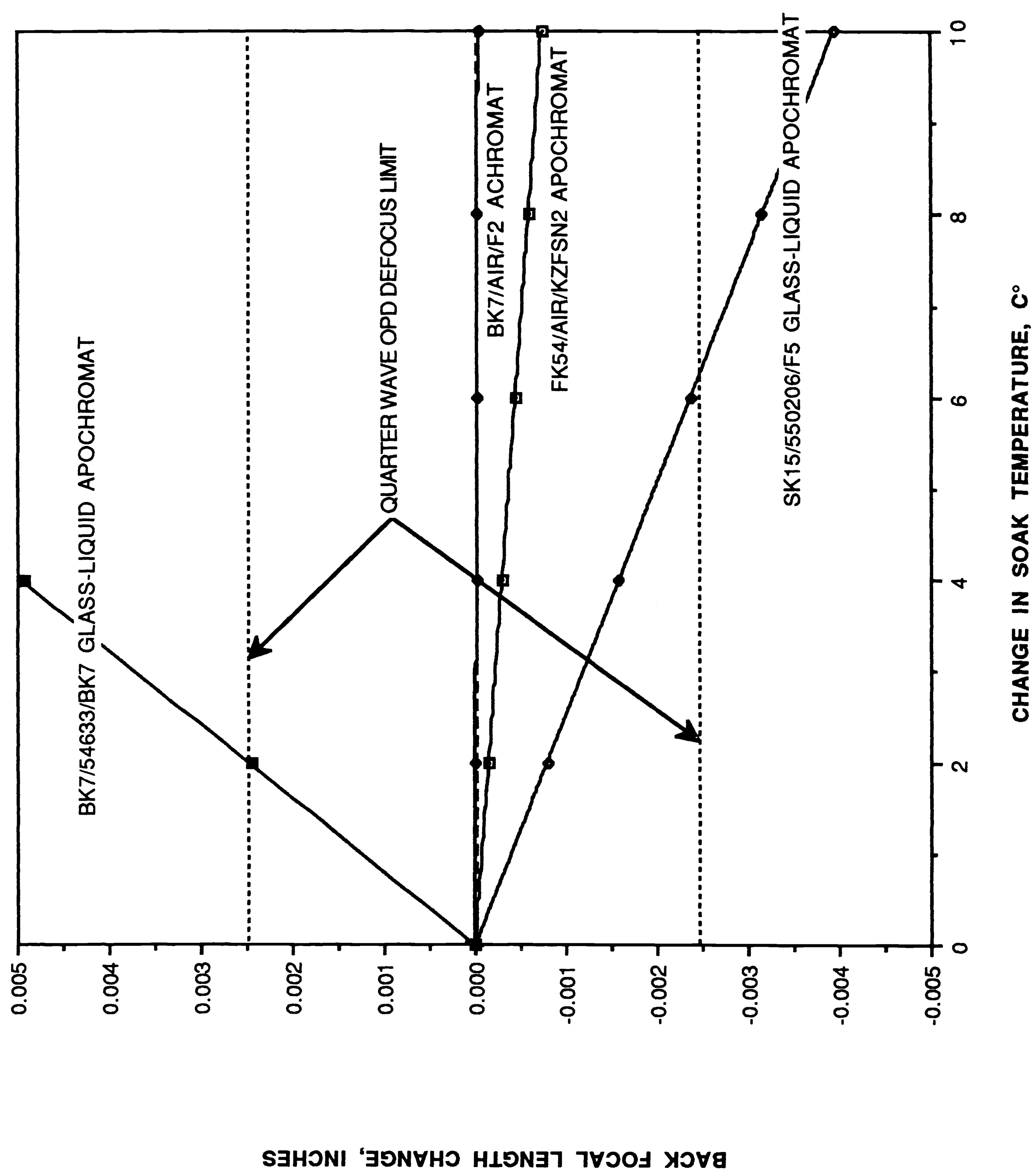


Fig. 6 Focal length change with temperature in single liquid apochromats.

5 INCH DIAMETER, F/8 (40" EFL) TELESCOPE OBJECTIVE

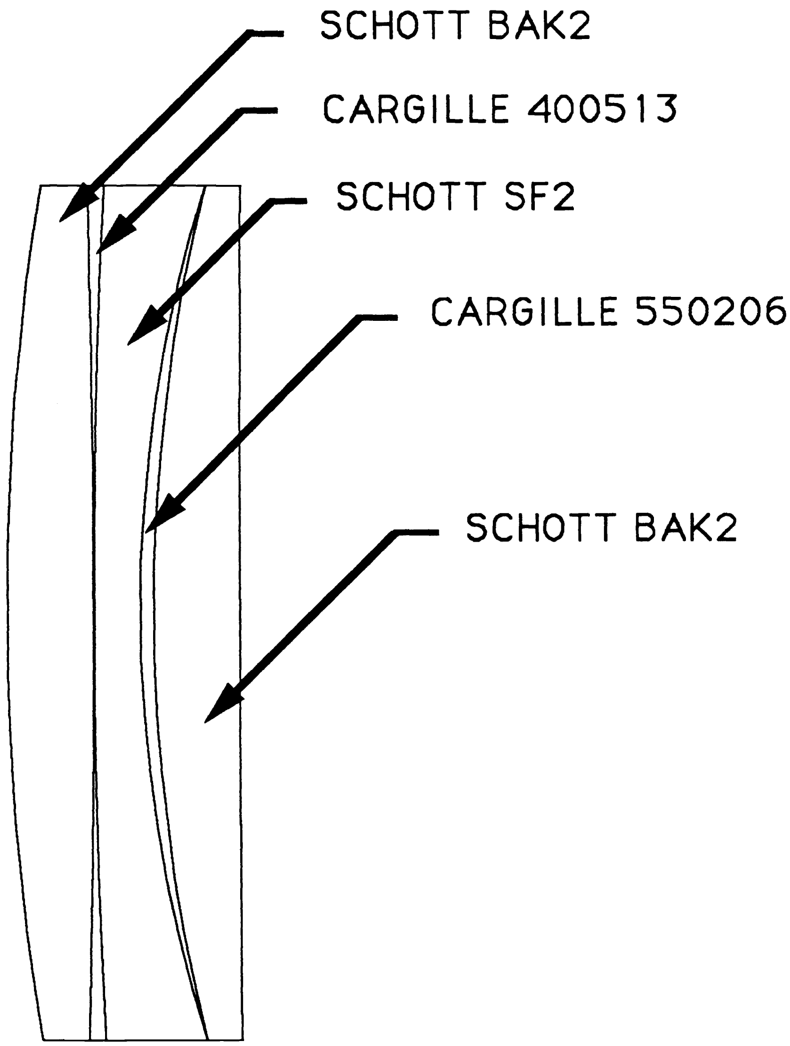


Fig. 7 Two-glass, two-liquid apochromat design using normal dispersion glasses and abnormal dispersion liquids. This design is corrected for coma, spherical aberration and chromatic aberration and its focal length is unaffected by modest uniform changes in soak temperature.

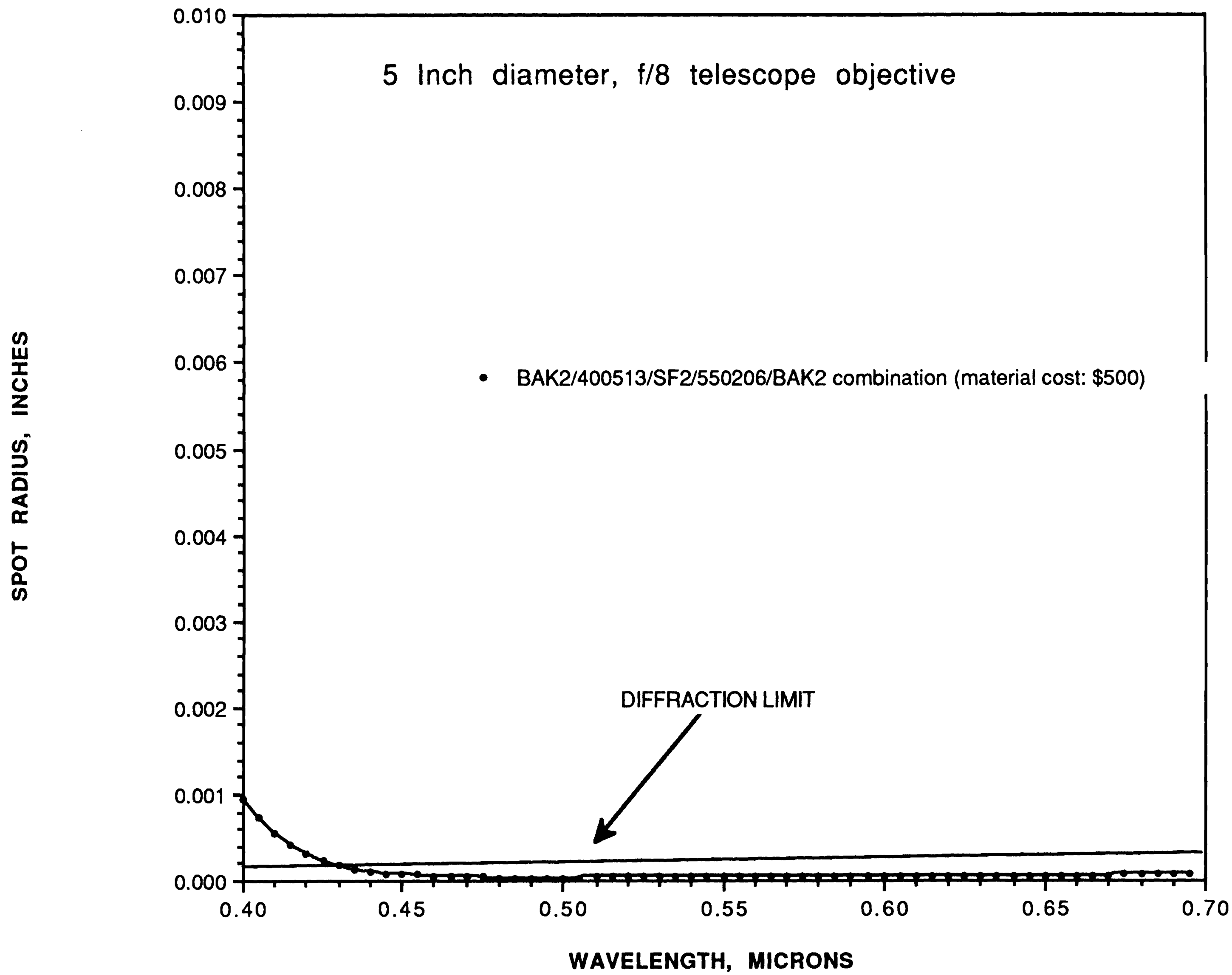


Fig. 8 RMS Spot radius vs. wavelength for a two-liquid, two-glass, athermal glass-liquid apochromat.

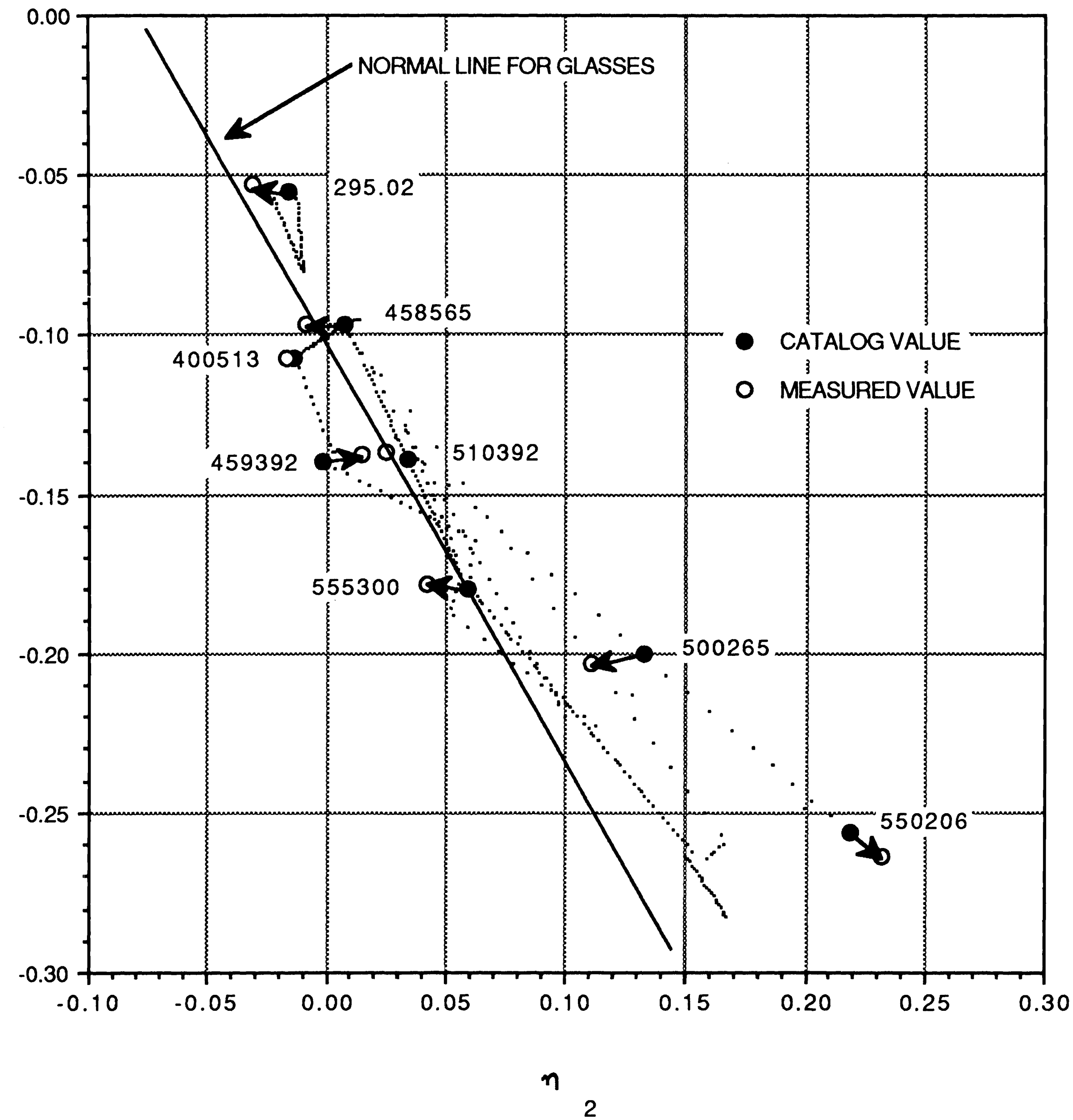


Fig. 9 Catalog and measured dispersion values compared for eight Cargille liquids

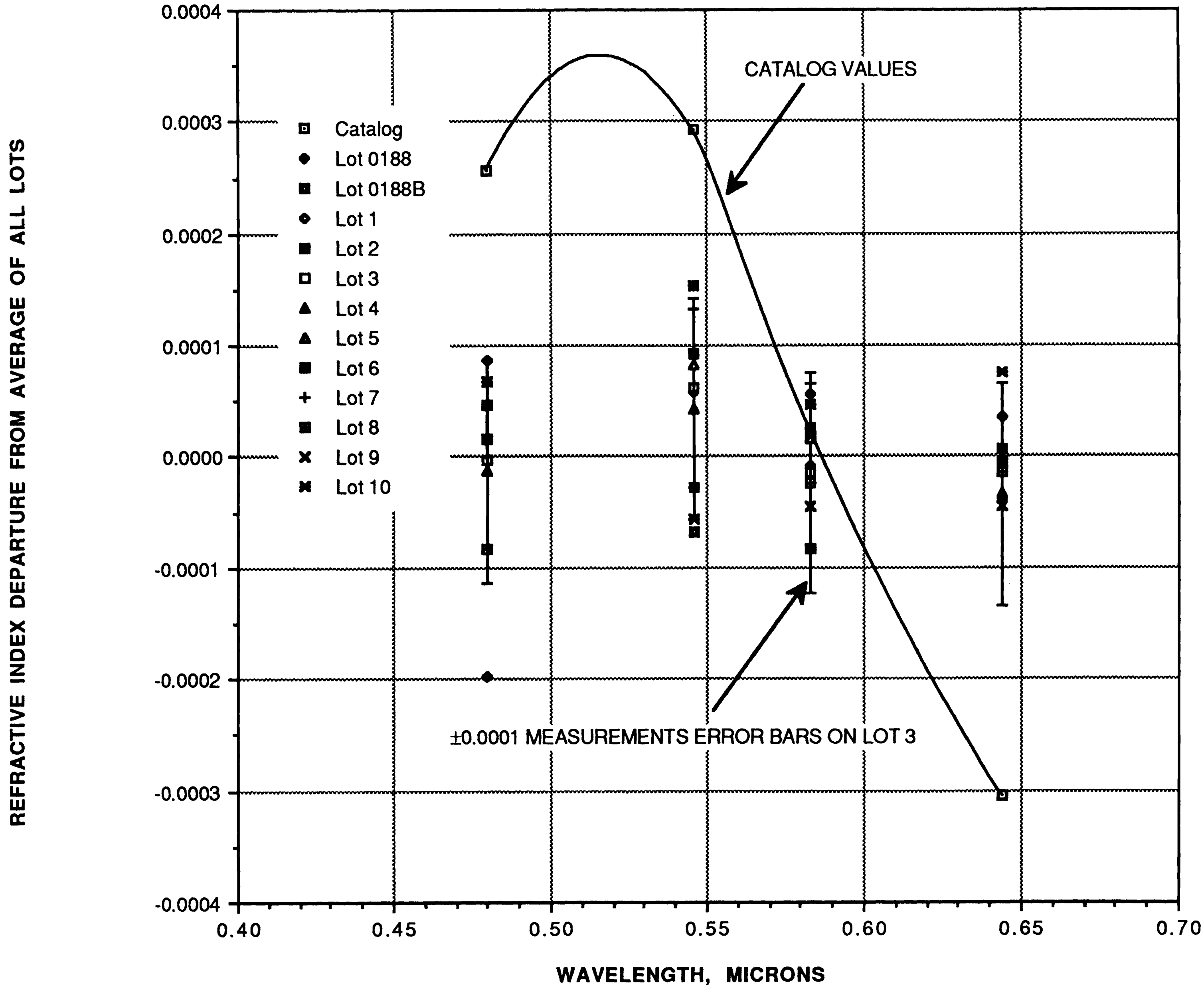


Fig. 10 Refractive index changes in 12 different lots of Cargille liquid 550206.

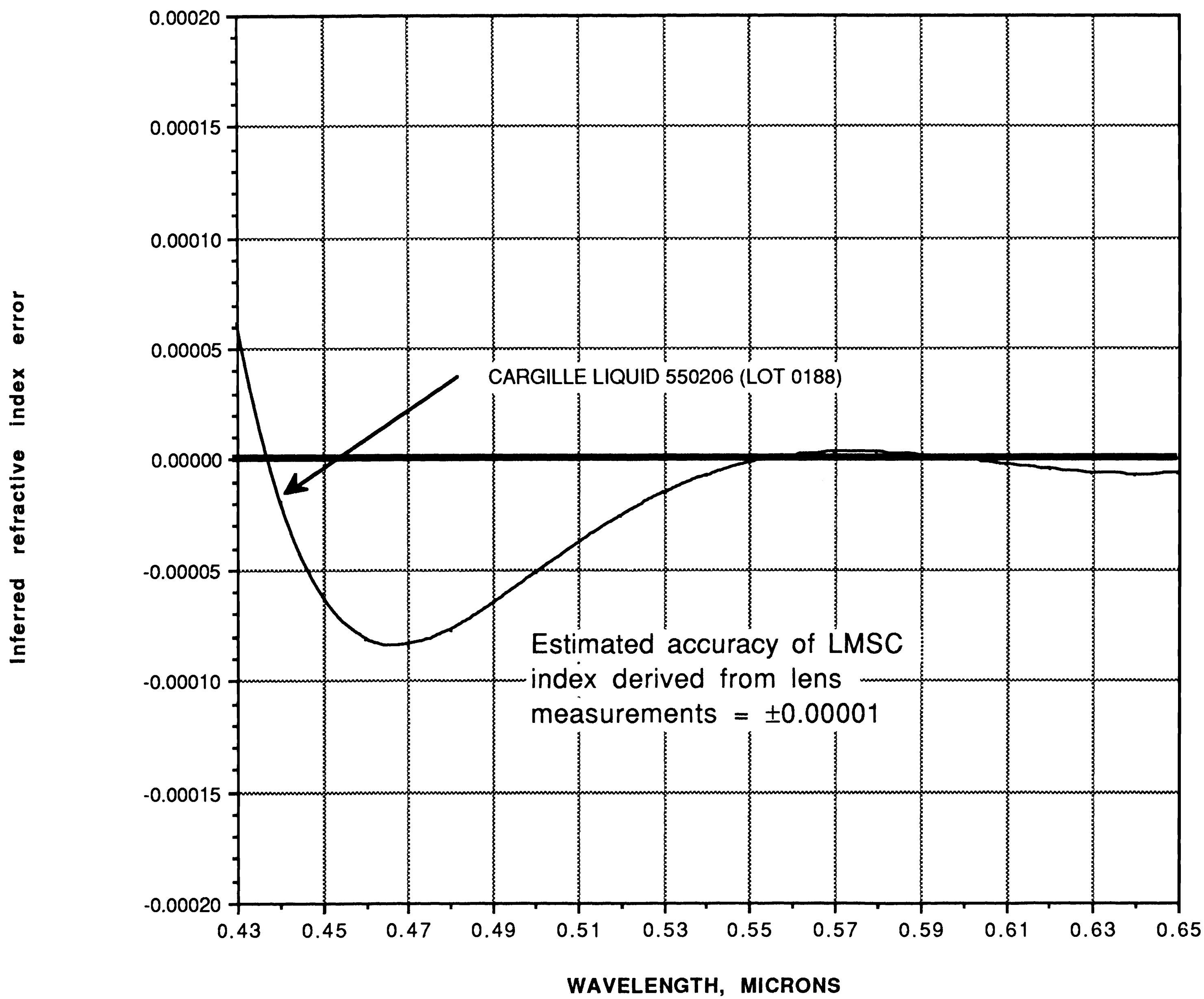
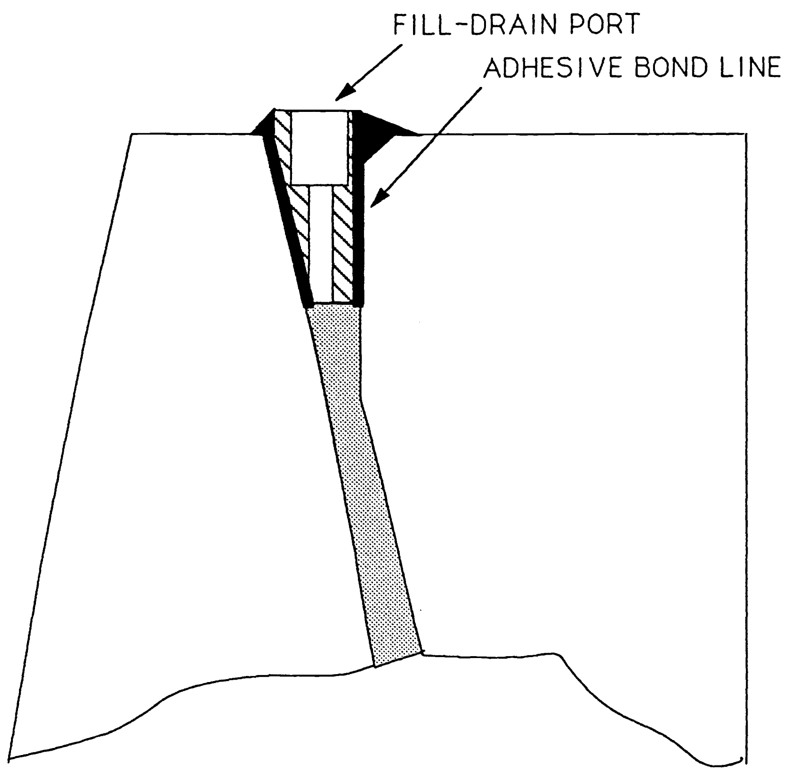
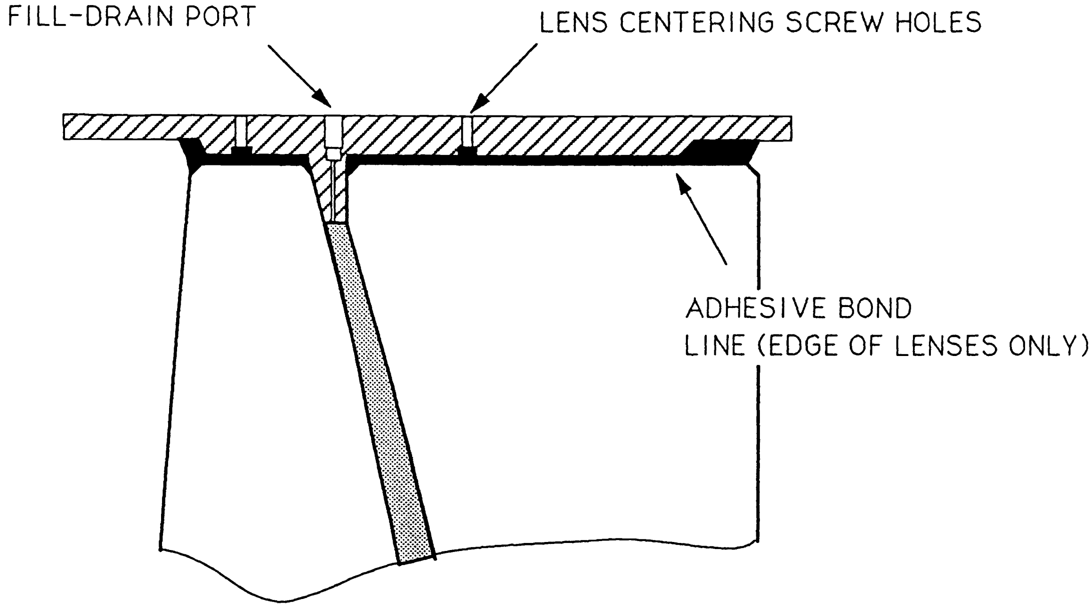


Fig. 11 Refractive index error of a dispersion model based on Cargille measurements (inferred from LMSC measurements of lens assembly).



FACE SEAL DESIGN



EDGE SEAL DESIGN

Fig. 12 Glass-liquid lens seal design options.

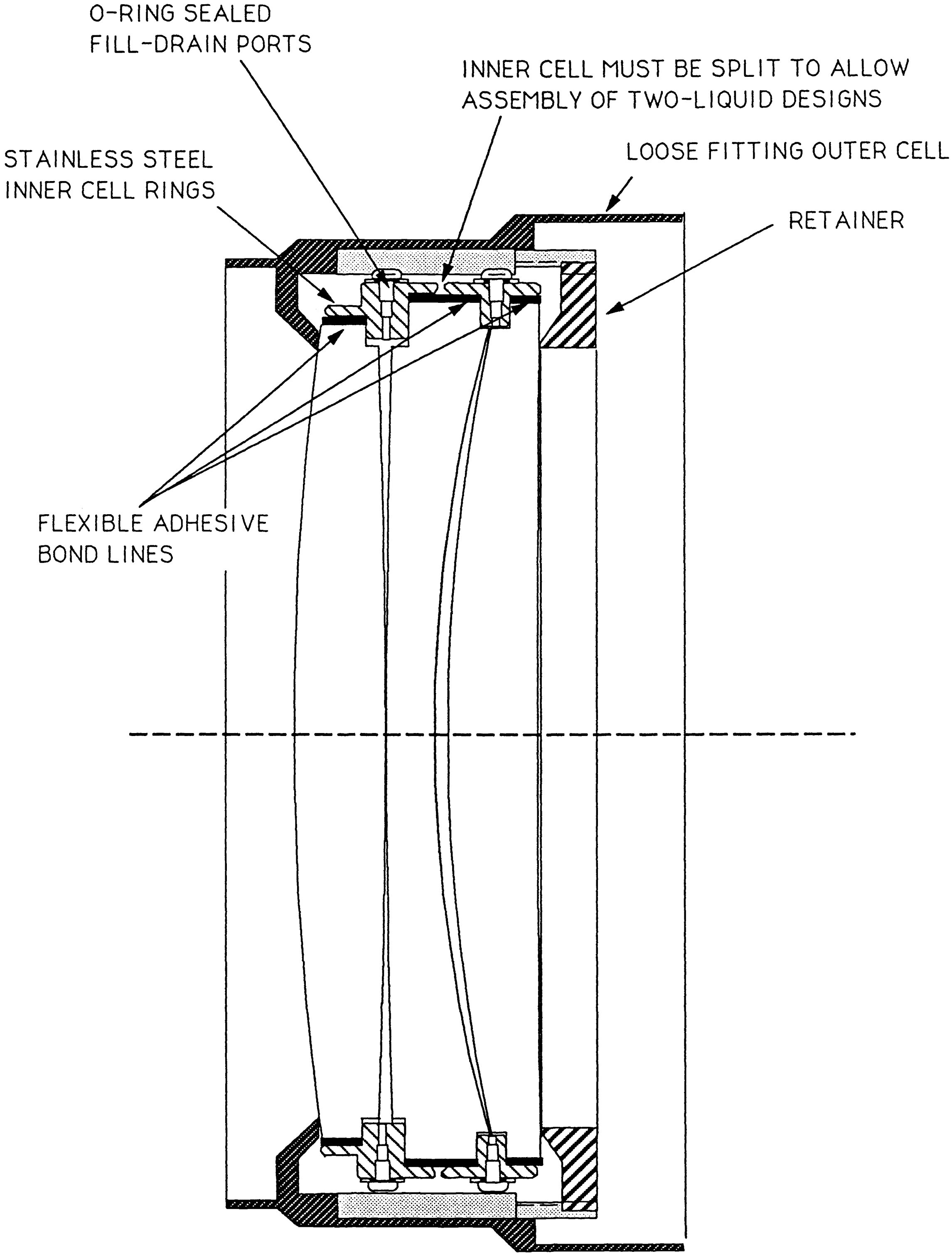


Fig. 13 Lens cell design details for two-glass,two-liquid apochromatic objective.