Chapter 4b. Survey of Apochromats (Triplet Systems).

Triplets form the mainstay of present day apochromatic designs. This is because by adding a third element it becomes much easier to manufacture high-performance lenses cost-effectively; and more combinations of glasses are available to do the job. Yet even here there are limits as one pushes for faster and faster focal ratios. If diffraction limited performance and exquisite color correction are demanded at f/7 for a 150mm lens, then it may be necessary to add a fourth element. Or a radical departure from the closely spaced lens arrangements which we have seen so far may also be contemplated. The Petzval lens in which there are two widely separated doublets may prove helpful (cf. Chapter 5). Of the rich variety possible in three-element lens combinations, we will survey a sampling in the present chapter.

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The next step forward in the design of practical apochromatic triplets for amateur astronomy came when it was realized that although cementing large lens elements was not possible, filling the gaps between them with a very thin layer of oil (or special index matching gel), and sealing the edges of the lens was feasible. I do not know when this realization occurred. Certainly, James G. Baker, the famous American optical designer, understood it by 1963, when he suggested building various large half- and full-apochromatic objectives cemented together with "liquid cements...now available" [cf. Baker, p. 125ff.]. Probably the realization occurred to various people independently of one another.

At present, a common method of sealing the edges of oil-spaced lenses is by means of polyimide pressure-senstive tape, which goes by the tradename of "Kapton." This tape is very effective at sticking to the glass despite the oil, and forms a durable long-term barrier against leakage. As for spacing oils, many different types can work (including plain cooking oil!), but ideally one would like an oil or gel which matches the index of the glasses involved, is inert, and evaporates very slowly (therefore silicon oil has often been used). A great number of oil-spaced triplets have been manufactured since the 1970s and I personally know of lenses over 20 years old which show no leakage of oil or deterioration. So oil-spacing can be considered a permanent or at least long term solution. If the oil layer ever becomes dirty or damaged in some way, it is possible to separate the lens elements, renew the oil, and retape the lens without harm to the glass.

The first person I know of who introduced an "oil-immersion" type of apochromat to amateur astronomy was Wolfgang Busch, who independently invented the procedure of oiling (1). In 1977 he published an important article in the German popular astronomy magazine Sterne und Weltraum ["Stars and Space": for the article, cf. 1) & 2) ; for an English translation, cf. 3)]. In it he described how to make a short-flint triplet easily from prefabricated sets of lens blanks which he in conjunction with H. Reichmann Precision Optics of Brokdorf, Germany, were selling as kits [cf. W. Busch, "Herstellen eines fast apochromatischen Fernrohr-Objectivs aus vorgefertigten Teilen," in the "Tips für die Astropraxis" department of Sterne und Weltraum 16 (1977), pp. 338-341; also cf. "20 Jahre Kompaktobjektive mit Ölfügung," parts 1 & 2, in Sternkieker (nos. 1 & 2, 1995), pp. 18-19; 77-78]. Accompanying the article was an advertisement from the Reichmann company offering kits for two apertures, 130mm and 150mm both at about f/15. Since Busch's work has been so little known in the English speaking world, in what follows I offer more extended coverage of it than of other, better known designers or lens types.

Busch considered his design to be an improved type of half-apochromat, though in practice with nearly full apochromatic performance. His kits and procedures for producing the objectives were ingenious, and it is unfortunate this his contribution to the wide-spread dissemination of apochromatic objectives among amateur astronomers in recent decades has been so little known outside Germany.

Busch's optical design was broadly as follows: his lens consisted of sandwiching a piece of Schott KzFN2, a slightly abormal-dispersion short-flint, between two pieces of Schott B270, a type of crown glass not normally used in high precision optics, but similar to the ordinary K-type Schott crown glasses. Such a sandwiching arrangement of one type of glass between two specimens of another glass will be seen later in this chapter (cf. Table 9) when we consider the high performance triplet ED apochromats. In principle, the color correction and performance of Busch's lens should be similar to the short-flint doublets we saw in Chapter 4a, since the same types of glasses are involved. But Busch had two cards up his sleeve which altered that performance fundamentally for the better. The first and most important was the oil-spacing. By filling the gaps between the glasses with oil, he essentially nullified the interior surfaces' contribution to the lenses' wavefront errors, a feature we have discussed previously. Then too, the oil film automatically regulates the spacing and tilt between the individual lenses, largely removing the causes of coma in the air-spaced Taylor and Zeiss B objectives.

Busch's second card was to split up, as it were, the crown element of a standard short-flint doublet into two pieces, placing them one in front and one in the rear, and dividing the optical power between them. By doing so, he could achieve weaker curves on all the lens elements and diminish the monochromatic aberrations associated with strong curves, especially the spherochromatism. He could also in this way have enough degrees of optical freedom to correct coma, and fully protect his short-flint element from weathering, since it would be sandwiched between two weather-resistent exterior crown elements, and excluded from humidty and chemical attack by the oil layer. Indeed, Busch left his protype triplet outside in the weather of Hamburg, Germany for two years before exhibiting it at a meeting in Cologne in 1976 [cf. "Herstellen...," p. 338]. The weather-resistence was further enhanced by Busch's choice of glasses, since his short-flint was one of the most chemically stable which Schott made, and the crown glass is nearly inert.

But Busch's great merit is shown in how he developed his design into a lens which could actually be made by an ordinary ATM without any more equipment than is needed to make a Newtonian mirror. Part of the driving force behind his choice of glasses was the realization that if the difference in the index of refraction from crown to flint was sufficiently small, it would be fully possible to leave all four interior surfaces of the lens combination fine ground, but unpolished. The oil film would fill in the grinding pits and no reflection would be seen between adjacent interior surfaces. The fine ground surfaces would look entirely transparent to the naked eye!

To demonstrate this astounding fact, the editors of Sterne und Weltraum magazine displayed on the first page of Busch's article a photograph of a finished objective left with fine-ground interior surfaces. Below the lens lies a sheet of music, partly covered by the lens and partly left uncovered. Close observation of the photo shows that the lens has just been oiled and that the oil is still spreading between the elements. At center the lens appears beautifully transparent where the oil film lies. But then comes a larger annulus of glass which the oil has not yet reached. This area appears fine ground and matte.

Moreover, three years later in 1980, B. Wedel of the Wilhelm Foerster Observatory in Berlin published an independent appraisal of a 150mm f/15 Busch objective [cf. "Ein Vergleichstest: "Immersionsobjektiv" von Wolfgang Busch--Zeiss-B Objektiv," Sterne und Weltraum 19 (1980), pp. 422-423]. Wedel noted that everyone's scepticism concerning transparency vanished as soon as the objective was actually seen, and that some experienced planetary observers actually felt that the Busch objective slightly outperformed a 150mm f/15 Zeiss B, brought in to allow direct comparison with an apochromat of known high-performance [cf. also W. Rohr, "Erfahrungen mit einem Immersions-Objektiv HAB 130/1900," Sterne und Weltraum 18 (1979), pp. 313-314].

According to Wedel, comparative photographs of M3 taken through both telescopes showed the same limiting magnitude, although the Busch objective gave a somewhat darker background. On the other hand, the Zeiss B showed slightly sharper images when the photographs were examined under a microscope. Despite shining a laser through the Busch objective, Wedel could see no more scatter from the unpolished interior surfaces than from the polished exterior ones. Whereas, photoelectric measurements demonstrated the theoretically superior color correction of the Zeiss B. Visual assessment, however, failed to detect any practical difference in performance.

Thus, it was a draw. Wedel and his observers gave high marks to the Busch objective, comparing it favorably to the Zeiss lens. Since according to Busch himself, one could build his objectives from the kit for about 1/3 the price of a comparable finished lens, clearly this type of objective represented a very good value to the enterprising ATM.

I can myself corroborate much of this from personal experience, having built and used three Busch objectives. The oil films render them completely transparent. No scattered light is visible during a star test, lunar or planetary observation, or when examining a bright light bulb directly through the objective. The interior glass surfaces appear as if completely polished, and the objectives performed magnificently.

But Busch offered still more. One of the most formidable obstacles to amateur construction of refractors is certainly the need for a carefully made lens cell. But a complete cell in metal was offered as part of the kit. Another obstacle is the need to "dewedge" the lens elements. "Wedge" consists in the non-uniformity of thickness as one proceeds around the periphery of a lens. In other words, at 12 o'clock (say) on the lens as you face it, you have a thickness of "x," whereas at 6 o'clock you have some other thickness. Hence, the lens as a whole has a slight "wedge" component to its shape, rather like a prism. This error, if left uncorrected, will stretch a star image into a short spectrum, just as a real prism will. The spectrum is, of course, the aberration called "lateral color" which we studied in Chapter 2.

Normally an optician will grind away the wedge-error, but an ATM familiar only with mirror-making will not possess the know-how or have the proper equipment to measure and verify the result. Hence, the ATM's objective lens may show lateral color. But lateral color can also arise from decentration of the lens elements with respect to one another. Busch overcame both these problems by making his KzFN2 element somewhat smaller in diameter than the B270 elements which surrounded it and by providing four plastic centering screws built into the lens cell. The centering screws pressed lightly against the KzFN2 and allowed the user purposely to change its centration, thereby also changing the amount of lateral color produced by the objective. This meant that even if the lens elements had some wedge, the user could compensate by adjusting the centration of the middle element. Thus, the user could remove any lateral color, arising from fabrication errors, during use at the telescope. Even more ingeniously, the user could compensate for atmospheric dispersion in stellar or planetary images by similarly adjusting the lens. I have myself performed such adjustments on Busch objectives and they work perfectly.

Busch's HAB ["Halbapochromat Bausatz"] system was therefore extremely practical and really did put a high-quality half-apochromat within reach of a mirror maker, without the need for additional know-how or fabrication equipment. The kit itself came with a set of excellent instructions by Busch, which I have seen courtesy of H.C. Schröder, an engineer in Germany who also supplied me with a detailed prescription for the 130mm f/15 objective, as well as with an engineering drawing and list of the kit's contents as supplied by Reichmann Precision Optics. According to Reichmann, the kit contained the following: 3 lens elements, bevelled, edged round and curve generated; 1 lens cell, threaded with a retainer ring and black anodized; 4 plastic centering screws; 4 different glass filters for checking the color correction; 1 unit of special oil for contacting the lenses; grit, polishing compound and pitch; detailed working instructions; and 1 grinding tool for working the exterior lens surfaces.

The instructions from Busch told in some detail how to grind the interior lens surfaces together, as well as how to use the grinding tool on the outside surfaces, and when to stop. The level of detail and various reminders are appropriate to the needs of someone who has successfully finished one or two paraboloidal mirrors. Much more interesting, however, are the instructions concerning oiling, polishing, figuring, and testing. Busch recommends using a slight amount of oil, just enough so that after a number of hours, the oil layer will finally expand to reach the outer edge of the lens. No taping is required or indeed possible because of the centering screws.

After oiling, the assembled objective is inserted into its cell, and then polished and figured on its exterior surfaces. The very valid reason for doing this is to avoid flexure of the lens elements, if they are polished individually on the usual grinding stand or machine. This could introduce zonal errors or astigmatism, especially in the hands of an inexperienced lens maker. With the whole objective assembled in the cell, the exterior lens surfaces become in effect far stiffer and more resistent to flexure since the exterior lenses rest on those below them. The total stack up of glass is quite stiff and the oil layer (properly applied) is incompressible.

Now the one real difficulty with Busch's lens (a prescription for which will be given in a moment) is that it requires a somewhat aspheric exterior front surface. But in a stroke of genius, Busch tells how to produce the required asphere almost automatically. He describes how to cut a paper ring, place it between the first and second lenses resting on the oily layer between, and then how to polish the outer surface of the first lens with somewhat more force than usual. Because the paper ring only the supports part of the front lens (its outer periphery), and leaves the rest (midsection) unsupported, more polishing action will occur over the ring and in its vacinity. Less polishing will occur in proportion as one moves toward the center of the lens. Thus gradually with persistence an oblate ellipsoidal surface will arise, which is exactly what is needed.

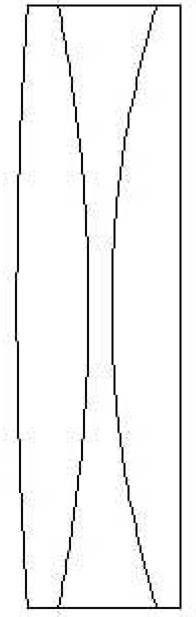
For testing, Busch suggests using the Foucault or Ronchi test with a slit source. He outlines four test methods: autocollimation against a flat mirror; use of a Newtonian telescope to create a collimated beam feeding the objective under fabrication; use of a finished Fraunhofer achromat for the same purpose; and barring those methods, use of a bare slit placed at a large distance and nulling the objective for blue light. All these methods should be valid, and armed with them the ATM has everything necessary to make a finished lens. No wedge testing, no spherometry is necessary; one does not even need to polish four of the six surfaces! It was a marvelous kit and a clever plan! Alas, it was little known outside of Germany. But certainly Wolfgang Busch's name and achievement deserve to be known by lovers of fine apochromatic lenses. Perhaps never before had anyone marketed a refractor kit of any kind that was so wholly practical, so clearly and completely thought out and described.

A Busch-type lens may be formed as follows:

Surface	Type	Radius	Thickness	Glass	Diameter	Conic
Object	Standard	Infinity	Infinity		0	0
Stop	Standard	1081.885	19	B270	160	0.449
2	Standard	-405.421	6	KzFN2	160	0
3	Standard	268.536	18	B270	160	0
4	Standard	Infinity	2220.457		160	0
5	Standard	Infinity	-0.064		39.407	0
Image	Standard	-846.714			39.421	0

Table 4: 150mm f/15 "HAB"-Type Semi-Apochromat

The layout of the lens looks as follows:



4. 150mm f/15 "HAB"-Type Semi-Apochromat

The ray fans come next:

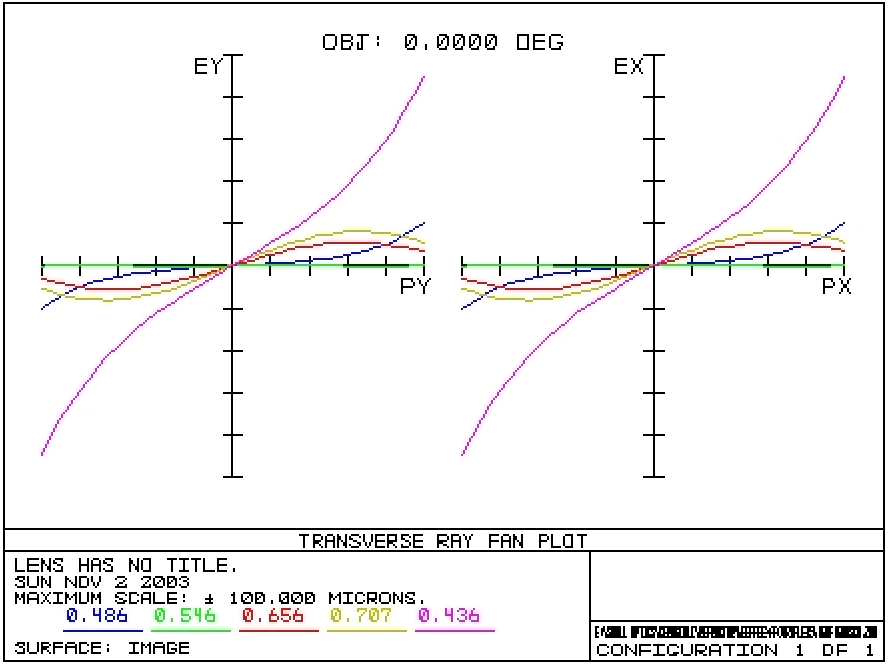


Figure 7: Ray Fans for 150mm f/15
HAB"-Type Semi-Apochromat

And the spot diagrams, in which I have omitted deep red (0.707 micron) and violet (0.436 micron) in order to make the Airy disk more clearly visible:

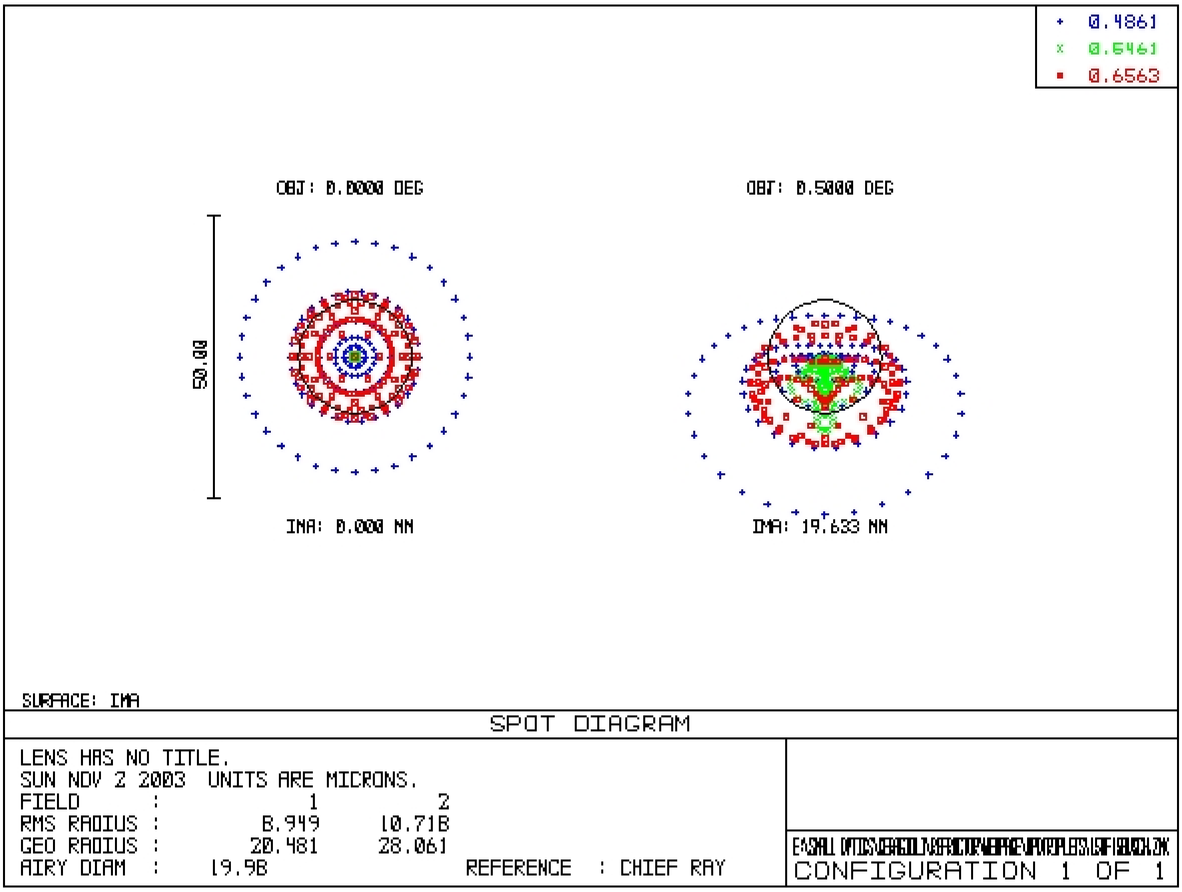


Figure 8: Spot Diagrams for 150mm f/15 "Busch System"-Type Triplet

Obviously, the performance is not as good as that given by the Taylor or Zeiss types of apochromats, but it is still respectable and far better than an achromat. The red rays just fill the Airy disk, while the blue form a disk no more than twice as large. Violet is not well controlled, but since it is so faint this hardly matters for visual observing. There is a small amount of coma, but its magnitude is trivial and could not be seen in practice. Overall, the Busch objective has achieved an outstanding balance between performance and practicality. The kits are no longer available, and KzFN2 has gone out of production. But similar and better corrected lenses can be formed from KzFSN4 and the ED glasses.