Introduction

It has been my experience that there is something about a long-focus refractor that draws people to it. If you take one to a public star party, it will attract the longest line. If it contains a lens that you made with your own hands, you have an effective answer to the question “What kind is it?” You will certainly provide that answer with a great deal of pride. The “wows” you hear, as spectators look at the crisp image of the Moon or Saturn, will be well worth the effort it took to take it out and set it up on a cool dark night. But, make a refracting lens? That almost seems to be impossible at first thought—even for those people that have made one or more mirror objectives. Doesn’t that require some sophisticated machinery, or skill beyond that endowed upon us mere mortals? The answer is that many people have made lenses. They used their hands and ordinary tools much the same way mirrors are made. Since no parabolizing is needed, it is probably easier to make a good refracting lens than to make a good mirror. Yes, care and patience are required. You can do it!

This book is about making your own refracting telescope. Although most home-built telescopes made today are classic Newtonian reflectors, commercially made refracting telescopes have, in recent years, experienced a substantial revival in popularity among a select group of observers. In the late 1970s, I designed and made the lens for a refractor which took First Prize for optical excellence at the 1980 Stellafane Convention on Breezy Hill in Springfield Vermont. During that time, and for the next decade, I offered refractor and mirror kits to the telescope making community. I am an engineer, not an optician, but I have made two refractor objectives (4-inch and 6-inch), a paraboloidal mirror, test plates, and a set of optical flats. That experience, and the experience of others with whom I have corresponded, has given me much valuable insight into how the amateur can go about making a refractor with a high probability of success. One of my customers at that time was Perry Remaklus, who I later learned is the publisher of Willmann-Bell books and also a winner of Stellafane awards. Willmann-Bell publishes books devoted to astronomy, optics, and telescope making. Sometime after I retired in 1993, Perry suggested that I expand upon the little 20-page instruction booklet that was provided with the refractor kits. I accepted the opportunity and, since then, have devoted a considerable amount of time bringing these experiences and observations together in this book, which I believe is the most comprehensive statement on the subject since Rev. William F. A. Ellison’s seminal work *The Amateur’s Telescope* was first published in 1920. However, unlike Ellison’s time, we now have the means to easily “complete the loop” in that the computation of curves can be accomplished with readily available computers and lens design software or, as I provide, spreadsheet programs, which can be found on a CD-ROM at the back of this book. In addition to this software I devote a portion of this book to providing a basic description of the underlying optical design theory so that you will not have to just blindly "plug in numbers" to the programs.

As noted before, there seems to be a general misconception that making a refracting lens is somehow much more difficult than making a paraboloidal mirror. Nothing could be further from the truth. It is true that it will take longer to make the lens, because there are four surfaces to grind and polish. However, these four surfaces are all spherical. You will have to grind them to a specified radius, but I will show you how to accurately measure these radii as you work them to the desired value. You will need patience but, you do not need elaborate machinery or specialized knowledge.

In writing this book, I have frequently written in the first person. I would like you to consider these words as those of a coach standing alongside as you work. While standing there, I can offer some general advice as well as some background regarding the process or the theory behind it. Just as a coach cannot convey everything in one sentence, a writer cannot cover everything in one paragraph. It is necessary to build up some background and then go on to other areas of the work. For the reader, the whole process may not come together until near the end of the discussion. It is therefore suggested that, if you want to get comfortable with the work, you read the instruction and then go back and read it again. If you undertake the design and fabrication of a lens, you will probably read some of the sections several times.

I have generally used English units of measurement except where metric units are normal, such as the wavelength of light or the focal length of eyepieces. I tend to be annoyed when I read an article and see the conversions written out every time a measurement is mentioned, for example 2.30 inches (5.843 cm.). I have done this only rarely. A list of conversion factors is given in Appendix E.

This book provides details on how to design and make a two-element aplanat, a lens corrected for color, spherical aberration, and coma. It is not necessary to be a mathematician to design a lens. High school math is more than adequate using the methods and spreadsheets provided with this book. Spreadsheet ray tracing programs are provided with the CD-ROM. The equations used in ray tracing are also provided for those who want to delve more deeply into the subject. Other spreadsheets are provided to progress through a series of ordered steps to arrive at a well-corrected lens design. Methods are also provided so you can evaluate your design for residual aberrations.

For those uninterested in design work, seven well-corrected lens designs are provided. Five of these are by an expert professional and two are by the author. The apertures of these lenses range from 3 inches to 8 inches, and focal ratios from *f*/8 to *f*/15. All use the same crown glass, but three different flint glasses are used to provide different lens forms.

Detailed instructions are given for all of the fabrication processes. Purchasing the blanks, edging them (if necessary), achieving centered lens surfaces (de-wedging), grinding to shape, fine grinding, forming a pitch lap, polishing, testing, and figuring the lens are all covered. Scores of illustrations and photographs help explain the various operations. Since the surface radii and center thickness are so important in the performance of the lens, specific goals, or targets, are provided for these features as the forming and grinding processes are carried forward. These should help you avoid grinding the radii too short or grinding the lens blank too thin. There is also a discussion of methods to detect fabrication errors and how to correct them.

For the novice with no prior experience working optical surfaces, I strongly advise making, testing, and figuring a small concave spherical surface such as the mirror for a reflecting telescope. Instructions are provided to get you started. If you make a mirror in accordance with the dimensions given, it will meet or exceed the Rayleigh ¼-wave criterion and can be made into a fine Newtonian telescope to use as you work on your lens. The experience that you gain working the surface to a specific radius will eliminate considerable frustration, and possible loss of material, when working on your lens. However, based on my experience selling refractor lens kits, more than a few determined souls will ignore this advice and eventually persevere to produce an acceptable instrument. For that eventuality, I have provided extensive background material on things like glass, abrasives, and pitch along with the use of various measuring tools and the setup of your workshop. In short, this is a "How to" book.

Why build a refractor? The reasons are many and vary from person to person. Would you like a telescope that never goes out of collimation? Or that does not have tube currents? Or doesn't exhibit coma as you move the image a little off-axis? Is a perfect diffraction image without a central obstruction or diffraction spikes a thing of beauty to your eyes? Do you want a telescope that you can easily set up and view the Moon, or split tight double stars, at night, and then use the next day either viewing the Sun (with filters) or terrestrial objects? Do you get a kick out of making things with little more than your hands that are precise to a fraction of a wavelength of light? Or have you noticed that there are not many 50- or 100-year-old Newtonians being used today; while "antique" Clark, Unitron, Brashear, Zeiss and Cooke refractors are routinely used (and highly valued) by their happy owners. Perhaps it is the Newtonian's open tube and the ever present spiders looking for a dark place to spin their webs (and soil the mirrors) that is at the bottom of this "disappearing Newtonian" phenomenon. A well-made refracting telescope is far more likely to survive and become a family heirloom. If you are a dyed-in-the-wool ATM, you know that many of the telescope designs being developed today use a combination of mirrors and lenses, and building a refractor is a good way to pick up lens working skills while making a superb instrument. I could go on, but you get the idea; there are many reasons.

This book is organized into four groups of related topics. These are:

1. **Processes and materials for lens making.** Chapters 1 through 3. The first chapter provides a short outline and discussion of the steps involved

in making a lens. Chapters 2 and 3 introduce the equipment you will need and the properties of the three essential materials for making any optical element.

2. **Making a Refractor Lens.** Chapters 4 through 12 provide detailed instructions, illustrated with diagrams and photos, to lead you from rough glass to finished lens. You will learn how to grind the glass to shape, measure the critical lens shape parameters, polish the lens surfaces, and test and figure the lens. This group ends (Chapter 12) with prescriptions for seven well-corrected lenses.
3. **Associated Items.** Chapter 13 discusses various concepts and materials for the cell and tube assembly for your finished lens. Chapter 14 provides detailed instruction for the fabrication of three useful optical elements: an objective mirror, optical flats, and test plates.
4. **Optical Design.** The final three chapters cover optical design. Topics include optical fundamentals, ray tracing, and a design process for an achromatic doublet lens corrected for spherical aberration and coma (an aplanat).

There are seven appendixes with articles on a method for testing refracting lenses using a parabolic or spherical mirror, cementing lenses, relative optical glass costs and glass cross references for three manufacturers, cleaning optical elements, conversion factors, and structural considerations applicable to telescopes and mountings. There is also a bibliography of selected reference material and a glossary. The included CD-ROM contains Excel spreadsheets for the work presented in the book.

While this book is directed toward the design and fabrication of an achromatic refractor, the material relative to grinding, polishing, and figuring lenses is equally applicable to any optical work.

There is some elementary mathematics in this book—basic algebra, and even more basic trigonometry. For those who can't stand math—relax. You can ignore every equation and still make a superb lens. All the practical material is contained in Chapters 4 through 12. There are seven prescriptions (Chapter 12) that provide the design information needed to make a lens.

For the rest of you, I have not gotten into the derivation of the design equations; however, I have presented the information needed to understand the process and do your own design and analysis work if you so choose. If you want to extend your understanding deeper into optical theory, the bibliography provides a selected listing of source material.