INTERNATIONAL SERIES OF MONOGRAPHS IN INFRARED SCIENCE AND TECHNOLOGY

General Editors: G. A. Boutry, P. Goerlich, T. S. Moss, S. Passman *and* W. K. Weihe

Volume 1

RETICLES IN ELECTRO-OPTICAL DEVICES

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WITH AN APPENDIX

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PERGAMON PRESS

OXFORD · LONDON · EDINBURGH · NEW YORK

TORONTO · PARIS · BRAUNSCHWEIG

Pergamon Press Ltd., Headington Hill Hall, Oxford
4 & 5 Fitzroy Square, London W.1

Pergamon Press (Scotland) Ltd., 2 & 3 Teviot Place, Edinburgh 1

Pergamon Press Inc., 44-01 21st Street, Long Island City, New York 11101

Pergamon of Canada, Ltd., 6 Adelaide Street East, Toronto, Ontario

Pergamon Press S.A.R.L., 24 rue des Écoles, Paris 5e

Friedr. Vieweg & Sohn Verlag, Postfach 185, 33 Braunschweig, West Germany

First edition 1966

Library of Congress Catalog Card No. 65-28562

PRINTED IN GREAT BRITAIN BY
PAGE BROS. (NORWICH) LTD., NORWICH

(2629 66)

Preface

THIS book has been written for the optical designer and engineer who wishes to understand reticles in order to apply them to the working solutions of everyday problems as well as those of the once-in-a-lifetime design problem. It is intended to give a working understanding of principles, supported by specific examples traced logically as well as chronologically. The book refers to a reasonable amount of patent literature, since this is one of the few sources of detailed treatment of reticles.

The book was written for two reasons: because I have listened to too much mistaken opinion about the reticle as a substitute for everything, including good sense, and wanted to set the record, if not completely straight, at least a little less bent; and because I believed there was no other publication available in one set of covers, in or out of the open literature, that attempted to cover systematically the more important concepts and applications.

The book begins with a discussion of the form and purpose of the early reticle or scale and leads into the more modern concept of a reticle—that of a light-modulating device. Chapter 2 considers the reticle in terms of radiometry and the various operations performed in carrying out some precision measurements.

Chapters 3 and 4 are concerned with the properties of reticles as they affect the generation of error-signal problems and set forth the principles upon which well-established solutions were founded. Chapter 5 is concerned with early tracking studies. Chapter 6 treats background noise and the tracking problem. Chapter 7 discusses problems in the measurement of Wiener spectra. Chapter 8 is concerned with aerial photography and the *V/H* sensor.

Spatial filtering has been treated in Chapters 6, 7, and 8 and the Appendix. I have purposely ignored a major series of techniques and papers concerned with some beautiful mathematical concepts pertaining to the topic of spatial filtering, the lacy fabric of which I consider inappropriate; however, the Appendix does include a discussion of analytical techniques applied to reticles as space filters. This Appendix was written by Richard Legault. Chapter 9 concludes the monograph with a discussion of reticle fabrication techniques.

It will be obvious to the more informed readers that some material and some specific numerical examples are not presented in the text. Much effort on my part and considerable thought on the part of Herman G. Eldering have gone into an attempt to dig up such material, which often exists in old reports deep inside dusty files. These antiquities were never declassified and thus are not available for quotation. This left me two alternatives. I could prepare requests for declassification and permission to publish, or I could proceed to publish without benefit of such material. My estimate of one to two years of delay in publication date was the deciding factor in publishing the monograph as it now appears.

I would like to note also that there are many interesting devices and some methods discussed in a translation of a recent Russian text on infrared guidance techniques* which I believe would make an interesting companion volume to this monograph. Similarly, the German work of World War II has been reported quite well, especially by Edgar W. Kutzscher in a paper entitled "The Physical and Technical Developments of Infrared Homing Devices". His contributions appear in a collection of papers† of the Nato AGARD conference of April 1956.

I would like to express sincere appreciation to associates D. W. Montgomery, H. Morris, J. B. Conlon, and W. L. Wolfe, whose help and whose criticism made some of the above chapters longer, and some shorter than originally intended.

* I. Z. Kriksunov and I. F. Usol'tsev, *Infrared Equipment for Missile Homing*, 2nd printing, October 30, 1964, Office of Technical Services, U.S. Department of Commerce.

† *History of German Guided Missile Development*, E. Appelhaus, Braunschweig, Germany, 1956.

Foreword

Reticle is the term now applied to a large class of optical devices producing the forms of modulation that allow a large variety of instruments to separate effects of targets from their backgrounds and to produce appropriate signals that make possible a variety of processes from measurement to guidance. Under ideal conditions in a few laboratories, the radiation from a source of interest can be isolated and the stray, extraneous radiation from the floor, walls, and ceiling as well as from the room lighting fixtures can be ignored. In more cases than not, the ideal circumstances does not apply, and a major part of the experiment lies in the careful planning of means and methods to separate the signal from the noise or the wanted from the unwanted radiation. In the case of instruments used in the field to measure or to track radiating sources of interest, the problem often is one of separating signals from sources of radiant noise perhaps orders-of-magnitude greater in their signal-generating properties.

One of the important methods of separating the radiant signal from noise is dependent upon differentially modulating the two. When the source is under the control of the experimenter, he may well choose to modulate directly the source of interest and separate the signals produced by it in his detection system through the use of a corresponding filter matching closely the characteristics of his chosen modulator. Often the source is distant and/or not under direct control, as in the case of a star, an aircraft, or a missile. In such cases, the reticle is often the receiver component principally responsible for the modulation separating the source of interest and the background.

Early work on reticles was largely empirical. Later work was done by a small cadre of applied scientists and engineers who rarely, if ever, published their methods or analyses in the open literature except as patents. As a result, a recent paper, also unpublished, indicated that the work is still empirical. Such is not the case. Reticles are designed with both malice and forethought, principally by those who have long been using or designing them and to whom the design process is not a logical but an automatic one. The preliminary states are usually skipped, since the paramters are well known and probably committed to memory. As a result, a conversation between two skilled in the art is not unlike that of two girls meeting by chance and resuming their conversation where they left off a day or two ago—the thread and substance of which is completely unintelligible to their escorts.

Much of the technology is the result of work done during and immediately after World War II. Very little has ever been thrown open to general use, mostly because there are newer pursuits for those who did the original work and because it is more challenging to do the new than to write about the old.

This book is written from a storehouse of old remembrances and rekindled enthusiasms residing not only with the author but with a host of former associates who literally emptied their files in an effort to help verify and substantiate that which I remembered to be true. Chief among these whose help I found invaluable were Fred Sonne, Lawrence Nichols, Herbert Hewston, and Caroline Kruse.

The book probably never would have been considered without the frequent encouragement of Werner Weihe and Sidney Passman; never actually started without the help of Paulette Tansey, who collected and organized much of the early material; and never completed without the kind and patient understanding of my wonderful wife and three long-suffering daughters.

Contents

CHAPTER 1

Introduction

"Reticle: a small net; a collection of wires or the like in the focus of the eyepiece of an optical instrument . . . ."
(*Webster's New International Dictionary*, 2nd edition)

IN their simplest form, reticles are simply devised markings or fibers placed at an appropriate location in an optical instrument to provide a convenient reference or scale. In their more complex form, reticles may possess intricate geometrical patterns used to modulate or demodulate optical beams or images, to impart information into or extract it from a beam, or to generate specific functions linking mechanical responses to basic properties of a controlling beam or image.

Typical simple reticles are the cross-hairs in a cathetometer and the scale in the eyepiece of a measuring microscope.

The measuring magnifier of Fig. 1.1 is a simple but effective instrument employing a series of interchangeable glass reticles placed in contact with planar objects to be measured and observed through a suitable magnifier. In this application the least count of the reticle scale is the primary limitation of the fineness of measurement to be made.

In somewhat more complex instruments, one employs a device identical in principle but placed in physical contact not with the object to be measured but rather with its magnified image; the measuring magnifier thus becomes the eyepiece assembly of a compound microscope.

It is worth noting that magnification usually permits the measurement of finer linear detail but does not aid directly in greater precision measurement of angular dimensions other than by allowing one to view or to match boundaries of the measured object and the reference scale more easily. These simple reticle devices are basically linear or angular scales that extend through magnification and convenience one's basic ability visually to measure, to estimate, or to compare The last of these functions is so important that specialized forms of

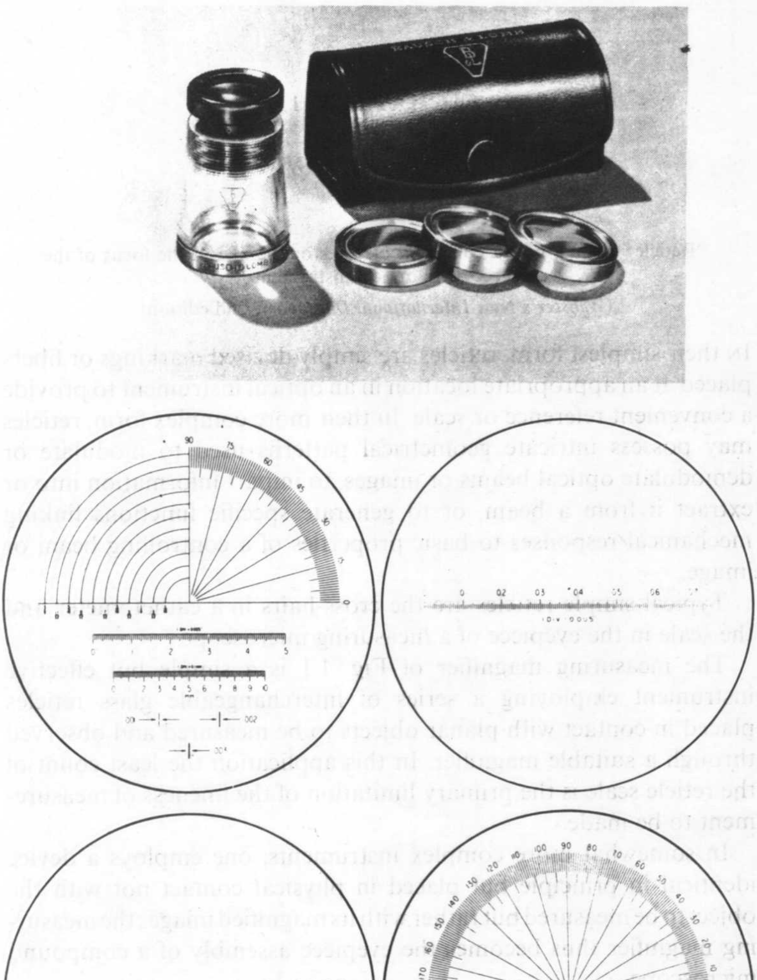

FIG. 1.1 Measuring magnifier with reticles (*Courtesy* Bausch & Lomb Optical Company.)

reticle magnifiers, known as optical comparators, are employed with projection screens in the inspection departments of good machine shops.

Reticles can be employed in other forms to scan a beam or image in order to extract some specific information, or such reticles can impress on the beam some characteristic to be read by a suitable detector or detectors, thus providing a specialized form of function generation that may be difficult to provide by more usual means. This class of reticle has, by its great versatility, found its way into a variety of guidance systems in remotely controlled vehicles. Such devices enable vehicles to guide themselves or "home-in" on a designated optical source, or merely to indicate precisely the position of an optical axis relative to a sight line from a reference source, i.e. a star.

These and related forms of reticles, in which the basic property of a reticle sorts shape (spatial filtering), or color (spectral filtering), or both, gave rise to an entirely new methodology. Although it was founded before World War II, it did not emerge into either a well-developed or a well-understood technology until the 1950's, when the usefulness of reticles as filters was accepted and pressed into a reasonably wide variety of applications.

The usefulness of reticles as predetection filters in electro-optical systems sometimes has blinded the designer to the basic fact that the reticle as a filter has a clearly defined insertion loss akin to that of electronic filters, acoustic filters, and optical spectral filters commonly used in photography.

An interesting form of reticle translates spatial or spectral parameters into the time or frequency domain, where well-developed techniques of electronics can be used to perform the proper processes dictated by information and communication theory. The resultant ability to extract pertinent information that may be present at a very low signal-to-noise ratio is not achieved magically. The process of improving signal-to-noise ratios by sharply selective filters involves filter insertion losses and, although resulting in a greatly improved signal-to-noise ratio, attenuates the signal.

It is always rewarding to be able to define in crisp, definitive terms the interrelations and dependences that occur in physical systems. It is not only satisfying to the tidy soul but is immensely practical in the direct enabling of engineering staffs to produce definitive and final designs without the endless empirical cut and try, design and test procedures. Thus, about ten years ago, I joined the cult of those who hoped to apply Wiener spectra to the characterization of backgrounds and thus to the design of better reticles. Though the theories are beautiful gems of symmetry and please the aesthetic senses of the mathematically inclined, the actual facts belie the necessary assumptions of isotropy. Gaussian distributions, and all the usual nice things that make noise theory and information theory a clear and lucid tool—when they apply—and a useless exercise when they don't.* Well, in our case they usually don't. However, the beauty overpowered the eye and dimmed the mind and the march was on in the new fad of writing elegant papers. The papers are still elegant and in many cases have provided an excellent means toward achieving progress—but usually under somewhat restricted related areas. I sometimes raise ire by remarking that such methods are an excellent first approximation in a choice of initial parameters for a reticle design, but there is presently so much background of experience that—for a first approximation—one can now work from experience, his or someone else's, and skip the tedium of the space filter design; and for a better approximation the method is not good anyway. I have often said it and I still firmly believe it.

Further, there has been a plethora of papers on reticle transforms in the frequency domain. These are undoubtedly valuable in enabling one to visualize much about reticle performance. There have been some broadly based doubts upon the validity of some of these procedures, and thus it is with interest that I acknowledge some of the more recent work by a group of colleagues at The University of Michigan who have reopened the study of space filtering and reticles from a quite rigorous point of view.

Their work to date would fill appreciably more than this volume, and though its value is more than apparent it cannot be included except as a greatly abbreviated section that outlines the problems of the previously accepted methods and puts forth one of the approaches of analytical study that appears to offer more promise. This synopsized version is the work of R. Legault, J. Ulrich, and W. D. Montgomery, who have made their work available for inclusion in this monograph even before they have published. Their introductory section, which explains the question of why the trouble, and the latter section, which indicates their approach, appear as the Appendix.

* D. Z. Robinson, Methods of background description and their utility, *Proc. Inst. Radio Engrs.* **47**, 1554 (1959).

Reticles have intrigued me since I first misunderstood and misused space filtering reticles in 1949. From that time on I have developed a series of reticles for specialized purposes and have slowly come to understand the function and the relation of reticles to equivalent detector mosaics, which demand far more equipment but in the limit can do a far better job.

The widespread lack of understanding about reticle usefulness and the prices paid for such utility in the form of insertion loss is one of the real forces behind the preparation of this monograph. In fact, late in 1954 two astrophysicists, whom I consider among the more competent, planned an experiment to measure infrared auroral emissions. Their radiometer was a cooled PbS detector coupled to a d.c. amplifier. I immediately inquired about the lack of a chopper or reticle.* The answer was terse: "We're not going to throw away half the incident radiation." Ten years later, in October 1964 at a conference on remote sensing at Ann Arbor, I asked the same question of different people but somehow got the same answer. Maybe it is ten years too late, but I have finally decided to write the information, impressions, and possibly some misinformation relating to reticles and their applications—starting with the problem of "throwing away half the incident radiation".

* In this monograph I consider a chopper to be a very simple form of reticle.

CHAPTER 2

Reticles for Radiometry

THERE are few problems in physical science that are more demanding, more time consuming, or more frustrating than the absolute calibration of a spectrometer. The problem is only one order of infinities less frustrating for the absolute calibration of a radiometer operating in a fixed spectral band.

The problems of variation of the detector's quantum efficiency with wavelength and the variation in irradiance from the usual calibration sources with wavelength, and the inevitable nonlinearity of detector response with level of irradiance at the detector give rise to the need for a means of attenuating the calibrating radiation in a precise and reproducible manner.

In spite of all the obvious drawbacks and lack of aesthetically satisfying and precisely controllable characteristics, photographic techniques are still by and large the best and most useful detecting and recording processes for spectroscopic use from the far ultraviolet through the near infrared.

Since film varies from plate to plate and from developer to developer, it becomes desirable, and at times necessary, to perform an absolute standardization on each plate–developer–development combination, plate by plate. Further, since many instruments are less than uniform in characteristic across the aperture, it is necessary to calibrate where the image will be or to calibrate all over the field.

As a result, one well-considered approach is to mask the image plane to a restricted field of view and, in a series of sequential exposures made by moving the plate, behind the mask to obtain a series of frames on which different calibration sources and unknowns are recorded sequentially in pairs. The moving-film "streak spectrograph" is similar in concept—a device that can be used at relatively high speeds but at the loss of the convenience of individual frames. In the conventional or streak spectrograph one then develops the single plate or film and, if the emulsion is uniform and the developing process equally affects all areas, he ends up with one record of a standard source and an unknown rigidly locked together for future study at leisure. Because of the characteristics of the source, the unknown, and the film, however, one may need a longer exposure for one wavelength region than another; this requires multiple exposures, the relative times of each being precisely measured or controlled.

In this process, the episcotister serves to give a well-defined reproducible ratio of adjacent exposures. In essence it passes, once during each revolution, the incident radiation for a series of definite periods of time in closely spaced images. Thus an episcotister may pass all of the radiation 1 per cent of the time at the minimum step and 99 per cent of the time at the maximum step. Such an episcotister would have one slot 1 per cent of the circumference for the 1 per cent transmitting region and one slot 99 per cent of the circumference for the 99 per cent transmitting region. Such sector wheels are precisely machinable and measurable, thus they are both very convenient and common in the better equipped spectroscopic laboratory.

The simplest means for providing a broad, dynamic range of exposures for both unknown and standard irradiance levels is through use of a stepped sector wheel or episcotister. Such a device is shown in Fig. 2.1. The episcotister can be located in a number of places in

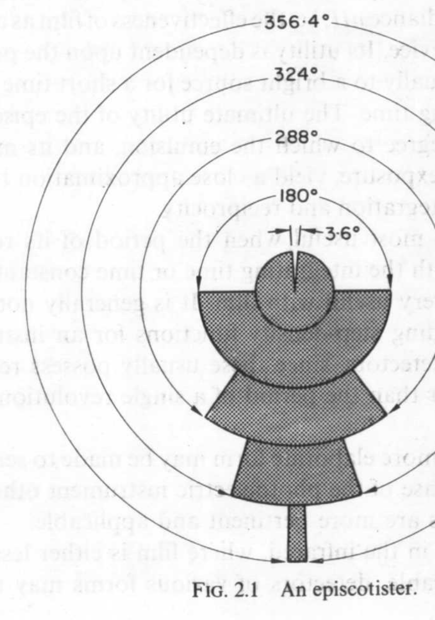

FIG. 2.1 An episcotister.

the optical system to provide effectively a step wedge, or neutral density filter of a large dynamic range in density, in a reasonable number of steps.

Through use of such a device, one may obtain perhaps five or ten simultaneous but variously exposed spectra overexposed for one particular line on the most exposed strip but correctly exposed for that line on the least exposed strip. Conversely, the fainter lines are washed out in the lesser exposures and are useful in the largest exposure step. In a similar manner, the range of densities from the calibration source can be matched moderately with those in the unknown line density, thus minimizing the need to interpolate along a photographic density vs. irradiance calibration or interpolation chart.

Considering the difficulty and complexity of the process, one can only bow in admiration and esteem to the scientific results that have emerged from what superficially appears as a nearly haphazard process. With possibly a man-year of a competent scientist's time, it is also possible to undertake the process of calibrating an instrument of this form.

The episcotister is one of the simple choppers used in radiometry. Primarily its utility is linked to the "reciprocity" property of film that results in equivalent exposure from a series of n pulses of irradiance H or one pulse of irradiance nH, i.e. the effectiveness of film as a nearly perfect integration device. Its utility is dependent upon the property of film to respond equally to a bright source for a short time or to a faint source for a long time. The ultimate utility of the episcotister depends upon the degree to which the emulsion, and its methods of development and exposure, yield a close approximation to these ideal properties of integration and reciprocity.

The episcotister is most useful when the period of its rotation is small compared with the integrating time or time constant of the detector. Thus it is very useful with film. It is generally not useful as a means of providing step-density functions for an instrument using photoelectric detectors, since these usually possess response times that are shorter than the period of a single revolution of the episcotister.

The episcotister in more elaborate form may be made to serve this function, but in the case of the photoelectric instrument other processes and techniques are more pertinent and applicable.

For measurements in the infrared, where film is either less satisfactory or not applicable, detectors of various forms may usually be employed more simply and effectively than the more common forms of photographic film.

For a large variety of purposes, the photoemissive detector with or without electron multiplication has become the widespread tool of common use for ultraviolet and visible spectrometry. Its adoption springs from its convenience, reproducibility, and sensitivity, which often outweigh the performance of the older photographic techniques. The speed of response of many of these detectors may best be expressed in microseconds or even in nanoseconds. In the ultraviolet, where primary standards of radiance are almost nonexistent, one may often indirectly employ a blackbody as a primary standard using a bolometer as a "transfer" or "secondary standard" detector. The bolometer, standardized against the blackbody, is now used to calibrate a secondary source such as a low-pressure mercury arc in the 2537 Å region. This secondary standard line source is then used as a working ultraviolet standard.

It must be noted here that the process outlined above is filled with difficulties, since the response of a good photomultiplier is several orders of magnitude greater than a good bolometer or thermocouple. Thus a secondary source effective for a bolometer response would completely overload a multiplier which is designed to work normally with very low-level irradiance.

Four simple and effective means are available to match detectors to a wide dynamic range of source radiance:

1. Use the photomultiplier with its gain set at 1 (i.e., as a diode), then use it as a multiplier with a gain up to 10^6.
2. Use the inverse-square relationship for source at a variety of distances from the appropriate detectors.
3. Use a spherical convex reflector as a precision attenuator with source mirror and detector geometry giving rise to a rapid attenuation function.
4. Use screens or reticles as precise attenuators.

The first of these four methods makes use of the variable gain in a photomultiplier that may be controlled either by varying the voltage applied to the multiplier or by varying the number of dynodes employed. For example, if but 4 of 10 dynodes are utilized, dynodes 5 to 10 are connected to the anode and acceleration voltages are applied only between the cathode and the first four dynodes.

Subsequent calibration of the multiplier gain vs. applied voltage