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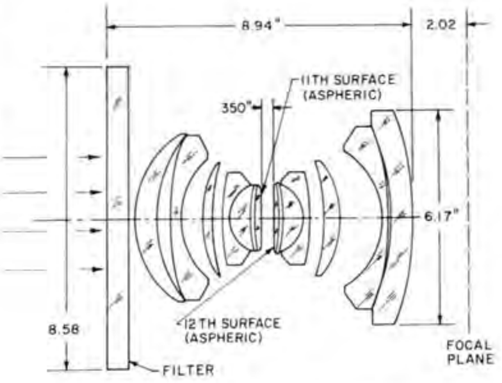

FIG. 1. Geocon IV configuration.

The Geocon IV Lens

The manufacturing and testing of a fast, high-resolution, wide-angle, low-distortion lens developed in the U.S.A. suitable for color aerial photography.

(*Abstract on next page*)

INTRODUCTION

THE SPECIFICATIONS OF the USQ-28 System, developed by Kollsman Instrument Corporation, called for the use of the Geocon IV lens that was designed by Dr. James G. Baker. Facilities for manufacturing the lens were established by Kollsman at its Elmhurst, New York, facility, which, to date, has produced fifteen lenses for use in the KC-6A Camera. The lens and camera calibrations were performed with the Fairchild Collimator Bank under the guidance of Mrs. C. Norton.

The Geocon IV lens contains 14 elements and a vignetting filter configured as shown in Figure 1 and weighs 39 pounds. Two highly precise aspherics are located at either side of the central airspace. The lens elements are mounted in a Meehanite cell, which exhibits excellent stability and closely matches the coefficient of thermal expansion of the glass. A 0.350-inch airspace is provided, permitting the use of a drawer-type, between-the-lens shutter and diaphragm, either of which can be removed for maintenance or repair without disturbing the lens-to-camera cone calibration.

Two filters are available with the lens: a yellow filter for black-and-white photography and a clear filter for color photography. Both filters employ compensating coatings to balance the illumination across the field.

LENS PERFORMANCE

Resolution tests of the nine most recent Geocon IV lenses on Plus-X emulsion have resulted in an AWAR[†] range of from 42.7 lines/millimeter to 46.6 lines/millimeter, with an average resolution of 44.4 lines/millimeter. These lenses incorporate changes which were introduced to eliminate field curvature from the original Baker design. One lens, which measured 46.6 lines/millimeter on Plus-X, was also tested on Panatomic-X and produced an AWAR of 61.5 lines/millimeter. The maximum tangenital distortion of the lens does not exceed ±8 micrometer at any point in the 94-degree field. Average radial distortion is also maintained within ±8 μm over an 85-degree field. Maximum radial distortion at any individual point within the 9-inch by 9-inch format is given in Table 1. It may be noted that the lens distortion asymmetry is controlled to within ±5 microns of the average value over the central 85-degree field. The Geocon IV lens was among the lenses recently tested for color performance at the National Bureau of Standards. This test,

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[*] Presented at the Annual Convention of the American Society of Photogrammetry, Washington, D. C., March 1969.

[†] Area Weighted Average Resolution.

TABLE 1. MAXIMUM RADIAL DISTORTION

Field Half-Angle	*Maximum Distortion at Any Point*
0°–30°	8 μm
32.5°–42.5°	10 μm
45°	25 μm

ABSTRACT: *The Geocon IV is the highly precise mapping lens specified and produced for the AN/USQ-28 Aerial Photographic Mapping and Geodetic Surveying System. The 6-inch focal length, f/5 lens utilizes a 94-degree field angle to produce 9-inch by 9-inch format photography. It is a 14-element, highly corrected lens system including two highly precise aspheric surfaces. The Geocon IV provides a lens/film AWAR in excess of 42 lines/millimeter on Plus-X emulsion. The average radial distortion is maintained within ±8 micrometers over the central 85-degree field. Tangential distortion does not exceed ±8 micrometers at any point in the 94-degree field. A yellow or clear vignetting filter provides for even illumination on black-and-white or color emulsions, respectively.*

which provided data on Geocon IV curvature of field, was conducted utilizing blue, green, and red illumination for both radial and tangential imagery. Figure 2 presents a summary of Geocon IV color focal displacement as a function of field angle on one color emulsion.

OPTICAL FACILITY

From the outset of the Geocon IV Program, it was apparent to Kollsman that production of lenses to these performance requirements would necessitate a specialized precision optical laboratory. A laboratory consisting of three environmentally controlled areas was established, therefore, at Kollsman's optical facility in Elmhurst, New York.

The first laboratory area contains polishing equipment and is used for spherical polishing of the Geocon IV elements and aspheric figuring. Special equipment, such as a Foucault knife-edge tester, was provided in this area.

The second laboratory area is utilized for precise mechanical measurements of the elements, for cementing, and for spacer adjustments.

The third area is the Test Laboratory, where lens performance is evaluated and necessary adjustments determined. For visual evaluation of the lens, a special 8-inch-diameter, *f*/7 parabolic collimator, mounted on a vibration-isolated, 10-ton seismic block, was acquired. (See Figure 3.) This collimator is

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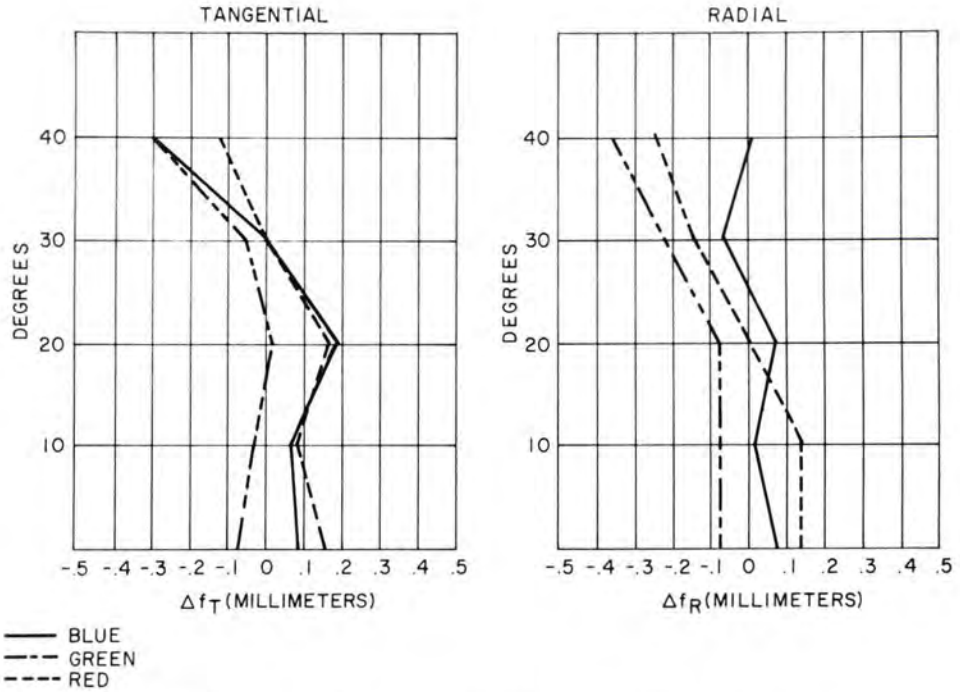

FIG. 2. Geocon IV curvature-of-field for three target illuminants.

extremely flexible in that it provides for a rapid interchange of test targets, filters, and light sources. In line with the collimator is an optical bench containing a nodal slide, an observation microscope, and a knife-edge holder. To obtain radial and tangential distortion measurements, the laboratory utilizes a Wild T-4 Goniometer adapted with fixtures for positioning and rotating the lens about its axis (Figure 4). Resolution testing is accomplished in the laboratory by a bank of ten collimators spaced at 5-degree intervals, from 0 degrees to 45 degrees (Figure 5). Each collimator contains a standard USAF 1951 resolution target and has a 20-inch focal length with a 2-inch aperture.

GLASS FABRICATION

After receipt of the raw blanks and associated melt data sheets, a series of computer

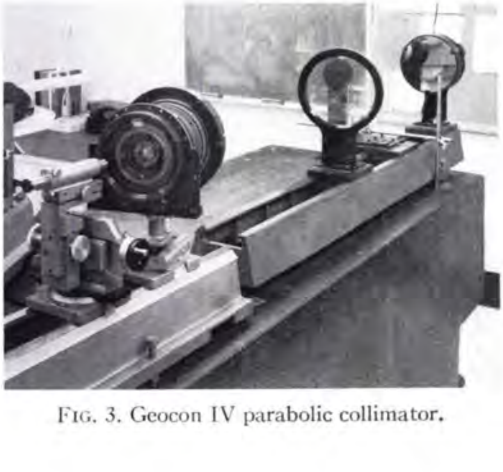

FIG. 3. Geocon IV parabolic collimator.

FIG. 4. Geocon IV distortion testing.

FIG. 5. Geocon IV resolution collimator bank.

melt-adaptation programs are utilized to optimize the design of the lens in view of the variations in index of refraction for a particular set of element blanks. The computer effort determines the optimum vertex thickness for each element prior to fabrication.

In order to minimize centering errors, edging is accomplished following the fine grinding of a convex side during fabrication. A conventional centering machine is used to establish a finished edge diameter perpendicular to one finished fine-ground surface. Thereafter, the second surface is lapped and constantly monitored with a special fixture designed and built at Kollsman and capable of detecting runout errors in the order of 25 microinches.

The two aspheric surfaces employed in the Geocon IV lens are located on either side of the central air space and are referred to as the 11th and 12th surfaces of the system. These surfaces are on the 7th and 8th elements of the lens and are part of two cemented quadruplets.

The form of the eleventh surface, as indicated in Figure 6, shows a maximum departure, within the clear aperture, of .000150 inch between the aspheric surface and a sphere of equal central radius. This amounts to about 7 wavelengths of yellow light. This surface is concave and has a raised edge of .0047 inch at the edge diameter.

The seventh element is first made as a spherical lens and then cemented to the front quadruplet. Aspherizing takes place after cementing, because the 0.143-inch-thick element would not maintain a symmetrically smooth form if deblocking were required. No aspheric grinding is necessary on the 11th surface, as it is within the range of fringe counting with the aid of a traveling microscope, 12 fringes being observed inside the contact crest formed at a 0.65-inch zone height when using the test sphere.

The SFS3 glass used is soft and is not susceptible to staining; however, during aspheric polishing, debris had a tendency to redeposit on the surface and cause greying. This problem was solved by finding the optimum combination of polishing agents and lap materials.

Polishing continues until each fringe is positioned and plotted and a match close to the theoretical curve is achieved. As zonal errors between fringes are not detectable in fringe-counting techniques, final smoothness is obtained by Foucault testing of the surface and by taking corrective action until a smoothness of 1/6 wavelength is attained.

The optical test used to obtain smoothness and form data is the classic Foucault test. Both the knife edge and the slit move simultaneously, with a monochromatic sodium lamp used as the light source, while the aspheric surface is viewed as a mirror, as

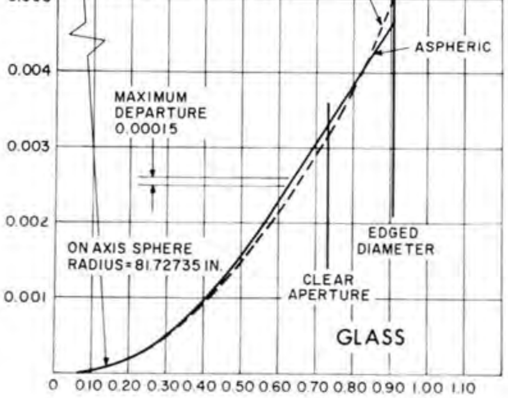

FIG. 6. R11 aspheric form.

shown in Figure 7. In both the R11 and R12 surfaces, auxiliary lenses are placed in front of the aspheric surfaces to produce a convergent wavefront. Because it has not been practical to design and produce simple auxiliary elements that would produce a precise spherical wavefront, the null obtained in the knife-edge test is only partial, and the entire surface is read and recorded as longitudinal focal positions of the microscope at increments of 0.1-inch zone heights. This information is plotted against a theoretical ideal curve.

The form of the 12th surface is illustrated in Figure 8. The aspheric surface falls away from central spherical radius by 0.012 inch at the edge diameter. As a result, in this instance, it was necessary to remove glass by aspheric grinding. Element 8, which contains the 12th surface, is first made as a spherical element and then cemented to the rear quadruplet. The quadruplet is then inserted and retained in an accurately machined, stainless-steel holding tool and mounted on a vertical spindle.

The grinding method used was developed by Dr. A. B. Meinel, then of Yerkes Observatory. A series of cast-iron tools, with the desired aspheric form but with opposite curvatures, are produced on a lathe. Each tool is made in steps, each new step being cut in increments of a 0.002-inch radius, with independent setting and measurement. The tool is then mounted against the glass on concentric spindles, carefully avoiding any oscillation. Using four tools in succession, with an appropriately finer abrasive at each tool change, tool wear is minimized. The random nature of the errors in the position of each step in making the tool statistically groups them around the desired curve, so that the average surface produced by the tools on the glass during grinding accurately follows the desired curve. Oblique visual inspection of the glass surface revealed concentric ridges that were smoothed by a glass tool of approximately opposite aspheric curvature. This tool was made by constant lapping and checking until the desired form was achieved. Although some sacrifice of form was caused by this smoothing tool, its use was more desirable than polishing out the ridges, which measured as much as 0.0002 inch.

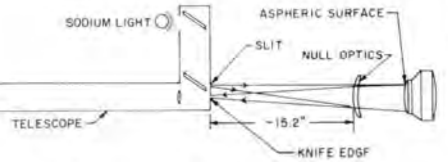

FIG. 7. Geocon IV aspheric testing.

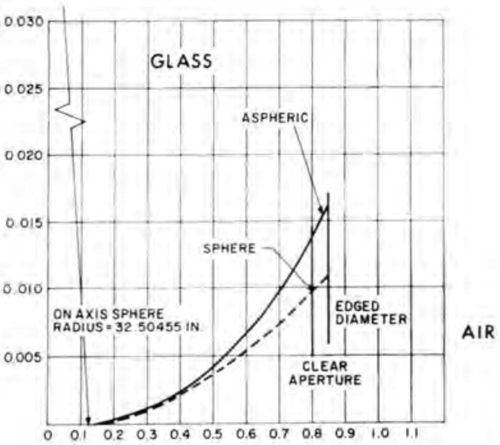

FIG. 8. R12 aspheric form.

Final polishing of the R12 aspheric surface resulted in many frustrating experiences and caused many delays in lens production at the beginning of the program. The 1/6-wavelength smoothness tolerance that had been first established seemed impossible to achieve. The need for this tolerance was verified in checking the Geocon IV on the optical bench where slight errors in smoothness of the R12 surface would result in degraded resolution.

Continuous investigation of the aspheric polishing tools indicated that no single type of polishing lap would do the job successfully. After much testing it was found that a combination of pitch and flexible lap, used alternately, finally resulted in satisfactory aspheric surfaces. In some instances, polishing laps 1/4 inch in diameter were used to remove defects that were on the order of 1/4 wavelength.

The cementing of the front and read quadruplets, which is performed prior to aspherizing, also presented some unique problems. Mechanical clamping devices, normally used to hold optical alignment during cementing, were avoided, because the elements on either side of the aspherics are approximately 0.110 inch thick, and such devices might contribute to distortion of these elements during the curing cycle. Instead, each element is added to the stack by cementing under gravity loading while in a leveled, rotatable fixture.

After applying HE-79 cement, the technician, utilizing a microscope, observes the excursion of a pinhole image transmitted through the cemented elements while rotating the holding fixture about its axis. Several corrections are necessary during the setting period, to reduce concentricity errors below 0.0001 inch. The adjustments made during this period are accomplished without the use of any mechanical constraint of the elements. After a two-hour of drying in air, the cement becomes tacky and all movement ceases. A two-day air-dry was found sufficient to join the elements permanently. This cycle is repeated until the six cemented interfaces are completed.

Because aspherizing was performed on the cemented quadruplets, the application of an antireflection coating on the 11th and 12th surfaces had to be accomplished on the quadruplet assembly. This could not be done at the normal coating temperature of 400°F because of the possibility of cement separation. Instead, an antireflection, cold-coating method was utilized which limited the temperature to 125°F and produced a coating meeting the requirements of MIL-C-675.

The Geocon IV lens filters consist of plano-parallel disks approximately 5/8 inch thick and $8\frac{1}{2}$ inches in diameter. The yellow lens filter is fabricated from Schott GG-495 glass and the clear filter from BK-7. The filter surfaces are polished parallel to within 5 seconds of arc and are flat to within $1\frac{2}{3}$ fringes over the clear aperture. Both filters employ an evaporated chromium gradient neutral-density deposit carefully calculated to produce an evenly illuminated film plane.

LENS ASSEMBLY

After the fabrication of the lens elements, the vertex thickness of each element is carefully measured to within 0.0001 inch and recorded. During the cementing of the quadruplets, vertex measurements are recorded after each cementing step to ascertain the amount of cement buildup.

The airspaces between the first and second elements and the 13th and 14th elements are achieved by spherical beveling, which is utilized to permit shifts of the first and last elements about the center of curvature of the surface facing the airspace to correct for tangential distortion. After the beveling operations, the actual measured airspaces are also recorded. Following accumulation of the actual thickness data and measured values of the beveled airspaces, a series of final assembly computer programs are utilized to find the optimum values for the five remaining airspaces which are adjustable at assembly.

Although the programs are capable of modifying lens-element curvatures to achieve the desired performance requirements, this, fortunately, has never occurred. This may be attributed to the tight control Schott exercises on the raw glass and the ability of Kollsman opticians to fabricate the elements precisely as prescribed by the prefabrication computer effort.

After the final computer effort, the lens is assembled as dictated by the computer output and checked on the eight-inch parabolic collimator for coma and astigmatism. Spacer changes, based on the observations at 43 degrees off-axis, are made to eliminate these aberrations, which generally require from two to six adjustments for correction.

RESOLUTION TESTING

After a lens has been optimized with regard to aberrations, the AWAR is determined in Kollman's Test Laboratory, utilizing the resolution collimator bank illustrated in Figure 5.

The ten-collimator array covers one-half of the lens diagonal in 5-degree increments and is set up on the vibration-isolated 10-ton seismic block. All 10 collimators are aligned with a theodolite so that their axes lie in a common plane. Angular separations have also been aligned and are held to within 1 minute of arc. The collimator objectives are airspaced doublets designed and manufactured by Kollsman with a clear aperture of 2 inches and a focal length of 20 inches. Seventy-five watt opal enlarger lamps serve as the illumination source in conjunction with a daylight correction filter. Illumination levels are controlled by means of insertable neutral density filters. A regulated power supply is utilized between the lamp timer and house power to assure isolation from transient voltage variations in the power line.

The lens under test is held in a fixture that permits rotation about the lens axis. Glass plates measuring 4 by 10 inches and coated with Plus-X emulsion are used for testing. The plates are mounted to a focal plane fixture that can move the emulsion plane in 0.001 inch increments to achieve the plane of optimum resolution. The focal plane fixture also permits vertical positioning of the plate so that 14 images of a semidiagonal can be placed on each plate. The focal plane fixture and lens holder are both mounted on a short optical bench and are aligned with a theodolite prior to each test. The Kollsman resolution test equipment is patterned basically after the collimator bank used by the National Bureau of Standards.

DISTORTION TESTING

All in-house radial and tangential distortion measurements for lenses are established using a T-4 Goniometer. The procedure used is based on the methods outlined by Spriggs & Livingston,[1] with modifications to tailor it to the low distortion values of the Geocon IV.

To determine radial distortion, a simulated lens cone fixture, containing a precision 9-by-9-inch calibration plate, is affixed to the lens mounting flange. The optimum flange focal distance, as determined by resolution testing, is established by three precision spacers between the cone and the lens mounting flange. This assembly is placed in another fixture consisting of two rigid steel discs and is then placed onto rollers affixed to the goniometer. This enables the lens assembly to be rotated about its axis, maintaining the aperture of the lens centered over the aperture of the telescope as the telescope traverses the lens field. The calibration plate is then aligned to the goniometer axes by autocollimation. Because the plate calibration engraving faces the lens, a wedge in the calibration plate does not affect the distortion readings but could cause misalignment of the lens-cone assembly during autocolimination. To minimize fixture errors and to exclude errors due to a 7-second wedge in the plate, the calibration plate is oriented so that its wedge axis coincides with one of the principal axes of the autocollimator. Plate alignment is checked by rotating the whole assembly 180 degrees and, if any errors are present, the collimator reticle line is placed precisely midway between the reflected images, as obtained from each rotational position and its 180-degree complement. This procedure assures alignment of the calibration plate perpendicular to the goniometer axis.

After alignment, the lens-cone assembly is rotated until the diagonal to be checked lies precisely in the plane described by the rotation of the observation telescope. The calibration plate contains engraved reference marks at 10-millimeter nominal intervals along four semidiagonals, to 150 millimeters.

The angular values of the plate calibrations observed through the telescope are recorded for the two diagonals 90 degrees apart. The angular value for each plate calibration mark, with respect to the center of the plate, is established by taking the difference between its angle as read on the goniometer and the value established for the central target. These values and their corresponding tangents are then recorded.

The Equivalent Focal Length of the lens is established by dividing the sum of the actual values for all four 20-millimeter plate coordinates by the sum of the four corresponding tangent values. The distortion values at the equivalent and calibrated focal lengths are then determined in a manner similar to that described by Spriggs & Livingston.

Tangential distortion is determined in the laboratory utilizing the goniometer filar micrometer adjustment. This method differs from the photographic test method, in as much as it lacks an accurate 90-degree reference as the lens is rotated. With the goniometer, we establish whether the diagonal line bowed when viewed through the lens. When a photographic plate is evaluated for tangential distortion, it is placed on the comparator so that one axis is aligned with the X-direction of the comparator. The distortion is then measured along the X and Y directions so that asymmetry of one diagonal, because of tangential distortion, can be readily established.

The lack of an accurate 90-degree reference is not important because the maximum tangential distortion occurring anywhere in the field equals the square-root of the sum of the squares of the tangential distortion of each diagonal.

Tangential distortion is established by measuring the extreme ends and center of a diagonal line with the filar micrometer. The lens and plate assembly is then rotated 180 degrees, and measurements are repeated. The end readings are averaged separately for each reading position and their differences taken. In order to obtain tangential distortion values in micrometers, it should be noted that the magnification ratio for the lens/telescope combination varies as one traverses from the on-axis position to the outer angles because the oblique ray path length of the lens changes by the reciprocal of the field angle cosine. For a 6-inch lens like Geocon IV, one filar micrometer division is 1.6 μm on-axis, and, therefore, 2.3 μm at 45 degrees.

CONCLUSIONS

The Geocon IV lens offers outstanding performance for both black-and-white and color emulsions in a compact, low-weight configuration. Following the successful com-

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[1] Spriggs & Livingston, *Instructions for Calibrating Aerial Mapping Lenses with Wild T-4 Goniometer*, Wright Air Development Division Technical Note 60-268, November 1960.

pletion of the lens development program, production lenses have been manufactured which consistently meet the demanding performance requirements. Based on tests performed by the National Bureau of Standards, the Geocon IV performance with color emulsions is exceptional.

The authors wish to express their appreciation to Mr. H. Pearl and Mr. K. Ziegler of the Kollsman Precision Optical Laboratory for the many unique techniques they have developed in bringing the lens from development to production status, as well as for their contributions to this paper.

Mathematical Geodesy, M. Hotine. U. S. Government Printing Office, Washington, D. C. 20402. 416 pages, $8\frac{1}{2}$ by $10\frac{1}{2}$ inches, cloth binding, \$5.50.

This comprehensive treatise, covering the main aspects of theoretical geodesy, has been published as ESSA monograph #2. Hotine's stated objective—"to free geodesy from its century-long bondage in two dimensions"—has been achieved in a systematic manner.

Dividing the text into three parts, he first introduces the basic mathematical tool of tensor calculus to the reader, and derives applicable properties of curves and surfaces. In the second part he develops and analyzes the properties of suitable coordinate systems from a continuous differentiable scalar function of position. The application of these bases to current and classic geodetic problems constitutes the third part.

Hotine's style and logical structure of the text, in conjunction with the excellent format, clear formulation and modern notation facilitates reading and the understanding of mathematical concepts. Chapters are short, suitable for intensive study, and paragraphs are sequentially numbered.

The mathematical basis, given in Part I, consists of 11 chapters. Cartesian vectors and their covariant and contravariant components are defined, followed by a discussion of curvilinear coordinate systems and vector transformations. The rules of tensor manipulation are next presented, clearly and concisely, demonstrating the independence of tensor equations from the coordinate system. This naturally leads to testing for tensor characteristics and a discussion of metric tensors and related topics. Covariant differentiation is then presented, as a necessary prelude to the excellent treatment afforded the intrinsic and extrinsic properties of spatial curves and surfaces in Chapters 4–8. The properties of contour, surface, and volume integrals, derived in Chapter 9, are followed by a most complete examination of spatial conformal transformation. Part I, concluding with a discussion of the mapping of surfaces onto a sphere, serves as an excellent primer or refresher in applied tensor calculus.

The geometric properties of various coordinate systems are derived in Part II. The first system considered is the astronomic coordinate system ω, ϕ, N with its spherical representation, and isozenithal differentiation i.e., the change of its metric properties along the N-coordinate lines.

Normal coordinate systems, discussed in Chapter 15, facilitate and simplify the derivation of metric properties by making the N-coordinate lines perpendicular to the ω, ϕ surfaces. This simplification in the derivation of theoretical relationships is continued by using normal coordinate systems with triply orthogonal surface coordinates, and is exceedingly well illustrated by the concise and elegant solution of the Darboux equations.

The properties of geodetic coordinate systems are then derived in which the N-coordinate lines become straight. These are further refined by considering symmetric systems, in which the geodetic torsion is made zero at all points on the base surface. Chapter 19, concluding Part II, gives an excellent treatise in the transformations between coordinate systems.

Part III, consisting of 10 chapters, applies the results of the previous derivations to the solution of geodetic problems. The concepts are employed in deriving the outline of solutions only; detailed numerical problems and step by step solutions are deliberately avoided. To have included them would have jeopardized Hotine's objective and precluded a clear understanding of essential relationships among the various geodetic concepts.

The first four chapters of Part III (Ch. 20–23) consider the gravitational field and its representation. Initially, it is demonstrated that the Newtonian gravitational field can be considered as a special case of the ω, ϕ, N coordinate system. Representation of the po-

(*Concluded on page 391*)