photography which may be used for photogrammetric purposes with minimum error due to unknown tilts. The mount stabilizes the camera throughout roll and pitch angles of ±8 degrees and compensates for drift angles up to ±15 degrees. This mount also automatically makes connection of the electrical circuits and the vacuum line when the camera is installed.

VIEWFINDER

The television type viewfinder provides the photo navigator with a view of the area below and forward of the aircraft. Two fields of view are selectively available to the operator—one a 40 degree field of view at approximately unit magnification, and the other a 10 degree field at approximately 4 times magnification. The optical system is stabilized for roll, pitch and relative azimuth. In addition, the navigator has control of line of sight and can scan from vertically downward, forward to the horizon, as well as through an angle of 45 degrees to the right or left. Use of the television type viewfinder results in maximum flexibility of installation, and also makes possible simplifications in stabilization of the line of sight.

As previously mentioned, this system was conceived to provide a solution for the requirements for high performance photo reconnaissance equipment or installation in modern, high density, high performance aircraft. The analyses have indicated a great similarity in the general characteristics of practically all of the advance aircraft and missile systems, insofar as they affect photo reconnaissance systems and equipment. It is due to this fact, and because of the high performance, light weight, low power consumption, reliability and automatic operation characteristics built into the equipment just described, that it is especially adaptable to the needs of present-day and future aerial weapons systems. The complete system, or portions, thereof, in various combinations or with slight modifications, are especially well suited for use in missiles or with the pod-mounted concept now being advanced for manned aircraft.

THE PLANIGON STORY*

Eldon D. Sewell, Chief, Aerial Photographic Branch, Engineer Research and Development Laboratories, Wright-Patterson Air Force Base, Ohio

MOST of the Members of this Society have heard of the planigon lens. Many have seen it and know something about its design and capabilities. Only a few are familiar with the great effort required in the quantity production of this lens. I would like to tell you a part of the story of the organizations responsible for making the planigon lens militarily feasible. This is a success story with a happy ending, but there were many anxious moments. I will not attempt to mention the names of everyone who contributed toward the success of this lens because I fear that I might overlook someone whose efforts have equalled those with whom I am familiar.

A low distortion lens called the Topogon V was brought to this country from Germany in 1945 by an Army representative. It was turned over to the Air Force which, in turn, let a contract to the Bausch and Lomb Optical Company for study and analysis, and for determining if it could be produced in this country. Under this contract the lens was successfully analyzed and the formula determined. The formula was then modified so that standard American glasses could be used. As part of this contract, the Bausch and Lomb Optical Company made three lenses in each of three focal lengths—namely, four-inch, five-inch, and six-inch. Tests with these lenses were sufficiently convincing to cause the Air Force to negotiate with Bausch and Lomb and two other optical companies—The Curtis Laboratories of Los Angeles and The Goerz American Optical Company of New York City—for the quantity production of over seven hundred of these lenses.

---

* Paper read at the Society's Semiannual Convention and Trade Show held in Statler Hotel, Los Angeles, Calif., Sept. 7–10, 1955.

The remarkable work performed by these three companies represents a new milestone in the American optical industry. The quantity manufacture of the metrogon lens, with its thin edges, short radii, and precise alignment, was a challenge to the Bausch and Lomb Company prior to and during World War II. All of the problems connected with the metrogon lens plus many more, including exacting requirements for radial and tangential distortion measurements, made the planigon production a king-size challenge. The entire story of its production does not equal the Bausch and Lomb story multiplied by three, nor were the problems of the Goerz American Optical Company the same as those of the Curtis Laboratories. It must be kept in mind that all of these companies are experienced in the field of optics. They have solved many difficult problems before.

Imagine the looks of surprise when Dr. Curtis announced to his staff that he had just been awarded a contract for building 150 planigon lenses. Probably the first question he heard was, "What is a planigon lens?" He explained that it is a six-inch focal length f/6.3, wide-angle, low distortion mapping lens. According to the specifications, the radial distortion must not exceed 20 microns nor the tangential distortion 15 microns. At this time someone probably pointed out that 20 microns was only 0.020 of a millimeter, and that there was nothing in the plant that would measure to the required accuracy. Also, what is tangential distortion, and how do you measure it? It was soon obvious to the entire staff that here was a lens that would require special study, special grinding equipment, special test equipment, special mounting, and special care. New nomenclature had to be learned, like "calibrated focal length," "principal point of auto collimation," "point of symmetry," "tangential distortion," and others. A bank of precision collimators, a precision comparator, and an instrument for measuring tangential distortion had to be designed and built. Assembly began as soon as elements became available. To this point, it appeared that making planigon lenses was just another tough job, but when assembly began it soon became evident that planigon lenses like a lot of personal attention. Even though great effort is made to grind each element to specified radii and thicknesses, no two are exactly the same. Each set of elements requires slightly different air spaces, and each element must be carefully oriented with respect to the other elements to produce optimum resolution and desirable distortion characteristics. Minor changes in the index of refraction of the glass in an element becomes important in the planigon. Slight changes in the thickness of the corrector plate were made to achieve desirable distortion values. Even though a photographic calibration method is desired in calibrating cameras, it is not best for use during assembly as some of the manufacturers discovered. In order to calibrate a lens photographically, the lens must be fully assembled. If the magnitude of the distortion is excessive, or if the curve is not properly shaped, the lens has to be disassembled, slight changes made in orientation or in corrector plate thickness; then reassembled and recalibrated. Not only was this time consuming, laborious, and nerve wrecking, but there was no assurance that the specification could ever be met. Thanks to energetic and conscientious workmen, the lenses finally began rolling off the production line. In spite of the great care that went into the grinding and assembly of the first planigon, some of those produced by Curtis and Goerz just barely met the distortion requirements, and then only after many hours of chasing microns around.

The specification limiting the radial distortion to 20 microns was written to fit the lens design and not the military requirements. It had been shown by the Engineer Research and Development Laboratories and others that distortions of greater than 10 microns can be detected with modern precision photogrammetric plotters and beyond 15 microns the effects become harmful. However, since the first planigons had distortions between 15 and 20 microns, it was decided to remove the remaining distortions with cams, correction plates, or correction lenses. After delivery of the first production lenses from two of the three suppliers, it was evident that it would not be possible to select one or two or even three curve shapes which could adequately correct all lenses. The planigon was still being very individualistic.

About this same time other troubles began to appear. The KC-1 camera specification also had a limit of 20 microns for the radial distortion of the finished camera-lens combination, allowing no tolerances for mounting the lens in the inner cone and for differences in calibration procedure between the camera manufacturer and the lens manufacturers. Some of the lenses which had 20-micron distortions when tested by the lens manufacturers were found to have 23 or 24 microns distortion when they became a part of a camera. It should be pointed out that most of this was due to differences in calibration results and not to faulty camera machine work. The Fairchild Camera and Instrument Corporation has done an excellent job with the KC-1 camera. Mrs. Norton, Chief of the Optical Technical Section of that organization, has contributed much to the success of the planigon lens with her careful and unbiased calibration of many lenses. She quickly realized that the calibration of the planigon lens required a higher order of accuracy than the calibration of the metrogon, and trained her organization accordingly. I know of no one in photogrammetric support operations who is more highly respected for her sincerity, ability, and enthusiasm than is Mrs. Norton.

Now back to our troubles. In order to keep production going on the KC-1 cameras, it was necessary to make an adjustment of 5 microns to the camera specification—allowing a total distortion of 25 microns. It should be mentioned here that most of the Bausch and Lomb lenses were easily meeting the original specifications. The Curtis lenses looked good except for an unwanted negative distortion in the region of 10°–25°. The Goerz Optical Company had not started delivery of lenses, although a number had been assembled and calibrated. This company was having difficulties similar to the Curtis Laboratories. I do not know for sure, but I have a suspicion that Bausch and Lomb was having trouble too because deliveries were very slow at first. However, they appeared to break through the trouble and were able to complete their contract first.

In an effort to salvage something from these lenses with large distortions, it was decided to eliminate all distortion requirements beyond 42½ degrees. However, the lens manufacturers were required to keep all calibration curves within an envelope ±10 microns wide about any selected average curve. This wasn't a good solution to our problem, but it would give us a chance to reduce the distortion by using a correction cam, plate, or lens.

About this time, the Goerz Company discovered that, by using a correction plate with a higher index of refraction than previously used, a more desirable radial distortion curve could be produced. A short time later, the Curtis Laboratories made the same discovery and the dark clouds started rolling away. Although the curve shapes still were random, the magnitude of the distortion was generally less. Once more, specification changes were made to take advantage of the progress we were making and the knowledge we were gaining about the behavior of the planigon. These changes were the last ones. The radial distortion requirement beyond 42½ degrees was still eliminated, no curve shape was specified, and the radial distortion of the lens must be less than 12 microns. The Air Force and Corps of Engineers felt that with distortions never exceeding 15 microns (in the finished camera) all photography made with such cameras could be treated as being distortion-free, thus eliminating the need for correction cams, lenses, and plates.

Now it was up to the lens manufacturers to produce lenses meeting these requirements and, according to the calibration reports available, they have done a remarkable job. The curves below show the new planigon look (See Figure 1). This envelope of curves contains the curves of 42 Curtis lenses, 35 B & L lenses and 20 Goerz lenses. The greatest distortion is 12 microns out to 42½ degrees. The Curtis and Goerz lenses are all from recent production—since changing to the new corrector plate. The B & L calibration curves are taken from Fairchild KC-1 camera calibration reports. Of the 67 examined, 35 had distortions of 12 microns or less, 17 had distortions of 15 microns or less, and the other 15 had distortions up to 20 microns. The fact that so many of the B & L lenses, even after being mounted in an inner cone, have distortions of less than 12 microns is a tribute to the exacting workmanship of personnel in that organization.

The tangential distortions for the lenses mentioned above are under 10 microns, so they too can be ignored for photogrammetric work. The average of the area weighted average resolutions (AWAR) for the 97 lenses mentioned is almost 24 lines/mm. The lenses are relatively small in size and are not excessively heavy, weighing

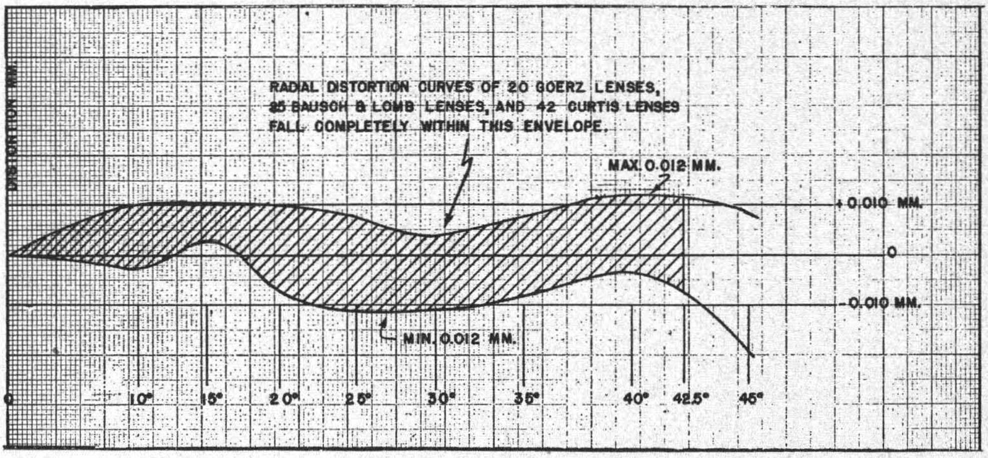

FIG. 1

about 7½ lbs. Over a hundred KC-1 cameras (these are essentially T-11 cameras with planigon lenses) have been manufactured for the Air Force. More will be heard about them as more mapping organizations become equipped to handle planigon photography

This is by no means the entire story of planigon production. To make it complete, I would have to relate the day-by-day struggle of the people at the Goerz Optical Company with tangential distortion—learning to measure it and then to reduce it to harmless magnitudes. I would tell about the temporary setback at the Curtis Laboratories when the head of the mechanical department was called to military service. Also, I would have to tell of the outstanding pioneer work accomplished by B & L in tangential distortion studies—work which has had a profound effect on all subsequent planigon assembly and calibration. The rest of the story can best be told by those who spent so many hours, weeks, and months solving, one at a time, the many problems connected with quantity production of planigon lenses.

We must not forget the optical and camera engineers of the Aerial Reconnaissance Laboratory (formerly Photo Reconnaissance Laboratory) for the expert guidance of this lens from its infancy to the present state. Also, the procurement people of the Air Materiel Command, Wright-Patterson Air Force Base, had a big hand in the final success of this lens because of their willingness to make necessary changes in contracts, specifications, etc., to take care of unexpected developments as they occurred.

A lot of people have contributed to the success of the planigon story. However, the story is still being written. The Bausch and Lomb Optical Company is now making planigon lenses with aspheric corrector plates. The plate is designed to give a nominal zero distortion over the entire format. The first lens calibrated with an aspheric plate gave distortions well under 10 microns. It is believed that the distortions are so small that any variations from zero may be due to the inability to measure the exact distortions.

There are other Air Force developments in the wide-angle precision lens field. Dr. James Baker and the Bausch and Lomb Company are designing new lenses. The aim of these contracts is to provide more light over the entire format along with low distortion.

With these distortion-free lenses, all we need to do now is to learn how to keep them exactly vertical or at specified angles while in the air. Work on this problem is continuing and the solution is getting nearer and nearer. When finally solved, the story of those who contributed to the solution will again show what can be accomplished by dedicated men willing to work.