THE NINE LENS AERIAL CAMERA OF THE COAST AND GEODETIC SURVEY.

by

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Instead of putting up with difficulties, we are always trying to build bigger and better machines to surmount them. We all know that there is little difficulty in plotting from an aerial photograph a house in correct position with relation to the road near which it is located. But when we have to combine a large number of these photographs into a plot which should join another large number of photographs without discrepancies, our task becomes difficult enough to justify considerable machinery.

If we could build a camera capable of photographing a field 130° square instead of 83°, as for example the ZEISS four lens or of 52° for a single lens, we would save quite a bit of flying. If the camera were daylight loading we would even save some flying time over the five lens by eliminating returns to the base for reloading.

The ratio of number of photographs from such a camera to cover the same area at the same scale with stereoscopic overlap would be 20 to 1 for single lens, 9 to 1 for ZEISS four lens and 4 to 1 for five lens photographs.

Assuming that the average error of a draftsman in drawing radial lines is 1/100 inch, the equivalent angular error of a line of the length of the air base would be about 12 minutes for single lens, about 8 minutes for Zeiss four lens and about 2 1/2 minutes for the wide angle photographs.

If we wish to draw contours from the photographs, such a camera would have 4 1/2 times the stereoscopic parallax of the single and of five lens and 2 1/2 times that of the ZEISS four lens photographs. These are the advantages which will accrue from the construction of the Coast and Geodetic Survey nine lens aerial camera, should it prove successful.

Surveyors have long appreciated the great advantages which result from increasing the area which can be photographed at a single exposure from the air. As far back as 1881 WOODBURY proposed a rapidly revolving lens to expose a number of plates and to increase the efficiency of balloon photography. Several other inventors have proposed improved multi-lens cameras and in 1904 SCHEIMPFLUG designed a camera with seven lenses grouped around a central lens pointing downward. SCHEIMPFLUG also developed a transformer for reprojecting the wing photographs to the plane of the central lens. But all of these plate cameras were somewhat impractical for ordinary use both because of the difficulty of carrying and changing the large number of plates required, and because of the uncertainties of balloon navigation.

During 1917, Major BAGLEY, U.S.A., developed the first multi-lens camera which was really practical for air photo mapping. This camera used a single film and with its three lenses increased the width of strip which could be photographed during a single airplane flight to nearly four times that of the single lens cameras. It was a thoroughly practical apparatus which operated satisfactorily under war service conditions. With the assistance of Mr. MOFFETT of the Geological Survey, a transformer was developed which gave satisfactory projections of the wing chambers into the plane of the central lens. This camera worked very satisfactorily with sufficient ground control but later, when experiments were conducted to determine the minimum amount of control which could be used to give maps of standard accuracy from its photographs, it was found that the radial line plots deviated considerably in azimuth if an attempt were made to extend the plots very far beyond control. A fourth chamber was added in the period from 1923 to 1927 to increase the accuracy of the azimuth. This gave such an improvement that still a fifth chamber was added in the period from 1926 to 1929. Note the phrase "in the period". Usually several years are required from the approval of the idea or first model to the completion of a satisfactory camera. The five lens camera which we have today is a thoroughly practical apparatus whose photographs yield much more rigid plots than can be obtained from single lens photographs with the same

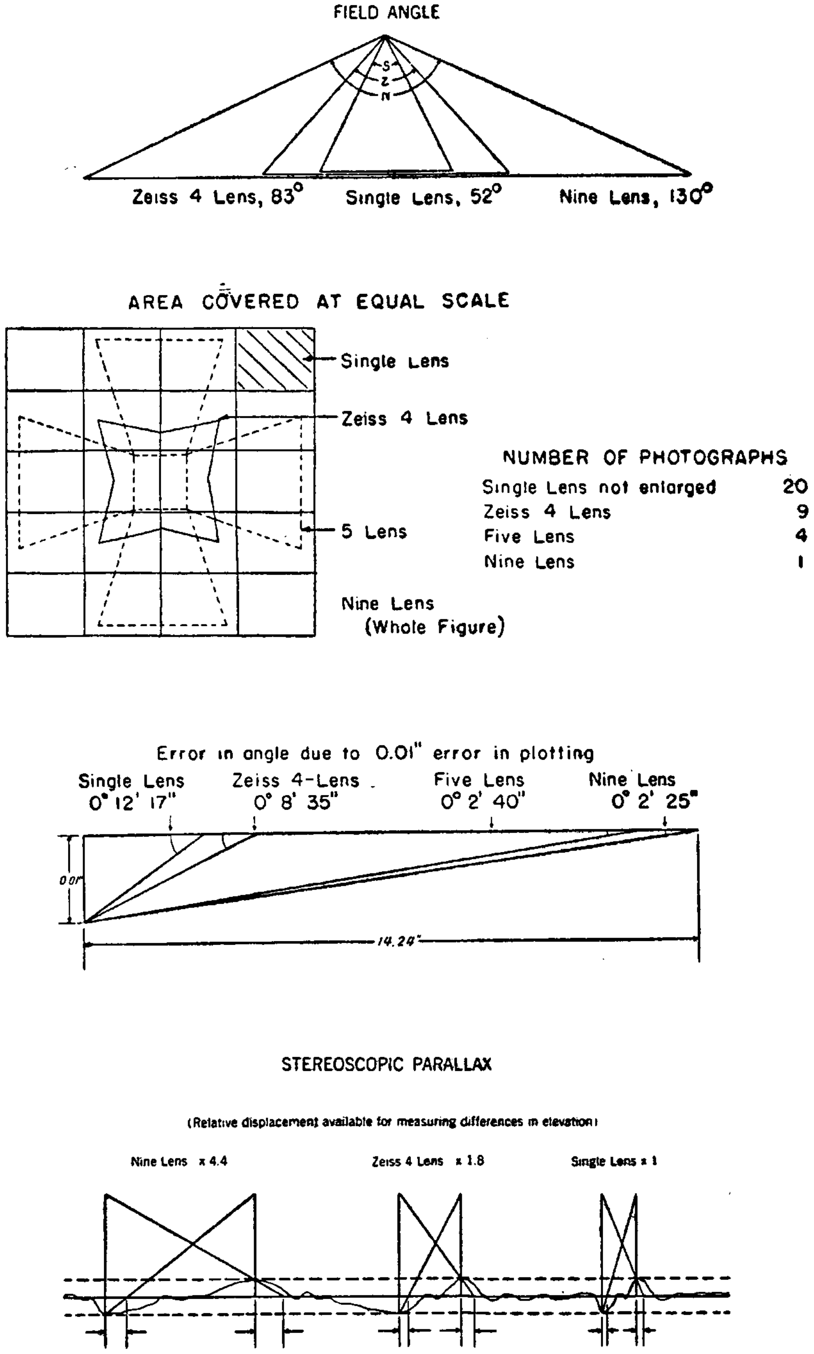

FIG. 1

amount of ground control. But in order to obtain sufficient overlap to use the five lens photographs in the stereoscope, it is necessary that the same number of exposures be taken along the flight strip as with a single lens camera. In order that the sections of radial line plots, made from the outer portions of its photographs, may be well conditioned, it is necessary that the camera be rotated 45° between alternate exposures. As much as we like the five lens photographs for maintaining accuracy in the photo mapping of the Coast and Geodetic Survey, we look forward to a camera which will fill up the spaces between the wing chambers of the five lens camera, and reduce the number of photographs which we have to handle in making our plots.

In 1926, Mr. Leon T. ELIEL applied for a patent on a nine lens camera which would completely photograph the whole of a square field of the same wide angle as the five lens camera. A model of a wing and the center chamber was made and took satisfactory photographs from the air. But the design resulted in a camera of excessive size if not made in a very short focal length, Largely on account of this and perhaps because of the question as to the possibility of holding the adjustment of the large number of mirrors needed in his design, no customers appeared for the camera and no complete model has yet been made. At about the same time, Photogrammetrie, Ltd., of Munich, Germany, applied for a German patent on a nine lens camera, using double reflection prisms in front of the lenses. Both Mr. ELIEL'S camera and the Photogrammetrie camera register all the images on a single film and transform these images to a single composite photograph. Five models of the Photogrammetrie camera have been made, only the last one or two of which have been successful in maintaining a satisfactory adjustment during the large temperature ranges encountered in aerial photography. Recently the English have built a seven lens camera of 120° field but otherwise very similar to the Photogrammetrie camera. Both of these cameras are of very short focal length. The short focal length entails such small images of the objects of interest to surveyors as not to be useful for mapping except on quite small scales. During the International Congress at Paris, a stereo pair of these photographs under magnification of five diameters was examined. While apparently the houses of a village could be made out and counted, it was actually quite impracticable to decide whether the apparent protuberances were straw-stacks, houses or trees. Since much of the value of aerial photographs depends upon the extraordinary amount of detailed information they afford, the sacrifice of this detail in extremely small scale photographs is not considered efficient, except in reconnaissance surveys for which economy of photo materials is extremely important.

This question of the most suitable focal length was the most troublesome of any encountered in the design of the nine lens camera. It is impracticable to do any great amount of enlarging during the transformation of the oblique negatives beyond that required to project them to the same scale as the center photograph because of limiting optical conditions of the transformer lens. For transforming the obliques at angles of 38 to 43° used in multi-lens cameras, any increase in the focal length of the transformer lens above that of the air camera introduces a marked increase in the acuteness of the transforming planes. On the other hand, a shorter focal length of the transforming lens requires an abnormally wide field. On this account, a one to one transformation is used. Moreover, the transformation requires that a horizontal object near the margin of the composite photograph be enlarged about seven times in a direction radiating from the center of a photograph and about 2 1/2 times in transverse direction. An enlargement greater than seven times requires extreme care and unusually good exposure conditions to yield satisfactory results with present materials and technic. Considerable progress has been made recently in reducing the grain size of high speed emulsions but for average conditions encountered in the production of a large number of photographs, it was considered best not to count on much enlargement after transformation.

It is necessary that scales at least as large as 1:10,000 and 1:20,000 be used for the Coast and Geodetic Survey topographic mapping in order that the topographic surveys may be used to furnish shoreline for the hydrographic sheets when sounding the adjacent waters. Also, it is undesirable to photograph at an altitude of less than six thousand feet because of the rough air ordinarily encountered at lower altitudes. These conditions indicated an 8 1/4 inch focal length for the camera. This focal length in turn limited the field angle which could be included by the camera without producing a photograph too large to be handled conveniently in plotting. A field 130° across the strip-producing a photograph of 35 4/10 inches square was decided upon. This was considered as large a photograph as could be handled in plotting since the center of the photographs must be examined carefully in many of the steps of map compilation.

It was considered essential that the aerial photographs be taken on a single film because of the difficulty of handling, setting and mounting accurately nine separate negatives and prints for each exposure. For this reason it was decided to use lenses with parallel axes, projecting their images on a single film and securing the necessary deflection of the side images by means of prisms or mirrors. Prisms, excessive in cost and size, would be required for the focal length selected and considerable difficulties would be encountered in holding the adjustment of such prisms because of the lag in expansion which would occur between the glass and the metal used for mounting them. It was, therefore, expedient to use mirrors for the deflection of the side images in the camera.

The 8 1/4 inch focal length would require a camera 48 inches in diameter if the double mirror arrangement, indicated in Mr. ELIEL's patent, were used. Fortunately the development in recent years by Ross of England of an *F*4 lens, satisfactorily covering a field of 68 degrees, made it unnecessary to use a double reflection to obtain the 130 degree field for the camera.

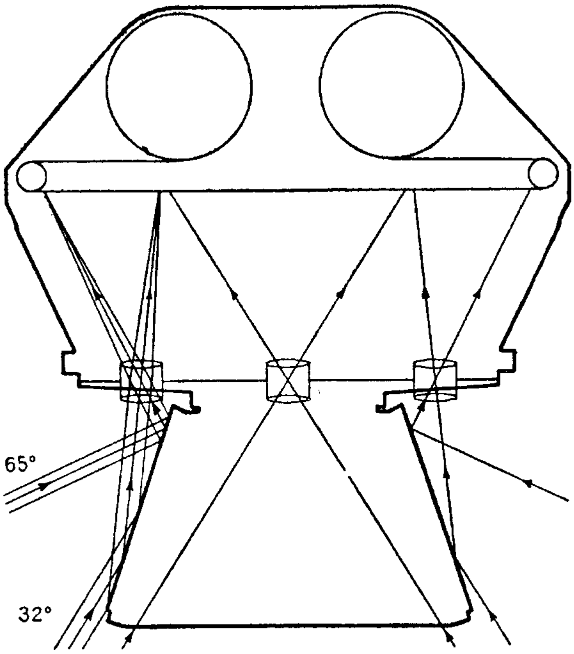

FIG. 2

Diagram of Coast and Geodetic Survey nine lens Aerial camera shows the general layout which was finally adopted for the camera using a single mirror in front of each side lens. The single mirrors required by this design will be 9 1/2 inches long and about 5 inches wide. Each mirror is to be locked to the frame work by nine adjusting screws with lock nuts. The whole assembly will be adjusted by a carefully graduated focal plane plate and collimators set with a theodolite. Fortunately there are a number of old field astronomical instruments available in the Coast and Geodetic Survey which can be used for collimators without much extra expense. The mirrors are to be only 5/16 of an inch thick but it is expected to hold them flat on the frame within 5 or 6 fringes by means of the adjusting screws. They will be adjusted to flatness as they are viewed through a quartz flat at intervals between the adjustment to the correct angles with the collimators. The frame work supporting the mirrors and lenses will be made from the same billet of metal as the mirrors, and care has been taken to use the same thickness in the cross-section of its various ribs in order that the thermal expansion may be as uniform as practicable throughout the assembly. Several experiments in chilling a test mirror and support down to the temperature of 46° below zero indicated that the mirrors will hold their adjustment through a large range of temperature. The steel to be used has 0.35 % carbon and about 14 % chromium with only a trace of nickel. This high chromium steel has been found by the Interferometry Section of the Bureau of Standards to have a very uniform thermal expansion, a stable molecular structure and to afford an excellent surface for polishing. A precise adjustment of the mirrors is necessary because any error in their adjustment will double the errors on the composite photograph. The usefulness of the camera as a surveying instrument will depend almost entirely as to whether it will be practicable to hold the adjustment of its optical elements. We are encouraged by the results of the experiments and although the adjustment will be a painstaking and time consuming process, we feel optimistic about the ultimate success of the design for holding adjustment.

A second critical feature of the camera is the requirement for simultaneous exposure in the several chambers. Between the lens, shutters actuated by electrical solenoids, developed by the Army Air Corps and the Fairchild Aerial Camera Corporation for the five lens camera, have been adopted for the nine lens camera.

These shutters are actuated, not merely tripped, by an electric impulse and they must work simultaneously if they operate at all. The specifications require shutter speeds of 1/50 and 1/80 of a second.

We are not quite so confident about the definition in the wing chambers of the camera. The Ross lens used has satisfactory definition for one to one photographs but it has a zone between 15 and 25 degrees from the optical axis in which curvature of field causes loss in definition which may become appreciable as the images are enlarged during transformation. Since these images are likely to be somewhat poor on account of the longer light path through atmospheric haze, it may be necessary to use a different lens for the wing chambers in order to obtain better definition. The use of two different types of lenses would reduce the field of the camera. For this reason it has been decided to try the Ross lens for all the chambers in the first model. But little less in definition and the loss of only about 15 % to 20 % of light is expected at the mirrors. Their stainless steel surfaces are to be coated with evaporated aluminium or rhodium at Cornell University. Mr. R.C. Williams of the Cornell Physics Department has developed a process of coating high chromium steel with aluminium which gives a surface so hard that it cannot be scratched with a wooden point and which retains about the same reflectivity as aluminium on glass.

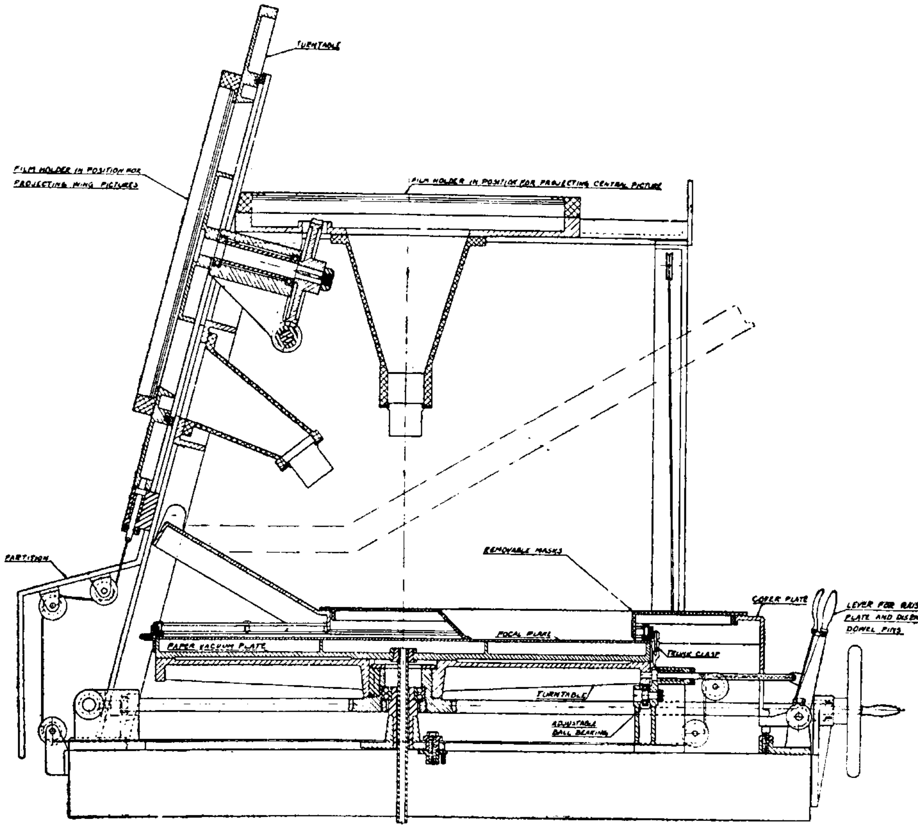

Fig. 3

The nine separate images on the film will be tranformed to a single composite photograph in a two lens transformer. The film will be placed in a carrier which has provision for centering and measuring the shrinkage of the film for a single eye piece magnifying ten diameters. The film carrier is placed on a turn table from which each wing image is projected to its position on the composite photograph held on another revolving table below the lens. The two revolving tables are geared together to keep them in step but accurate registering with the component setting is to be secured by means of dowels. Masks are placed over the part of the composite which is not being projected. Provision is made for using either paper or film held flat on a vaccum back or glass plates for the composite. The film carrier is removed from its turn table when the printing of the wing chambers is completed and placed over another lens for the projection of the central chamber at one to one ratio. Practically every element of the transformer may readily be adjusted and clamped to allow for small errors of machine work. Provision is also made for changing the positions of the lenses and the turn table to compensate for variable film shrinkage.

The film for the camera will be 23 inches wide and about 200 feet long, providing for 100 exposures. It is expected that the camera will be daylight loading and a special spool with concave ends with opaque leaders and followers is being tried for this purpose. An automatic device for indenting the film between each exposure provides for cutting the film between exposures, if desired, prior to development. The film is to be held flat in the focal plane by a vacuum back with an electric pump of 1/2 cubic foot capacity as a source of vacuum. Tests of a model vacuum back in the Bureau of Standards low pressure tank indicated satisfactory performance with such capacity at 20,000 feet altitude. The collimating marks are to be photographed on the film by a set of lamps and lenses at each corner. Images of levels, a watch, a data card and a counter will also be photographed at the same time. The image of the counter will be so placed that it will appear at the corner of the transformed photograph so that hand numbering of the photographs will not be necessary.

A telescope sight will be mounted directly on the camera so that the camera will be automatically oriented when the images of the ground follow the drift lines in the sight. Travelling lines are provided in the sight which are driven in synchronism with the ground image by means of a variable speed mechanism which also automatically operates the shutter release to maintain the desired percentage of overlap of the photographs. In fact "all modern improvements" are to be included in the camera except a provision for photographing the horizon. A tilt of only one minute will cause a difference in correspondence of about 1/50 of an inch between two composite photographs which overlap 60 %. On account of the large aperture necessary for a lens sufficiently fast to photograph the horizon through the red filters required, it would be impracticable to photograph the horizon on a scale large enough to determine the vertical within 4 to 5 minutes of arc. Since the difference in correspondence will give more accurate results with any ordinary amount of control, it was decided to omit the equipment for photographing the horizon from the camera.

The camera will be about 25 x 27 inches in size, about 31 inches high and will weigh about 300 pounds. It is to be handled and transported always on its own gimbals resting on a cart when not in the airplane. A special hoisting device will be used to raise the camera through a hatch cut into the bottom of the airplane. A Bellanca "Pacemaker" or Fairchild 1-A is the minimum size of airplane which can be used to carry the camera.

The design of the camera is based on data furnished by the National Bureau of Standards. The advice of the scientists in the Bureau of Standards, particularly of Dr. I.C. GARDNER, Chief of the Optical Instrument Section, has been sought on practically all questions. The mirror and lens specifications were written after tests conducted there, and the finished parts will be tested in the laboratories of the Bureau before they are accepted for use in the camera.

The camera is being built by the Fairchild Aerial Camera Corporation, which assumes full responsibility for its mechanical operation. The Coast and Geodetic Survey will make the optical adjustment. The Fairchild Corporation has done an excellent job in designing to meet the exacting and rather complicated specifications and we all hope that we shall have a successful camera. The contract price for the first model is $ 24,350 which will be paid in a lump sum, if and when the camera makes 500 satisfactory exposures.

If the camera is a success, there is no question but that its advantages will be ample justification for the expenditure of time and effort. One fourth to one twentieth the number of photographs to plot and a stereoscopic parallax of two to four times that of other cameras are worth striving for. In order to do contouring, a rectifying camera to rectify the nine lens photographs and a projector will be necessary. Preliminary designs are being prepared for this equipment. But if the camera is an unqualified success, the advantage of 2 to 4 times the stereoscopic parallax will doubtless lead to the construction of these additional devices.

It is not easy to visualize the effect of this camera on surveying and mapping as we now know it. Imagine an entire quadrangle within the scope of one photograph on a scale of 1:27,000. Allowing 60 % overlap, both along and between the strips, only six or seven photographs will be required per quadrangle at 1:24,000 scale. The need for adjusting radial line plots should largely be eliminated. On account of a stereoscopic parallax of two to four times that of present cameras, it should be practicable to extend the advantages of stereoscopic mapping to more level terrain as well as reducing the cost of topographic mapping considerably below that possible with present methods of equipment.

NOTES ON SURVEY APPARATUS AND INVENTION.

(Extract from *Empire Survey Review*, London, July 1935, page 172).

The First Theodolite. — The name first given was *theodelite*, for which Leonard Digges was responsible. According to Gunther the word is a corruption of *athelida* (found in W. Bourne's "Treasure for Travailers", 1578), itself a corruption of the Arabic *al'idhāda* (whence "alidade") ; but it is noteworthy that the Oxford English Dictionary is non-committal on the etymology and definitely rejects the Arab origin. Thomas Digges described his father's instrument in 1571 ; his description shows that it was not a theodolite in the modern sense. The mediæval instrument of this nature was the *plane astrolabe*, or circumferentor as perhaps we should now name it. One of these made in Valencia in 1086 is in the museum of Cassel ; another of 1240 is in the British Museum. (H.D. Hoskold, "Notes upon Ancient and Modern Surveying and Surveying Instruments, Trans. Inst. Min. Eng., 1900). The plane astrolabe made by Ribera (1529) was apparently the best known of these instruments. According to E.A. Reeves (Fothergill Lectures, Society of Arts, 1916) the vertical circle was suggested by the astrolabe and the astrolabe and the horizontal circle by the circumferentor. The general principle of the design was this : from the centre of the graduated horizontal circle there rose a column to which was attached a graduated vertical semicircle ; the readings were referred to the horizontal and vertical direction of a rocking bar swinging on a horizontal spindle also attached to the vertical column, the bar carrying a pair of plain sights at its extremities. All the angle-measuring field instruments of the period conformed to this general type ; *e.g.* Waldseemüller's *Polimetrum* (1512), the *Cadrant Differential* of Rotz (1542), the Digges *Theodelitus* and the so-called "theodolite" of Humphrey Cole (1586). It seems that the vertical semicircle was a separate component, mounted only when required ; but there were doubtless minor variations from the type indicated above, which appears to have marked the maximum of development. Indeed, until the telescope was invented by Lipperhey in 1608 and Gascoigne in 1641 had devised the filar reticule for a telescope of the Kepler type, there was not much hope of these crude instruments leading to accuracy much greater than that of the plane-table order. The true theodolite did not appear until a later century, though (following Gascoigne) Huygens (1659), Malvasia (1662), Hooke (1665), Auzout (1666), and Picard (1669) had all applied the Kepler type of telescope *and* the micrometer to astronomical instruments.

The theodolite as we now know it was the invention of Jonathan Sisson, who invented also the Y-level. This maker has not received that meed of praise which is his due, but it is unquestionable that Sisson was a manufacturer superior even to Jesse Ramsden in some ways ; for example, he was able to construct *small* instruments. ("Surveying and Navigational Instruments from the Historical Standpoint", by Dr. L.C. Martin) (Trans. Opt. Soc. xxiv, N° 5, 1922-3). The late W.F. Stanley had previously published the same finding (op. cit., p. 214, 4th ed. by H.T. Tallack). Sisson's theodolite of 1725 had a circle of no more than 4 ½ inches ; its three verniers read to 6' ; the vertical circle gave altitudes up to 70°, read by a single vernier ; the level was set above and attached to the telescope ; the instrument was levelled by four foot-screws. But perhaps the most surprising feature of this small theodolite is that according to Dr. Martin it was furnished with *spirit* levels. Apart from this, however, Jonathan Sisson in 1725 constructed the first theodolite. He was also the inventor of the Y-level.

The Reticule. — The reticule dates back to Gascoigne's "perspicills with threads" (1641). The spider-web reticule was fitted to the theodolite by Troughton in 1775, but