Modern Instruments for Surveying and Mapping

New surveying systems utilizing photogrammetry and electronics speed production of topographic maps.

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Reliable topographic maps are the indispensable medium for planning and directing many kinds of modern scientific and engineering operations. The ever-growing need for such maps has mothered the invention of new and remarkable devices that in a relatively short time have relegated many of yesterday's surveying instruments to the museum shelf.

Until a few decades ago, the topographer (the man who made topographic maps) was a combination of engineer and artist-craftsman. He knew how to make engineering measurements with the classical surveying instruments of the time—the theodolite, the steel tape, the spirit level, the alidade, and the plane table. He also had the necessary talent for filling in map detail by on-the-spot observation and for interpretation of the terrain in relation to measured points—a talent that was partly scientific and partly artistic. The topographer rode or tramped or waded over the length and breadth of the area assigned to him. He originally relied entirely on horses for local transportation but later used the automobile to the extent feasible. With a few temporary field assistants, he did the job from beginning to end, and the resulting topographic map bore his imprint as surely as a painting bears in its composition the signature of the artist.

Although there are still many field tasks that require the services of surveyors and engineers, the field men of today are responsible for only limited portions of the mapping operation, which in large part are accomplished with new kinds of surveying instruments and transportation equipment. Nowadays, more than half of the surveying operations, particularly those entailing the actual drawing of map detail, are likely to be performed in a modern air-conditioned office by city-dwelling specialists using ingenious new instruments, far removed from the mountains and fields and woods being surveyed.

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Photogrammetric Instruments

The most important factor in the development of modern topographic survey practices is, by all odds, the use of aerial photographs and the application of the science of photogrammetry (obtaining reliable measurements by means of photography) (*1*).

The aerial photograph is now a familiar working tool in many scientific disciplines besides topographic mapping. The geologist, forester, agronomist, or any other scientist dealing with the character of the earth's surface must be familiar with the advantages and limitations of aerial photographs if he is to consider himself knowledgeable in his profession. The great impetus to the use of aerial photographs, however, resulted from the needs of the topographic engineer, and it was in the course of meeting these needs that modern photogrammetric instrumentation was developed.

To understand the problems of photogrammetry, it is necessary to recognize at the start that an aerial photograph does not, in itself, constitute a map (see Fig. 1). Because of variations in ground elevations, tilting of the aerial camera, lens and film aberrations, and other phenomena, the aerial photograph usually gives a distorted picture of the terrain. Furthermore, a single aerial photograph affords no means of measuring variations in the height of the terrain. For converting the information contained in the aerial photographs into accurate topographic maps equivalent to those based on conventional ground surveys, various plotting instruments have been developed. These instruments range from relatively simple devices, used for the production of maps of relatively low precision, to elaborate stereoscopic plotting machines designed for producing maps of a high standard of accuracy. These instruments are, in general, increasingly more complex as a higher degree of precision is attained.

Although there are wide differences in the mechanical details and in the degree of accuracy attained, practically all stereoscopic mapping instruments operate on the same principle (see Fig. 2). A pair of photographs taken at successive exposure stations and overlapping by about 60 percent are oriented in the instrument to recover their relative orientation at the instant of exposure. By means of a carefully calibrated projection system, each photograph is projected through a perspective center so that the angular relationships at that point are identical with those at the exposure station when the photograph was taken. A stereoscopic viewing system is provided so that a miniature model of the terrain appears to be created. The model can be brought to the desired scale and oriented with respect to both a horizontal and a vertical datum, as represented by ground-survey control points. Measurements are made by means of a "floating mark" whose position with relation to the ground surface can be plotted orthographically on the map while the floating mark is moved "along the ground" of the "phantom model" to trace map detail. Since the space model is similar in every respect to the terrain in nature, the tilt and relief displacements are automatically eliminated.

Stereoscopic plotting instruments may be classified, according to their projection system, as follows:

In the optical-projection system transparent positive prints of the photographs (called diapositives) are projected through lenses so that the angular relationships of the emergent cone of rays duplicate those at the taking camera. In two well-known instruments of American manufacture, the ER-55 (Fig. 2) (Geological Survey successor to the multiplex aeroprojector) and the Kelsh plotter (see Fig. 3), the images are projected directly on a tracing table platen at a finite distance and are viewed directly on the platen (*2*). In the German-made stereoplanigraph the projection is made through an objective at infinite focus, and the images are observed through an optical viewing system (*3*).

The mechanical-projection system utilizes space rods to carry out the projection. A space rod passes through a pivot corresponding to the perspective center of each photograph. The space rods can be made to move in any direction in space through this pivot point. When the instrument is properly oriented, and one end of each space rod is made to represent corresponding image points on the photograph, the intersection of the space rods represents the position of the point in nature. This principle is used notably in instruments of the autograph type (*4*), mainly of Swiss manufacture (see Fig. 4).

In the mechanical-optical-projection system the projection is made through a lens at the perspective center, but the connection with the measuring system is made through a mechanical linkage. Such a system is used notably in French instruments as well as in some of the earlier German ones (*5*).

The basic principles of these types of instruments were known and applied for many years prior to World War II; however, the continual improvement and refinement in mechanical, optical, and electrical elements have made the stereoscopic plotting instruments of today far superior in their capabilities to the pre-war models. Progress in this field is stimulated by a healthy rivalry among producers in Germany, Switzerland, France, Italy, Canada, Great Britain, the Soviet Union, and the United States; each of these countries has produced excellent instruments.

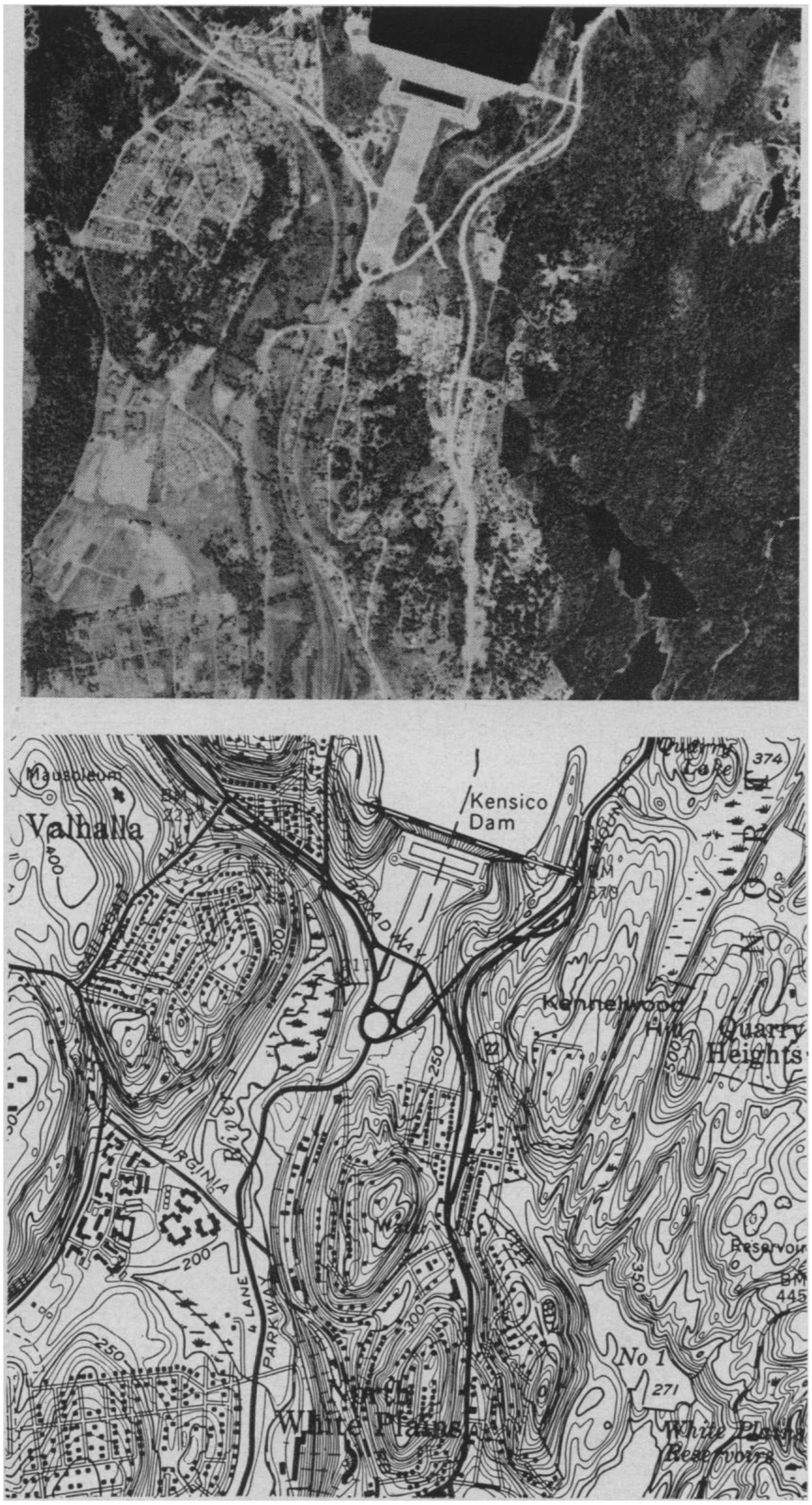


Fig. 1. Portion of an aerial photograph (top) used in the preparation of a topographic map (bottom). The map is a portion of the White Plains, N.Y., 7.5-minute quadrangle. Scale, 1:24,000. [U.S. Geological Survey]

Automation of Mapping Instruments

Currently, two major efforts in photogrammetric instrumentation are being made in the direction of automation. One of these efforts is aimed at automating the map-drawing operation itself. The other is aimed at utilizing modified mapping equipment in combination with electronic computing equipment to produce engineering data directly from the stereoscopic model without requiring a complete map as an intermediary.

The Stereomat

Automation of the map-drawing operation, while not yet practical for accurate topographic mapping, has been shown to be within the realm of possible attainment in the near future. A solid achievement in this field is the Canadian development originally known as "Auscor" (Automatic Scanning Correlator) and now called "Stereomat" (*6*). Further development of this apparatus has been undertaken by an American company.

The Stereomat (see Fig. 5) embodies a system of electronics and electromechanics which may be attached to a conventional stereoscopic plotting instrument to perform the following functions automatically:

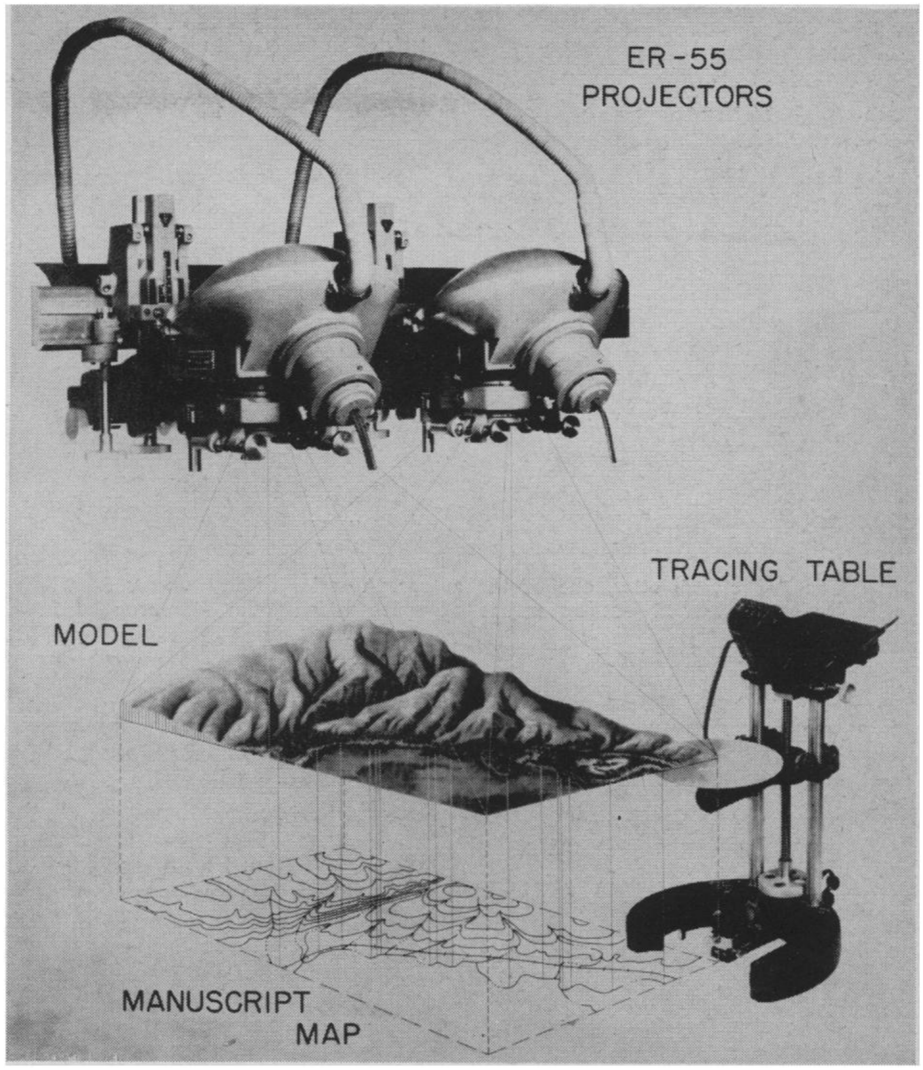
1) The system identifies corresponding points in the two photographs of the same object taken from different positions. This is accomplished by scanning the area around each point by a spot of light moving in a random pattern around and across the area being examined. The varying light impulses resulting from boundary crossings (between light and dark areas) in the photograph are converted to electrical signals by photomultiplier tubes. Associated electronic circuitry measures correlation of the electrical signals resulting from each photograph. The correlation is a measure of the common scanning area that is being searched. If the correlation is weak, the scanning pattern expands, and vice versa. Thus, points of image detail are identified by the pattern of surrounding images.

2) After identifying the images, the system determines the direction and magnitude of the parallax (failure of corresponding image rays to intersect) in both the X and Y directions separately. The circuitry thus produces two direct-current voltages, one for Y parallax and one for X parallax. The polarity of the voltages is dependent upon the direction of the parallax, and the magnitude is dependent upon the amount of parallax.

3) The X parallax error voltage is fed to a servo motor which actuates the elevation of the projection table. When the error voltage becomes zero, the servo motor stops and the index (floating) mark is on the terrain surface of the phantom model.

4) The Y parallax error voltage is automatically switched to appropriate servo motors which actuate the projection heads of the plotting instruments to remove Y parallax, thus completing relative orientation of the projectors.

5) In the contouring application, X parallax error voltage is combined with other information generated by the circuitry, to actuate X and Y servos which move the index mark in a horizontal plane in the direction necessary



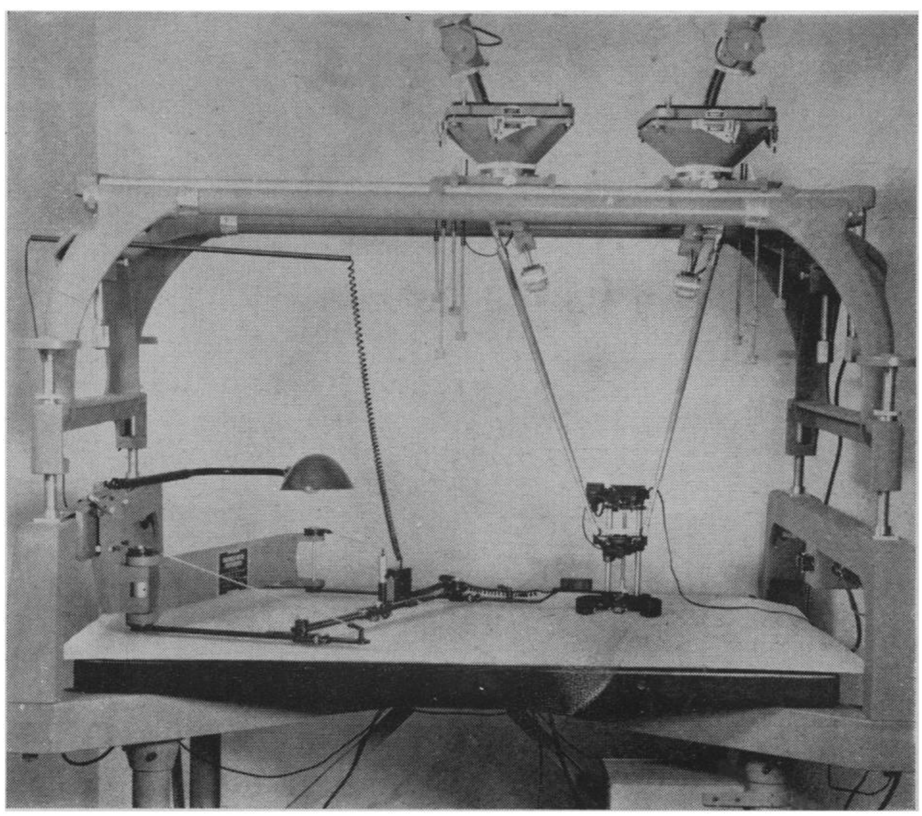


Fig. 2 (top). Mapping with a stereoscopic plotting instrument. [U.S. Geological Survey] Fig. 3 (bottom). The Kelsh plotter, an optical-projection mapping instrument with a direct anaglyphic viewing system (one photograph is projected in red, the other in blue; the observer wears corresponding spectacles with one red and one blue lens). [U.S. Geological Survey]

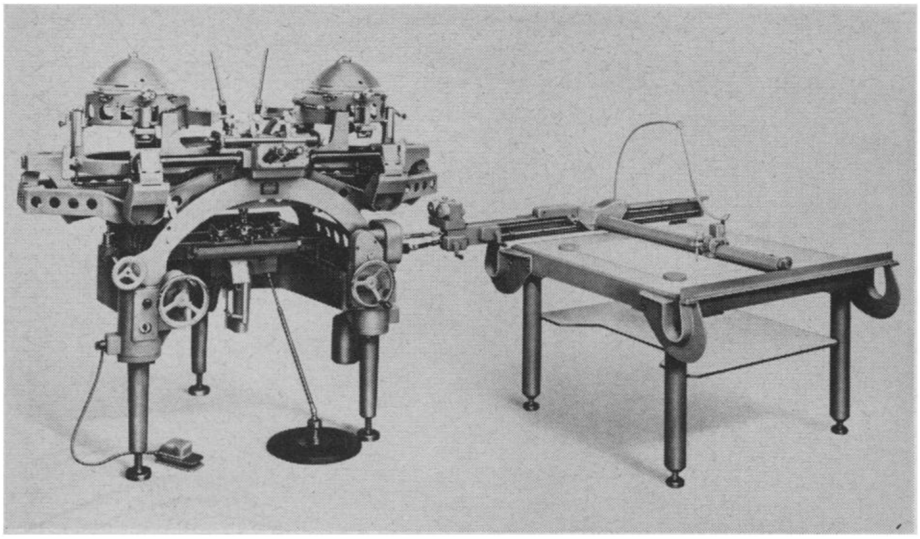


Fig. 4. The A-8 stereoplotter, one of the autograph series of instruments in which the projection is carried out by means of space rods. [Wild Heerbrugg Instruments, Inc.]

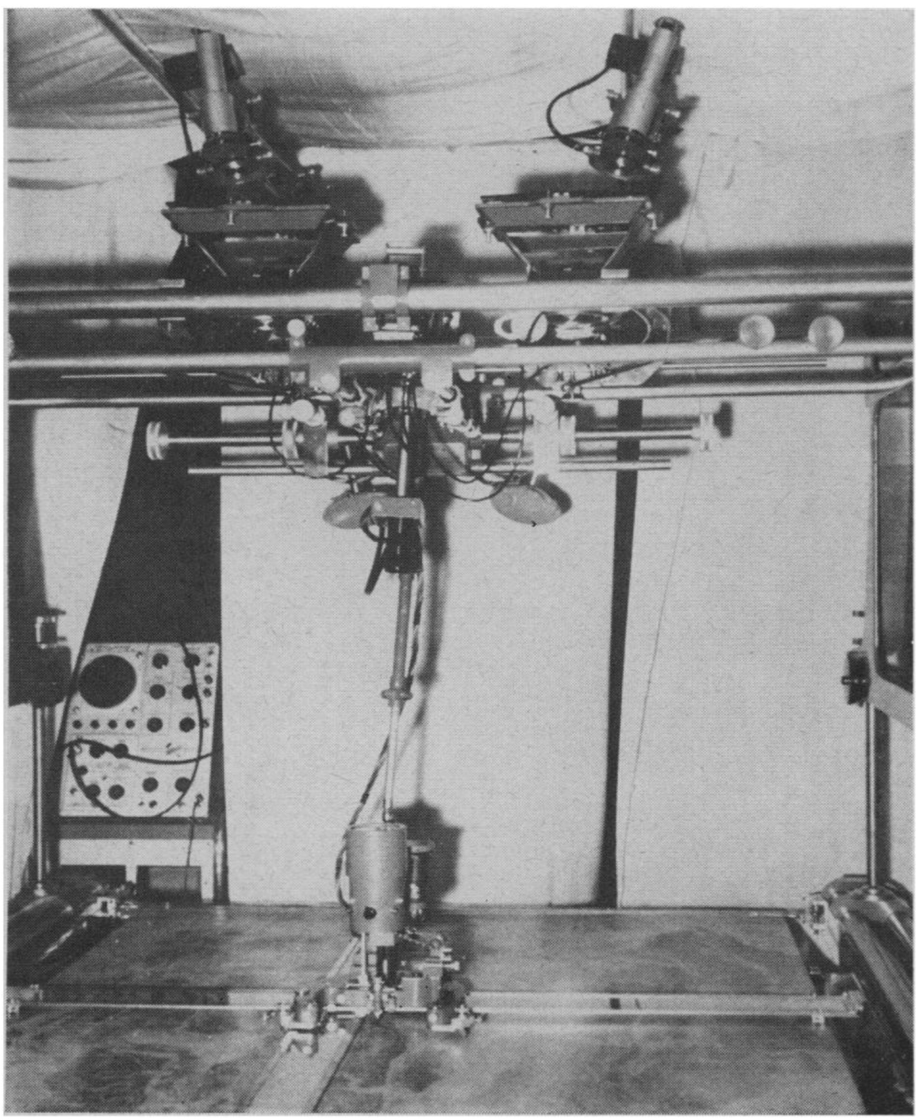


Fig. 5. The stereomat, an instrument combining electronic hardware with a conventional Nistri plotting instrument to achieve automatic stereoscopic perception. [Benson-Lehner Corporation]

to maintain the index mark "on the ground" at a given elevation. The index mark is thus steered automatically through the stereoscopic model so that its path is the locus of points of equal elevation, and a contour line is thus produced.

The Stereomat is a long way from being perfected, and the specialist who operates photogrammetric mapping equipment is in no current danger of being supplanted by a machine. Nevertheless, the indications are plain that automation will be a vital factor in the future of mapping instrumentation.

Automatic Engineering Computations

The nation's program of rapid expansion of the interstate highway system has placed a heavy burden of rather onerous computation on highway engineering staffs. For example, when a number of alternative routes are under consideration, an important factor in the selection is the relative amount of earthwork involved in the various alternatives. Earthwork computation by classical methods is a slow and costly process, completely out of tune with the urgency of the highway program.

The adaptation of photogrammetric mapping equipment to earthwork computation has helped to reduce this bottleneck in the highway program (see Fig. 6). In this adaptation, the tracing table of a conventional stereoscopic mapping instrument is hooked up to a read-out device which in turn feeds data to an electronic computer. Position and height readings of points on a highway cross section (or profile) in the stereoscopic model are fed to the computer, which is programmed to convert these readings to volume computations (*7*).

Orthophotoscope

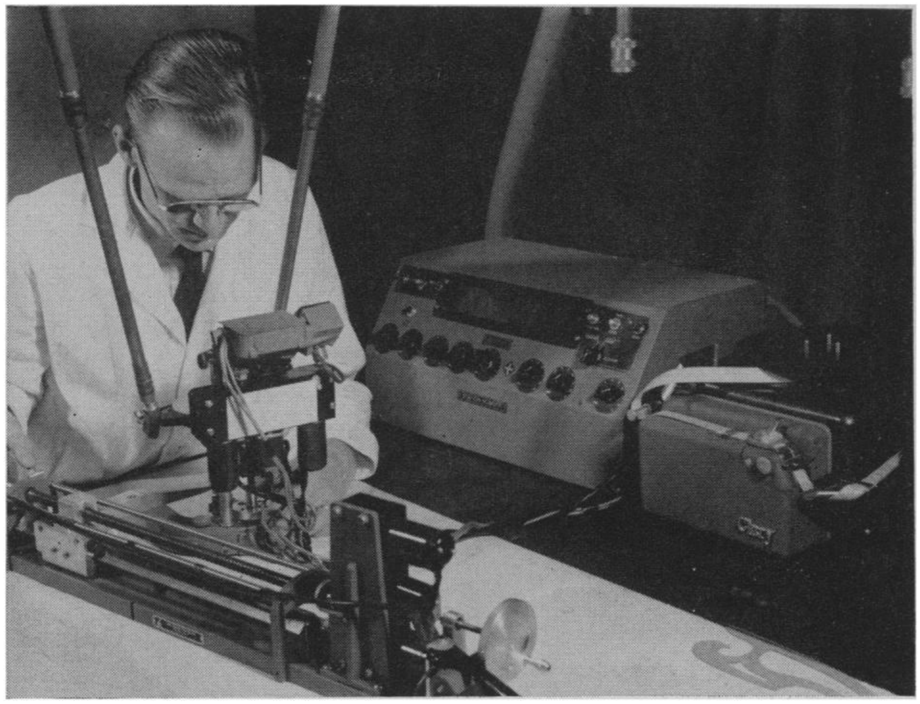
Efforts are currently under way to apply similar automation to the Orthophotoscope (*8*), an instrument recently developed by the U.S. Geological Survey to produce something long desired by the engineer, the geologist, the forester, and many others—a uniform-scale photograph with no distortions due to tilt and relief. These orthophotographs combine the scale reliability of a map with the wealth of detail afforded by a photograph (see Fig. 7).

The Orthophotoscope (see Fig. 8) combines conventional stereoscopic mapping equipment of the anaglyphic type (one image projected in blue, an overlapping image projected in red) with a means of exposing a sensitized film, bit by bit, through a narrow slit in a movable screen on which the model is projected. The elevation of the film is varied according to the terrain as the scanning proceeds. Tilt displacements are eliminated by proper orientation of the projectors. The sensitized surface is a blue-sensitive film which has no actinic response to the red light of the usual anaglyphic projection. The sensitized surface is thus differentially exposed by the projected blue image, always at the correct elevation to eliminate relief displacement. When the scanning is complete, the film is developed as a negative and the orthophotographs are printed from this negative in any quantity or on any scale.

The tedious part of the production of orthophotographs is the scanning operation, which requires that the operator continuously adjust the elevation of the film in order to keep the slit "on the ground" as the scanning proceeds. It is reasonable to expect that this height-adjustment operation can be made automatic by means of hardware similar to that used in the Stereomat.

Distance Measurement by Electromagnetic Waves

Although photogrammetric procedures are now the major means of making the detailed topographic survey, there remains the vital problem of providing suitable geodetic control (points of known position and elevation) to permit the map drawing to be related properly to horizontal and vertical datums. Such control is still obtained mainly by ground-survey methods, which are relatively high in cost. In some instances, the cost of ground-survey control has exceeded the cost of the photogrammetric operations. It is therefore only natural that intensive ef-



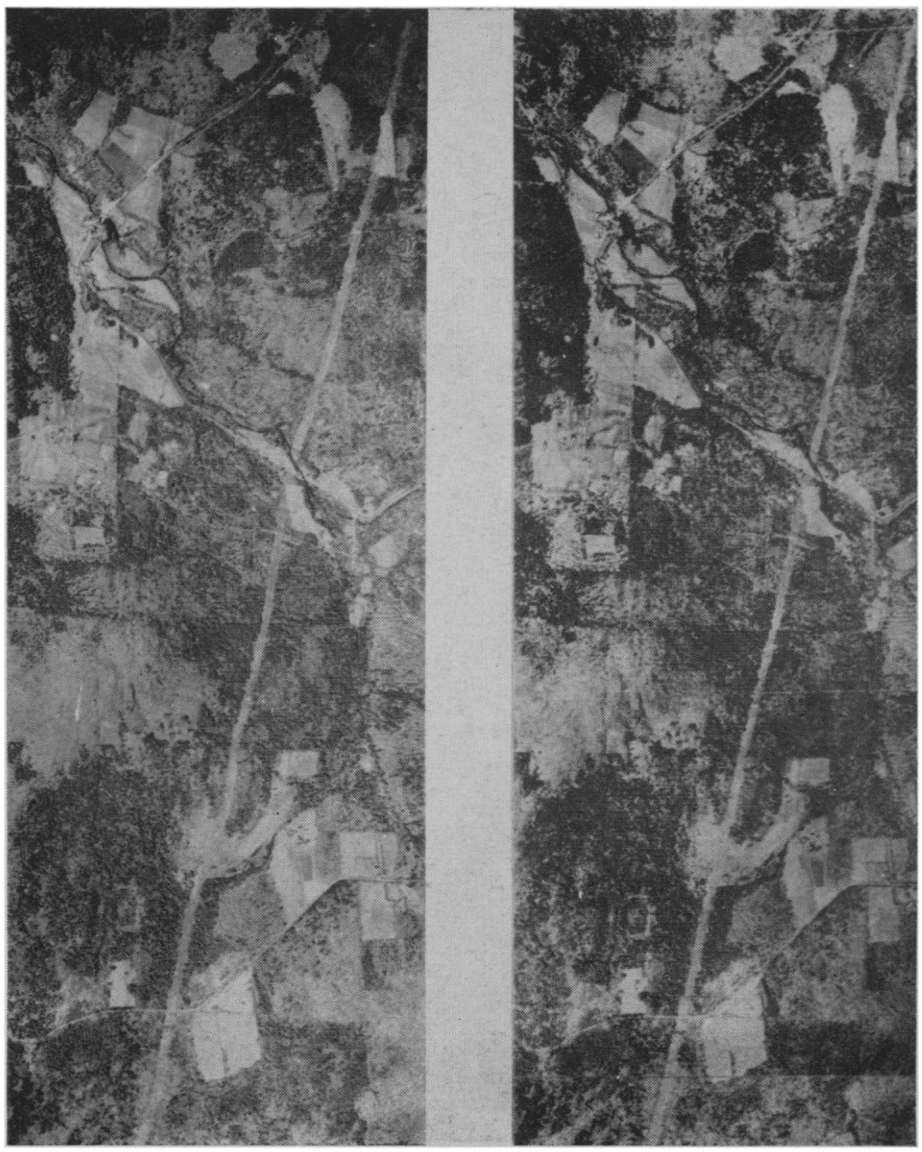


Fig. 6 (top). Hook-up of Kelsh plotter tracing table to read-out system for feeding data to an electronic computer for earthwork computation. [Aero Service Corporation] Fig. 7 (bottom). Corresponding portions of a perspective photograph (left) and an orthophotograph (right). In the perspective photograph the power line appears to be crooked, while in the orthophotograph it is shown in its true, straight alignment. [U.S. Geological Survey]

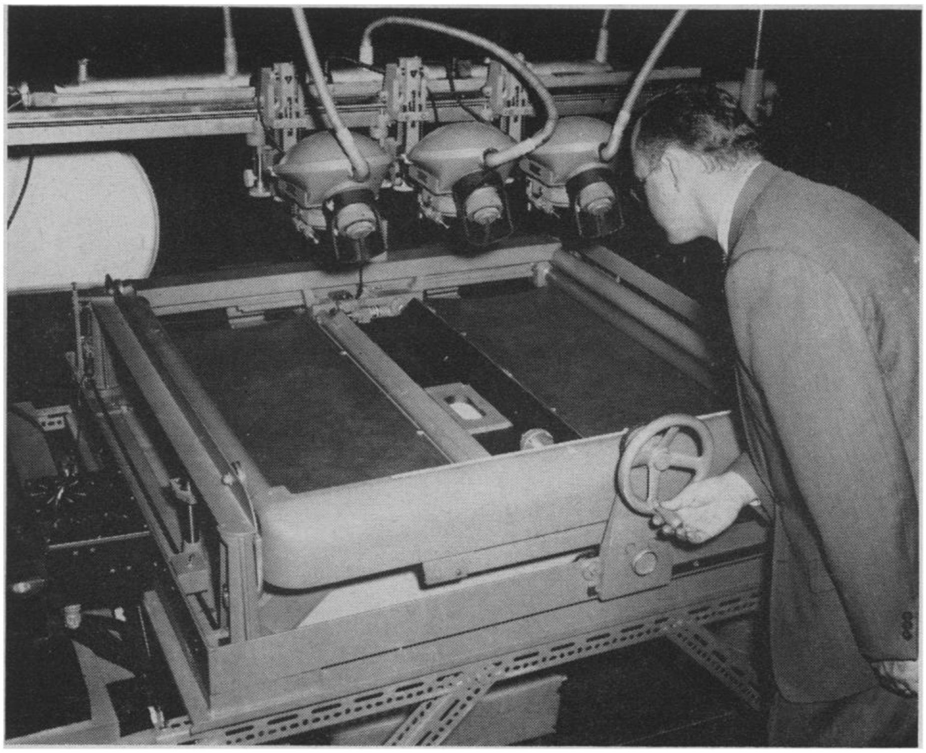


Fig. 8. The orthophotoscope, a combination of conventional ER-55 plotting equipment with a photo-scanning arrangement. [U.S. Geological Survey]

forts are being made to reduce the cost of this field work.

One of the critical problems in connection with field surveying is the problem of obtaining accurate and economical distance measurements for triangulation base lines and for traverse courses. As recently as a few years ago, the most reliable and economical method for accurate distance measurement in surveying work was the tedious procedure of direct measurement with a steel or invar tape. Much of this has been changed within the past few years by the introduction of new scientific instruments which exploit the modern techniques of electromagnetic wave transmission and electronics.

Geodimeter

The first successful development in this direction was the geodimeter, a system developed and manufactured in Sweden, in which a modulated light beam is directed from apparatus set up at one survey station to a reflector set up at a second station (*9*). The distance between the two stations is determined as a function of the phase relationships between the emitted beam and the reflected beam at various modulation frequencies and the precise value of the velocity of light. The system requires clear weather, darkness, and an unobstructed path between the two stations. Distances up to 30 miles have been measured with an accuracy good enough for geodetic base lines. The geodimeter also gives good results for short distances. It is not affected by moving or stationary objects in the vicinity of the stations or sight line.

Tellurometer

Soon after the introduction of the geodimeter, another valuable distance-measuring system, the tellurometer (see Fig. 9), became available (*10*). The principle of the tellurometer, developed and manufactured in South Africa, is essentially as follows: A modulated continuous-wave radio signal is transmitted from a master unit set up at one survey station; this signal is, in effect, received and retransmitted by a remote unit set up at the second survey station; the phase of the return signal is compared with the phase of the initial signal at several carefully selected modulation frequencies; these phase differences are read on the face of a cathode-ray tube and, through the relationship of the selected frequencies, are readily converted to transit time of the radio signal between the stations. The distance is derived as the product of the measured transit time and the known velocity of radio waves.

The tellurometer can be operated in daylight or darkness. It has the advantage of being able to penetrate haze, smoke, fog, clouds, and light rain; it will even penetrate a limited amount of foliage or timber if the obstruction is not located too near one of the stations. The optimum distance for tellurometer measurements is about 10 to 25 miles. Measurements up to 40 or more miles may be made under good conditions, although the accuracy falls off somewhat. Likewise, the accuracy falls off somewhat when the measured distance is less than 1 mile. The system is affected by reflections from nearby moving objects, such as waving grass or moving people or vehicles. Although some occasional "bugs" in the system are encountered,

Fig. 9. The tellurometer. Distance measurement with this instrument depends on the known velocity of radio waves. [U.S. Geological Survey]

experience to date with the tellurometer reported by the Geological Survey and other organizations indicates that the results are quite satisfactory.

The most recent development in this field, not yet in actual use, is an American system known as micro-dist (*11*). This system operates on the same basic principle as the tellurometer, although it differs in detail. In the micro-dist, readings are taken from a direct-reading counter instead of from a cathode-ray tube. Also, the master and remote units are interchangeable. Accurate measurement of relatively short distances is said to be possible.

Transportation and Communication

An integral part of the problem of making field measurements is the logistical problem of transporting men and equipment to the places where observations are to be made. The use of such modern vehicles as jeeps, "sno-cats," and helicopters (see Fig. 10) now enables the engineer to set up surveying equipment in swamps, in snow fields, on mountain-tops, and in other places that formerly could be reached only with difficulty, if at all. Communication is maintained by portable two-way radio.

Reconnaissance Systems

A number of other systems, mostly airborne, exploiting electronic and wave phenomena have been used successfully in reconnaissance mapping where the accuracy requirements are not so rigid. Some are described briefly below.

The radar altimeter (*12*) measures variations in the height of terrain, utilizing a radar beam emitted from an aircraft traveling at a constant pressure altitude.

Electronic tracking systems such as Shoran, Hiran, Raydist, and Decca can be used to determine the position of each aerial photograph exposure station with respect to two or more fixed ground stations or to keep the aircraft on a predetermined flight path. (By techniques of repeated measurement, such as are often used in geodetic ground surveying, Hiran has been used successfully for very precise measurement of lines too long for visual observation; distances as great as 500 miles have been measured this way.)

The Doppler system, entirely airborne, derives the speed of a photographic airplane from the frequency shift in a radar signal reflected from the ground and integrates this speed with respect to time, to obtain the distance traveled (*13*).

Radarscope photography (*14*) provides a means of obtaining survey data somewhat similar to poor-quality aerial

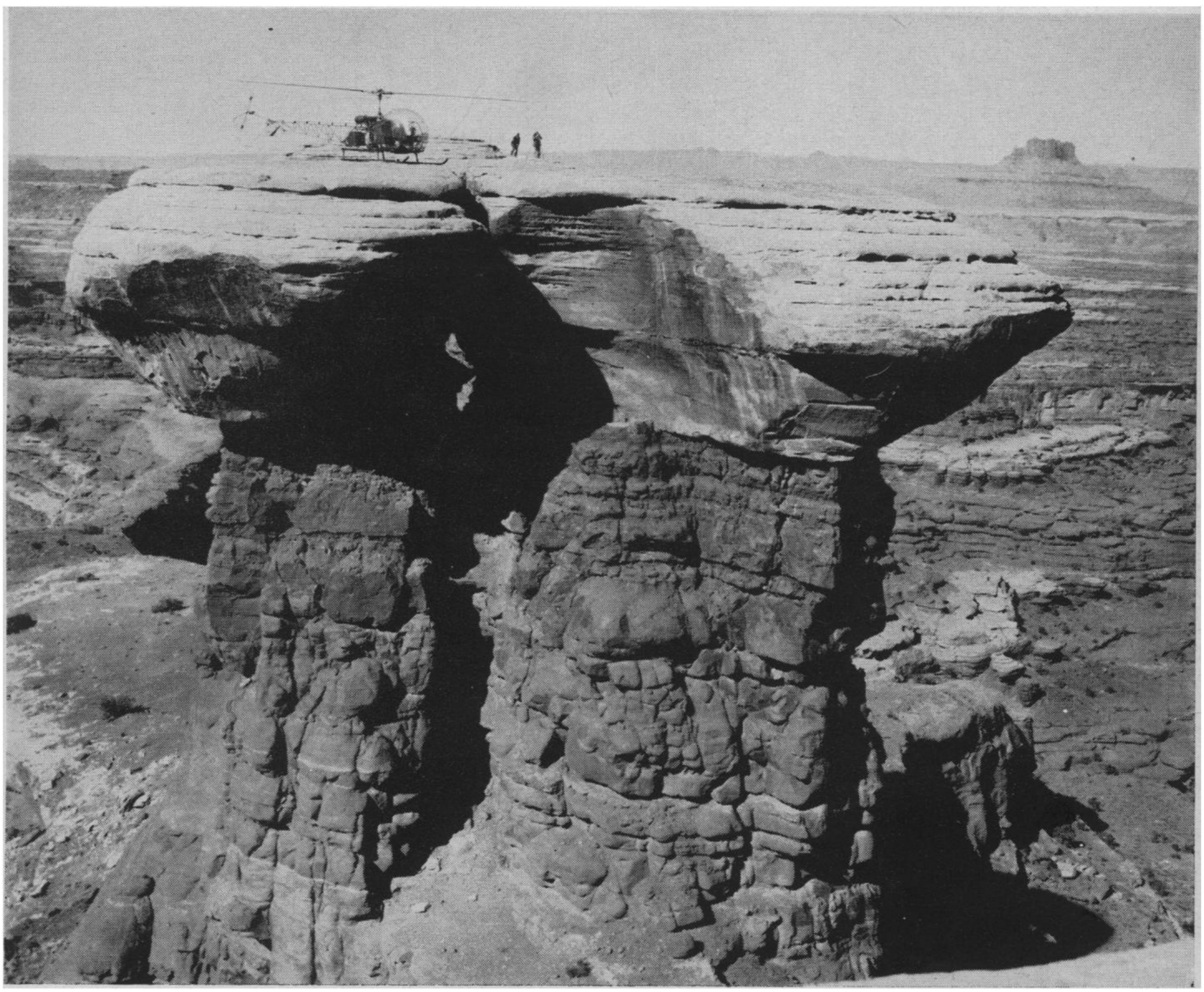


Fig. 10. The helicopter affords ready access to otherwi se inaccessible survey stations. [U.S. Geological Survey]

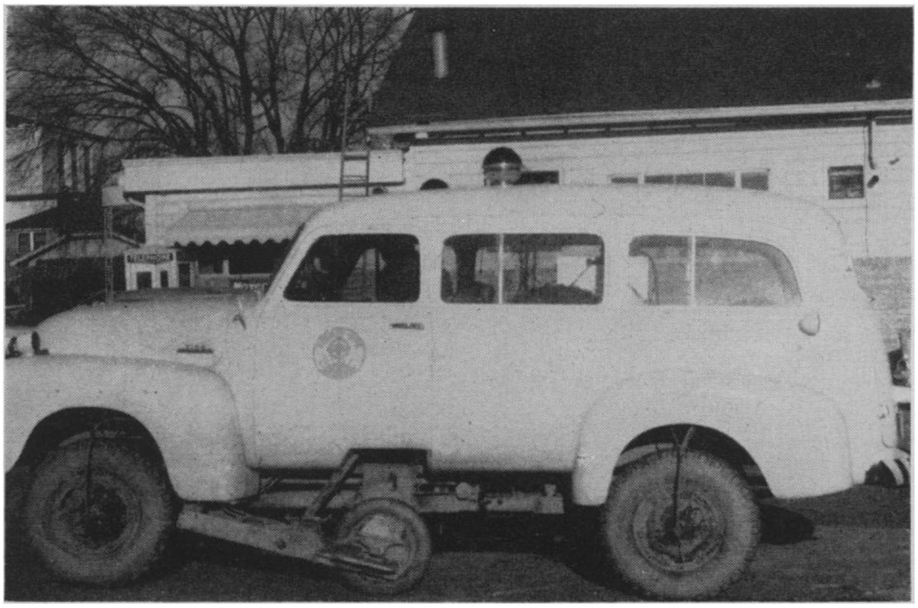


Fig. 11. The elevation meter. In this system, functions of the angle of slope and the distance traveled are integrated electronically, as the vehicle proceeds, to give height differences. The slope function is derived from the action of an electromagnetic field on a sensitive pendulum. [U.S. Geological Survey]

photography, without requiring good weather or light conditions. Although the data that can be extracted from radar photography is deficient in some respects, it meets a vital need when normal sources fail.

Height Differences by Carborne Electronics

An interesting solution to the problem of providing vertical control (fourth-order elevations on a number of selected "picture points") for some types of mapping projects is offered by the elevation meter (see Fig. 11), a system developed in the United States (*15*).

The equipment is mounted in a four-wheel-drive carryall truck provided with four-wheel steering. As the apparatus proceeds along the road, an electromagnetic field acts on a very sensitive pendulum in such a way as to generate an electrical signal whose strength is proportional to the sine of the angle of slope. Another electrical signal is generated by a revolution counter connected to a special fifth wheel, which measures the distance traveled. By means of an electronic integrator, the two signals are combined into a continuous and automatic record of the difference of elevation from an initial starting point. To eliminate dynamic effects, the vehicle must be stopped to take elevation readings. Proceeding at moderate speeds over readily passable roads, the elevation meter can produce about 50 to 100 miles of leveling per day, reliable within about 2 feet, depending on operating techniques and distances between controlling bench marks. The elevation meter should be particularly economical on large projects where an adequate network of roads exists.

Conclusion

The engineer's mission is to put scientific knowledge to practical use. Modern surveying and mapping instrumentation affords an excellent example of the accomplishment of this mission. Many of the principles applied are based on very recent findings of modern science, with hardly a pause in the step from completion of basic research to useful application.

There are still plenty of scientific problems left to challenge the ingenuity of the surveying and mapping profession, however. Instruments and techniques are needed for establishing geodetic control without ground surveys, for mapping the ocean bottom, and for mapping the moon, other planets, and space. Some work is already being done in each of these directions. One can hardly doubt that the solutions will be found.

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