58

HIGHWAY RESEARCH BOARD

Bulletin 258

Electronic Surveying

1960 Developments

National Academy of Sciences—

National Research Council

publication 767

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N.R.C. HIGHWAY RESEARCH BOARD

Bulletin 258

Electronic Surveying

1960 Developments

Presented at the
39th ANNUAL MEETING
January 11-15, 1960

1960
Washington, D. C.

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Foreword

Measurement of distances and angles on the ground to determine the horizontal position of specific points where permanent station markers have been placed has always been a difficult and time consuming task when the distances are measured by tape and/or determined from triangulation. New methods now available to everyone concerned with or having need for basic control data regarding permanent station markers need not be entirely dependent on the conventional, costly, and slow methods of traverse taping and angle measuring, and triangulation. Instruments, electronic in character, utilizing the speed of light as the measuring means can now be employed to achieve remarkable results.

Two such instruments have been in use for the past several years on control surveys in conjunction with the establishment of both basic and supplemental control for highway location surveys, especially those surveys accomplished by aerial photogrammetric methods. The experiences of five separate highway departments and of the U.S. Coast and Geodetic Survey in use of these instruments for such purposes under a wide variety of topographic and land use conditions, geographic locations, and weather are reported in the papers on the Geodimeter and the Tellurometer in this bulletin. Recently the U.S. Army Corps of Engineers completed tests on a third electronic distance-measuring instrument called the Micro Dist, which was developed in the United States. Based on these tests, this instrument proved its potential as an alternative for the Geodimeter and the Tellurometer.

By utilizing such instruments, surveys need not cost as much as formerly, yet their utility and their accuracy and their scope should increase manifold. These new methods also facilitate the ease of completion, and lower the cost of making highway surveys by aerial photogrammetric methods.

William T. Pryor
Secretary
Committee on Photogrammetry and Aerial Surveys

Contents

RELIABILITY OF ELECTRONIC MEASURING EQUIPMENT
Rex H. Fulton 1

THE TELLUROMETER FOR HIGHWAY SURVEY CONTROL
Austin C. Poling.. 8

TELLUROMETER USE IN CONTROL SURVEYS FOR MAPPING BY PHOTOGRAMMETRIC METHODS
Carl C. Winikka 13

EVALUATION OF THE TELLUROMETER FOR HIGHWAY SURVEY CONTROL IN MARYLAND
George W. Cassell and Charles W. Parks 21

EVALUATION OF THE TELLUROMETER IN HIGHWAY HORIZONTAL CONTROL WORK
H.H. McBride.. 25

THE TELLUROMETER AS USED FOR HIGHWAY CONTROL SURVEYS IN VIRGINIA
George W. Habel.. 29

Reliability of Electronic Measuring Equipment

REX H. FULTON, Assistant Planning Engineer, California Division of Highways

This paper gives the purpose, use and cost of the Model 3 Geodimeter for 1,200 mi of highway work, its mechanical and accuracy reliability based on more than two years of operation, and agreement of 325 mi of traverse with 125 USC&GS stations. Also included is a resume of brief experience with the Model 4 Geodimeter.

● THE GEODIMETER is an electronic device that measures distances by means of a highly collimated light beam projected to a distant reflector. The reflector returns the beam to the instrument where it is converted into electrical impulses and time intervals for distance computations. The Model 3 Geodimeter has a range of from 1 to 20 mi and the Model 4 has a rated range up to 3 mi. The accuracy of the instruments will be discussed later.

In September 1957, the California Division of Highways purchased a Model 3 Geodimeter for the purpose of extending second-order horizontal control surveys along proposed highway routes. Monuments are established at an interval of about 3 mi and used as a framework for subsequent detailed surveys for highway location, design, and construction. In practically all projects, photogrammetric mapping is involved.

The Model 3 Geodimeter is operated from headquarters to serve the 11 Districts on request. Two men are assigned to it as a permanent crew and additional district personnel are added on the job as needed. The traverse method is used almost exclusively, which consists of measuring the distance of each course in leap-frog fashion with the Geodimeter and measuring the horizontal angles for azimuth. A variation of this method is to measure several stations radially from one observation station. Vertical angles are also measured for the purpose of converting the slope distances to horizontal. All angles are measured with a one-second theodolite. Geodimeter readings are reduced to horizontal distance by means of a digital computer. All coordinate positions are referred to datum of the State Plane Coordinate System.

To date, horizontal control stations have been established along 1,720 mi of highway, which necessitated 2,780 mi of line actually observed.

The California Highway District comprising the San Francisco Bay area has recently purchased a Model 4 Geodimeter which is used for traversing short courses of 500 ft and more. To date, about 100 courses have been observed, the longest being 6 mi, all with better than second-order closures. The manufacturer rates the distance capacity at 3 mi, however, 6 mi have been observed and indications are that much longer shots could be obtained with adequate reflectors. Because of the limited experience with this instrument, no further consideration will be given to it in this paper. All data herein considered is based on the Model 3 Geodimeter.

In over two years of operation, it has never been necessary to stop work because of the failure of the Geodimeter to perform. This has been largely due to reliability of Geodimeter operators and good service by the distributor. Work stoppage has occurred on several occasions due to breakdown of automotive equipment, radio equipment, generator power supply, and weather, which consists of dense fog and severe storms. A variety of climate is available in California and the location of work is usually planned to avoid the worst weather. Observations made during rains, zero weather, desert heat, and high winds have all produced excellent results. Many observations are made between stations with over 2,000 ft difference in elevation and corresponding differences in temperature and air pressure with no apparent ill effects.

A large portion of the control surveys required observations in remote areas along jeep trails and pack stations and the instrument takes a beating, physically. The demand for work is large and consequently the instrument is never permitted to remain long in one area, but is transported from one rush job to the next. This does not permit an economical operation and the instrument gets a maximum amount of handling.

It has never been necessary to re-observe a line because of poor results, although lines have been re-observed on few occasions. The re-observations were made at the request of District personnel because of poor closures with existing monuments. Such re-observations have always accurately checked the first observation and proved that the error was due to some other cause. The results have served to build up confidence in the instrument.

Errors are occasionally made by the operator or computer, such as: recording data in the wrong delay column; arithmetic mistakes in averaging delay readings; confusing plus and minus signs; transferring data; misidentifying field stations; and poor estimation of distances between stations. Here again, it has never been necessary to re-observe a line because of such mistakes, as the errors are usually obvious when the data are carefully scrutinized. (The Model 3 Geodimeter requires that distances be scaled within 2, 000 meters (1. 25 mi), although 1, 000 meters is preferred, as +1, 000 and -1, 000 makes a spread of 2, 000.)

The light emitted from the Geodimeter is highly specialized and there has been no trouble from misidentification of the mirror station or from interference with other lights. Troubles have occurred from not following simple precautions, such as:

1. When numerous background lights are present, a compass should be used to orient the direction of search for the mirror, which is easily picked up with a flashlight. A compass is also valuable when no lights or landmarks are visible for orientation.

2. Poorly planned stations are occasionally set up where the line of sight crosses the highway and is constantly interrupted by passing vehicles.

The Geodimeter has many uses for bringing in control where triangulation would be difficult due to lack of, or poorly placed, existing stations to serve as a base line. The measurement and adjustment of angles in a triangulation survey demands considerable skill and continuity of operations to produce satisfactory results, that is, closures of 1:10, 000 and better. In highway work, most engineering personnel do not remain on survey work long enough to become thoroughly familiar with high-order accuracy. On the other hand, high accuracies are obtained with a minimum of time and effort with the Geodimeter. The Department has been fortunate in having operators for the Geodimeter with sufficient technical skill to understand its operation and rugged enough to fight the elements in getting the work done.

Because the Geodimeter operates on a light beam, it has required nighttime operation to date. The Department's personnel have become accustomed to night work and now prefer it to day work.

The Geodimeter will not penetrate dense fog. Since angles must also be sighted and turned in order to compute positions, this is not the disadvantage it first appears.

PROJECT DATA

Specifically, this paper is based on three traverse projects on Interstate Highway routes, which were carried out in cooperation with the U.S. Coast and Geodetic Survey. The California Division of Highways measured the traverse courses and ties to existing USC&GS control stations with a Model 3 Geodimeter and furnished the horizontal distance for each course. The USC&GS made the reconnaissance, set the stations, measured the angles, and computed and adjusted the coordinate positions.

In adjusting positions, the USC&GS considered each portion of traverse (consisting of several traverse courses) between triangulation ties. Adjustment was made by the method of variation of coordinates, using observation equations for both length measurements and horizontal directions. This method appears to have little relation to linear adjustment.

The Geodimeter measurements were obtained by standard procedures without any special effort. The operator who made most of the observations was new and had about 30 days experience before being placed in charge without superivison. Except by careful selection, there is doubt that all operators would become as proficient in such a short time. However, the instrument offers a challenge and is a source of pride for its operators, which results in a healthy attitude for accomplishing the work and obtaining replacements.

Table 1 gives the average amount of adjustment, standard deviation, and ratio of closure for each of the three projects to be discussed, as follows:

Project 1 required the largest adjustments to bring the distance measurements into agreement with existing USC&GS positions. It is located in Imperial County close to the Mexican border in an area where earthquake movements have periodically taken place. This may well be the cause for the relatively large adjustments.

Project 2 required the second largest adjustments. It is located in the San Joaquin Valley from south of Bakersfield at the foot of the Tehachapi Mountains to north of Kettleman City, which is also an area where earthquake movements have taken place.

Project 3 is primarily in the Sacramento Valley from Vernalis to Willows and required by far the smallest distance adjustments, although the Geodimeter measurements were made at a time when there was minor trouble with the instrument and were suspicious of its performance.

The data herein submitted is a tribute to the accuracy of the U.S. Coast and Geodetic Survey rather than electronic measurement equipment. Although the Department had some remarkable closures on their own work, only in rare instances are such closures made. The usual method is to begin and close the traverses on existing USC&GS or other stations, as one of the objectives in the extension of the State Plane Coordinate System, which can only be accomplished by extending known coordinate positions. Closures of any measuring device on its own work is no proof of the elimination of systematic errors. The classic example is chaining a closed traverse with a tape calibrated one foot short. Even through such a traverse closed flat on itself, the calibrated error in the tape would not be discovered. Theoretically the Geodimeter is probably capable of greater accuracy for measuring distance than is a theodolite for measuring angles. Since the calculation of coordinate positions requires the measurement and use of angles, the angular measurements become the weakest part in the survey.

The data herein presented consists of the adjustments made to the Geodimeter distances to agree with USC&GS positions. The USC&GS stations are the only recognized yardstick available for closing and adjusting the Geodimeter measurements. They also are the framework on which the State Plane Coordinate System is based. The USC&GS is recognized for its consistently good work and its surveys are accepted with confidence.

TABLE 1

Proj. No.	Description	Length Hwy. (mi)	No. of Courses	Length of Avg. Course (mi)	Maximum Adjustm't (ft)	Average Adjustm't (ft)	Stand. Deviation (ft)	Avg. Ratio of Closure
1	US Route FAI 8, State Routes 12 and 27, in Imperial Co. between Cayote Wells and Grays Wells	60	27[1]	2.37	0.781	0.269	0.259	1:46,600
2	US Route FAI 5, State Route 238, in Kern, Kings and Fresno Co. between Wheeler Ridge and 31 mi north of Kettleman City	122	38[1]	3.33	0.544	0.190	0.236	1:92,500
3	US Routes FAI 5E and 5, State Routes 238 and 7, in San Joaquin, Sacramento, Yolo, Colusa, and Glenn Co. between Vernalis and Willows	156	59	3.02	0.410	0.098	0.144	1:163,000
Total combined projects		338	124	2.97		0.164	0.223	1:96,000
Observed miles		368						

[1] One course to calculated tie eliminated.

The USC&GS surveys to which the three projects are adjusted were made by second-order methods (1:10, 000), although experience with the second-order surveys in general, indicates they are of higher order. The data presented represents a measure of the accuracy of USC&GS work rather than Geodimeter measurements, for the following reasons:

1. The data consists of adjustments made to the Geodimeter distances to agree with USC&GS positions.
2. The Geodimeter distance measurements are probably of higher order than the triangulated positions to which they were adjusted.
3. There is no absolute yardstick available for checking the measurements. Consequently the corrections necessary to bring the distances into agreement are considered to be adjustments, and not errors.

Figure 1 gives the amount of adjustment in both feet and meters. The adjustments for each course were arranged in sequence from the smallest to the largest and plotted as cumulative percentage for each project. No consideration was given to the length of courses.

There is sufficient data in the combined projects to indicate a smooth curve.

It is noted that the adjustments do not follow the probability curve. This is probably due to the fact that the adjustments of the Geodimeter distances to the USC&GS surveys do not represent absolute measurements. About 82 percent of the combined adjustments are smaller than expected on the probability curve. Note that 50 percent of the adjustments on the combined projects and 70 percent of the adjustments on Project 3 are less than 0.1 ft which are remarkably small, considering the average length of each course is 3 mi.

The plus and minus adjustments did not follow any particular pattern and have been disregarded. The combined adjustments consist of 54 plus, 69 minus, and 1 zero

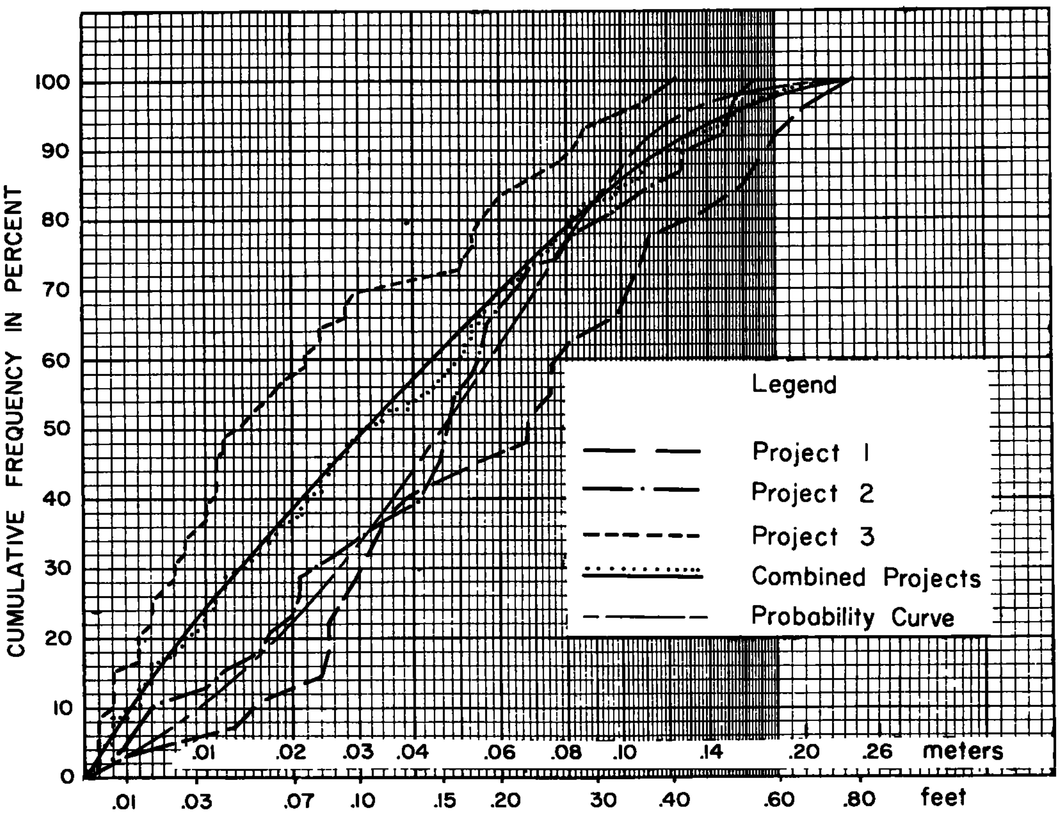

Figure 1. Adjustment per course.

readings. However, the small adjustments ran heavy to plus signs and the large adjustments ran heavy to minus signs, which resulted in an arithmetic mean of -0. 056 ft for the 124 adjustments of the combined projects.

Figure 2 gives the ratio of closure and was derived by dividing the length of each course by its adjustment. The ratios were arranged in sequence from the smallest to the largest and plotted as cumulative percentage.

The average closure is 1:96, 000 which is the average length of course divided by the average adjustment. The closure at the half mark is 1:135, 000. If an average was to be obtained from adding all the ratios together, a fantastic figure approximating 1:800,-000 would result.

Figure 3 gives the minimum ratio of closures for Geodimeter distances found in each of the three projects. The minimum ratios of individual courses are plotted in relation to their length. The figure indicates 11 closures (out of a total of 124) or 9 percent fell below the manufacturer's minimum rating for the instrument. The other 113 closures (not plotted) or 91 percent are well above the minimum rating for the instrument, ranging to infinity (see Fig. 2).

If there were an absolute yardstick for correcting the Geodimeter distances instead of the USC&GS stations, this would mean that the Geodimeter fell below its minimum accuracy 9 percent of the time and above its minimum accuracy 91 percent of the time. It is again reiterated that these ratios are based on adjustments to USC&GS surveys using second-order methods (1:10, 000) and is therefore more a measure of USC&GS accuracy than of the Geodimeter, which is probably of higher order. However, the minimum ratio of closure attained was 1:18, 000 which is well above second-order requirements.

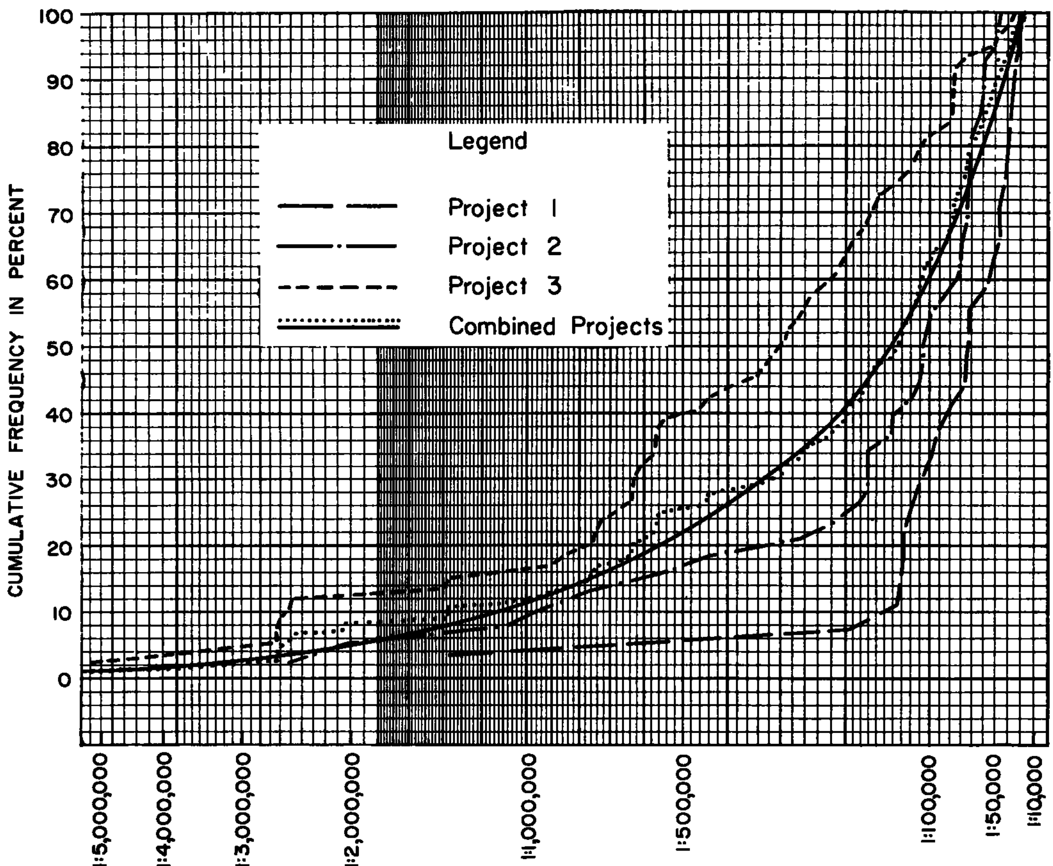

Figure 2. Ratio of closure for each Geodimeter observation.

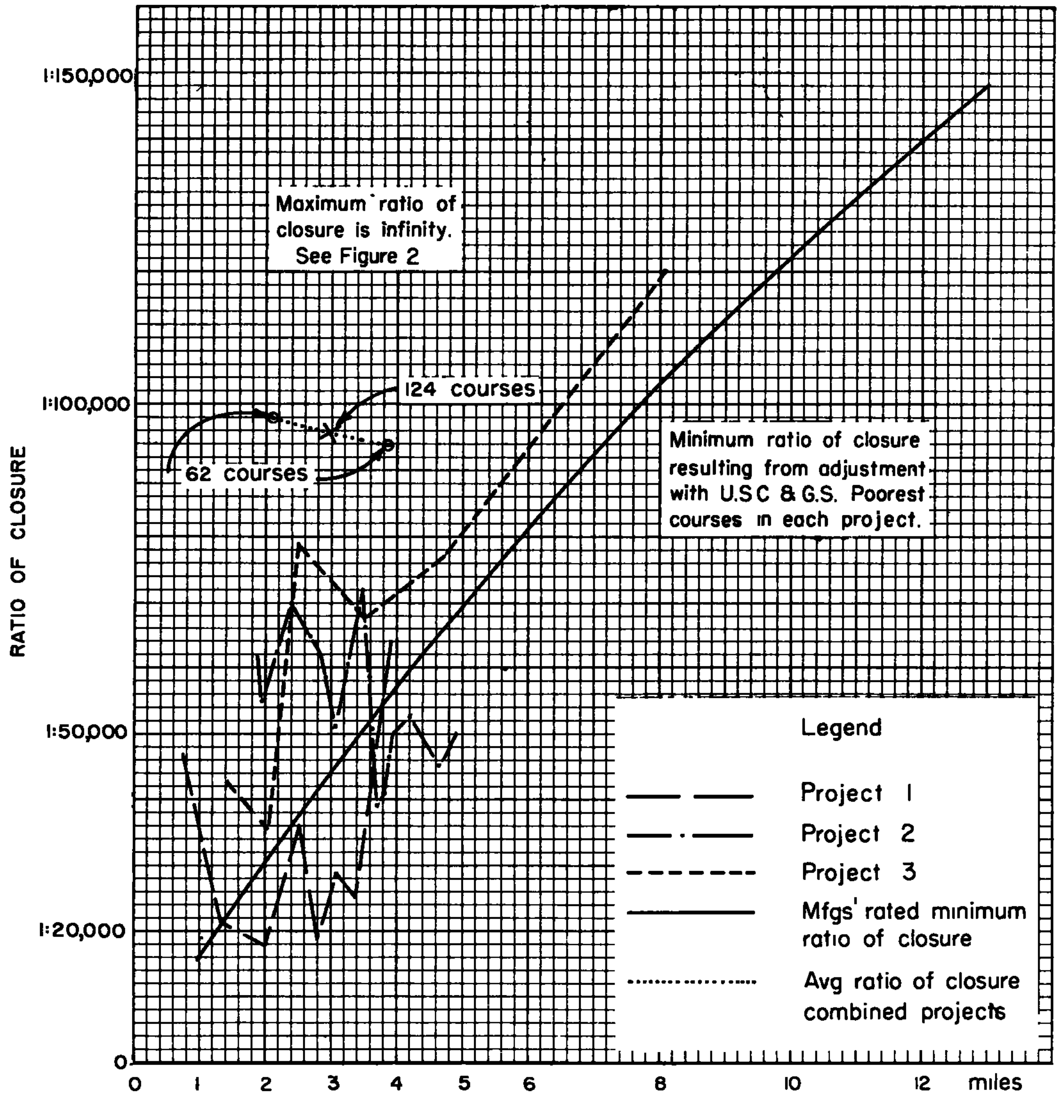

Figure 3. Length of observation in miles.

The manufacturer's minimum ratio of closure is based on the following maximum error:

$$\pm (0.1 \text{ meter} + 2 \times 10^{-6} \times \text{distance in meters})$$

or

$$\pm (0.32808 \text{ ft} + 0.000002 \times \text{distance in feet})$$

CONCLUSIONS

The results obtained indicate that the Model 3 Geodimeter is a reliable instrument for distance measurements. The accuracy obtained is better than required for highway survey purposes, however, high accuracy is obtained as a matter of course with normal procedure. Calculated carelessness on the part of the operator would be required to obtain poor results. Confidence has been created in the instrument through experience with good results. The minimum closure for the projects herein submitted is 1:18,000, the maximum closure is infinity, and the average closure is 1:96, 000.

The estimated cost of Geodimeter surveys as compared to triangulation surveys indicates a savings of about 40 percent. Intangible savings in survey costs are further reflected by confidence in the accuracy of the Geodimeter stations which serve as check points for correcting conventional surveys between such control points. This eliminates the necessity for re-running check lines.

Data relative to costs of establishing control surveys with the Model 3 Geodimeter are as follows (work in conjunction with the USC&GS not considered):

No. of projects	53
Total length, highway miles	1, 350
Total length, observed miles	2, 380
No. of observations	780
Average length per observation, miles	3.55
Cost of Geodimeter control surveys, per highway mile	$120
Estimated savings over triangulation methods	40%

The Tellurometer for Highway Survey Control

AUSTIN C. POLING, Geodesist, U.S. Coast and Geodetic Survey, Washington, D.C.

A brief history is given of the development of electronic distance measuring instruments and the general principles of operation. Also included is a summary of Tellurometer traverse measurements for highway control in eight states.

●THE DEVELOPMENT of modern electronic distance-measuring instruments can be traced back over hundreds of years to the early experiments of scientists such as Galileo, who were searching for the velocity of light. Other scientists who lived in a later period than Galileo utilized the toothed wheel and the rotating mirror in their experiments with the velocity of light. In 1875, John Kerr discovered the well-known Kerr electrical-optical effect which is utilized in the present Geodimeter family of distance-measuring instruments.

The Kerr cell was first employed by Karolus in 1925 in an instrument used for the determination of the velocity of light. Beginning about the year 1941, Dr. Erik Bergstrand, a Swedish scientist, used the Kerr cell in his experiments with the speed of light. The modern Kerr cell used by Bergstrand consists of an optical glass cell with two electrodes immersed in a nearly pure solution of nitrobenzene which, when used with crossed polaroids and an appropriate electrical field, becomes an electronic light chopper. After Bergstrand had found a good value for the velocity of light, with his newly devised equipment, over precisely taped distances, he decided to reverse the process and, holding the speed of light as a constant, measure distances. He named this instrument the Geodimeter.

THE GEODIMETER

Briefly, the principle of operation of the Geodimeter is as follows: A beam of light is transmitted through crossed polaroids and a Kerr cell, which modulates the intensity of the light beam at a frequency of 10 megacycles per second. This modulated light beam travels to a distant mirror or bank of retrodirective prisms, which reflects it back to a photocell where it is detected. By means of a suitable phase detector, the returning light beam is instantaneously compared in phase with that of the light just leaving the Geodimeter. The phase detector indicator is called a null detector. It indicates zero when the outgoing and incoming light pulses are in phase. A variable electrical delay is inserted between the outgoing light modulator and the phase detector so the phases can be brought into agreement.

The present Geodimeter family of distance measuring equipment consists of three types of instruments. To the first type belong the instruments designated Model 1, Model 2 and Model 2A, which are the same except for some refinements on the later models. These models are primarily designed for the highest geodetic accuracy, with particular application to the measurement of first-order base lines. The maximum range of the instruments is about 30 mi under favorable operating conditions. The instrumental error of Models 1 and 2 is of the order of 3 cm ± one-millionth of the length of the line being measured. The manufacturer claims an instrumental error for Model 2A of only 1 cm ± one-millionth of the length of the line being measured. This type of Geodimeter weighs over 200 lb and is rather bulky. Although this instrument has been used on towers, the USC&GS has found that due to excessive vibration in the tower structure, this is not practical. The reflector can be readily used on a tower.

A second type is the Model 3, a scaled-down version of Model 2A, weighing 58 lb. With this instrument, it is possible to measure distances up to about 20 mi with a maximum instrumental error of about 10 cm. This model is portable and may be used with unattended reflector stations.

The third type is the Model 4 which weighs 35 lb and mounts on a standard surveying tripod. Its maximum range is about 5 mi and the instrumental error is about 1 in. Over distances of less than one mile expendable reflectors such as plastic truck reflectors or reflecting tape may be used for the mirror station. This model was designed primarily for conventional traverse.

Geodimeter Field Experience

The Model 1 Geodimeter was obtained in 1953 and the Model 2 in 1956 by the USC&GS. Through October 1959, 98 lines have been measured with these instruments, over various types of topography such as mountains, desert, water expanse, rolling hills and flat cultivated areas. The average length of line was 16,480 meters (about 10 mi). The maximum and minimum lengths were 42,036 meters (26 mi) and 1,114 meters (0.7 mi). The minimum probable error for all 98 lines was 2.2 mm; the maximum was 9.9 mm. The Geodimeters have been checked against first-order taped bases and checks of 1/508,000, 1/535,000, 1/158,000 and 1/177,000 were obtained. These comparisons contain the errors in taping as well as the Geodimeter errors.

Repeatability of Geodimeter

In 1953, a taped base was established near Springfield, Va., for use as a standard to test the Models 1 and 2 Geodimeters. This accurately taped base is about 2,664 meters long and over a period of 5 yr it was measured by Geodimeter for 35 nights. Six individual measurements were made each night and an average length determined for each night's work. A study of the results of all these measurements shows a maximum difference between the taped distance and the Geodimeter distance of 1 part in 48,000. This particular night's measurement was made on the second night the Geodimeter was used. The results could possibly be due to the inexperience of the Geodimeter operator. The average length as determined from a mean of the 35 nights' measurements checked against the taped base by one part in 380,000. From this and other substantiating evidence, it is believed that the Model, 1, 2 and 2A Geodimeters are capable of giving a length to better than one part in 300,000, particularly for lengths of at least 5 mi.

Effect of Meteorological Conditions

In general, the accuracy of the Geodimeter is limited by the accuracy of the determination of the velocity of light, accuracy of the frequency of the light modulation and the meteorological conditions. Since the velocity of light is fairly well established and the frequency of modulation of light in the Geodimeter is very precisely controlled, the effect of meteorological conditions is the largest source of error in Geodimeter measurements. An uncertainty of one degree Centigrade in temperature, or $\frac{1}{10}$-in. of mercury in atmospheric pressure, will cause a one part per million error in the length measured. The relative humidity has a small effect, never more than a fraction of one part per million. Rain, mist or haze will prevent measurement and for lines of the order of 20 mi or greater extreme darkness is required. For practical purposes lines about 20 mi long are considered maximum.

THE TELLUROMETER

The Trigonometrical Survey of the Union of South Africa felt that there was a need for a new type of electronic distance measuring instrument. It commissioned the Telecommunications Research Laboratory of the South African Council for Scientific and Industrial Research to develop such an instrument. The requirements for this instrument were as follows: It should be capable of measuring distances of 10 to 25 mi over line of sight in daylight. It should have an error of no more than 6 in. in 10 mi or 1/100,000 over the range of 10 to 25 mi. It should be lightweight, portable and require a small amount of power. Such an instrument was developed fulfilling the stated requirements and was named the Tellurometer. Whereas the Geodimeter uses light waves to transmit measuring information over a line, the Tellurometer utilizes microwaves to transmit measuring information between a master and remote station. It is a phase comparison system similar to others used for distance and range work. It operates on the principle of the instantaneous sampling of the phase of independent oscillators at master and remote stations. This phase relationship of these independent oscillators at the remote station is relayed back to the master station and is compared on its phase indicating device. This phase indicator at the master station is a cathode ray tube similar to the small television picture tube. This cathode ray tube at the master station displays a circular pattern which is broken at one place. This break is the indication of the comparison of phases. It can be read by means of the graticule over the cathode ray tube, which is divided into 100 divisions. One division on the graticule represents about 6 in. in length.

If the master station is moved away from or toward the remote station, the break in the circular sweep on the cathode ray tube revolves one complete revolution for every 50-ft movement of the master station. Crystal modulation frequencies noted as A+ and A- are used to determine fractional parts of 50 ft. Crystals denoted by the letters B, C, and D are used to measure fractional parts of 50, 000, 5, 000 and 500 ft, respectively. Thus, the length of the line being measured must be known only to the nearest 10 mi.

Effect of Meteorological and Topographical Conditions

The effect of humidity in the refraction computation for the Tellurometer is about 100 times that for the Geodimeter. The effect of pressure and temperature errors is about the same as for the Geodimeter. An error of 1.0 in. of mercury in atmospheric pressure will cause an error of one part in a million. An error of 1 F (in the humidity determination) will cause an error of about the same order. Temperature and pressure are measured at the ends of the line. Then with the assumption that mean atmospheric conditions exist along the wave path, a rather large error in the refraction correction may be introduced. This is especially true for long lines.

The accuracy of the Tellurometer is affected by the terrain over which the lines are measured, due to unwanted reflections of the radio waves from the local topography. If a line is measured with high clearance in the middle, the intervening terrain should be covered by vegetation or trees to break up unwanted reflections. Lines with terminals on sharply elevated points above a flat, smooth, highly reflective surface should be avoided, although such lines can be measured with a good assurance of success if the instruments are tilted up at each end, 5 deg or more. High clearance lines over water should be avoided. Such lines can best be measured if both master and remote station are near the level of the water.

FIELD EXPERIENCE

The USC&GS obtained its first tellurometer measuring unit (1 master and 1 remote) in June 1957. After a few preliminary measurements it was assigned to the Coast Survey Ship "Explorer," operating in Alaskan waters, for use in making a traverse survey along the rugged south coast of Atka Island in the central Aleutians. Since 1957, four more Tellurometer units have been obtained by the USC&GS. In the summer of 1958, a Tellurometer traverse was run along the south coast of Amlia Island in the Aleutians. In the summer of 1959, the Tellurometer was used to traverse about 300 mi of Southeast Alaska in the vicinity of Dry Bay and Lituya Bay. Very good results were obtained for all the Alaskan traverse surveys. It is important to note that these surveys would have been almost impossible to accomplish without the use of the Tellurometer.

In the summer of 1958, a Tellurometer unit was assigned to a USC&GS party engaged in establishing survey control for highway projects in Virginia. Since that time, the USC&GS has employed Tellurometers for highway surveys in the States of Arizona, Idaho, Illinois, Tennessee, Maryland, Delaware, Pennsylvania and Maine, in addition to Virginia. These highway survey control points are usually established by means of

TABLE 1

SUMMARY OF TELLUROMETER HIGHWAY TRAVERSE—U.S. COAST AND GEODETIC SURVEY
(Through November 1959)

	Total Miles	No. of Lines	Avg Length (mi)	Avg Corr'n to Length
Maine	350	74	4.8	1/92,000
Idaho	106	51	2.1	1/89,000
Illinois	75	29	2.5	1/26,000
Illinois	79	32	2.5	1/32,000
Illinois	108	50	2.2	1/25,000
Illinois	75	32	2.3	1/50,000
Pennsylvania	128	58	2.2	1/94,000
Pennsylvania	120	35	3.4	1/50,000
Pennsylvania	188	46	4.0	1/40,000
Pennsylvania	150	30	5.0	1/120,000
Pennsylvania	139	55	2.5	1/40,000
Pennsylvania	168	43	3.9	1/70,000
Tennessee	31	21	1.5	1/55,000
Tennessee	86	77	1.1	1/42,000
Virginia	116	44	2.6	1/59,000
Virginia	35	12	2.9	1/84,000
Virginia	46	14	3.3	1/60,000
Virginia	161	39	4.1	1/80,000
Virginia	156	47	3.3	1/46,000
Arizona	28	6	4.5	1/85,000
Arizona	73	22	3.3	1/35,000
Maryland	41	23	1.8	1/46,000
Total	2,459	840	2.9	1/50,000

triangulation and Tellurometer traverse. The USC&GS has measured nearly 3,000 mi of Tellurometer traverse, consisting of nearly 1,000 separate line measurements. Some of the states own their Tellurometer units, which are used jointly by the states and the Coast Survey. About 8 Tellurometer units were employed in the measurement of the 3,000 mi of Tellurometer traverse.

ADJUSTMENT OF HIGHWAY SURVEYS

The highway surveys in some states are composed of combined triangulation and Tellurometer measurements. Due to errors of observation it is necessary to find corrections to both the observed horizontal directions and the measured lengths in order to have a consistent network which satisfies all geometric conditions. To accomplish this, observation equations are written for the triangulation and Tellurometer traverse and a least squares adjustment is made.

In the adjustment, the direction equations and the length equations are generally given relative weights of 10 to 1. This ratio of weights is based upon the inverse square of the ratio of the mean square errors of the two types of measurements.

A tabulation is given for 2,459 mi of Tellurometer highway traverse in eight states (see Table 1). Field work is continuing elsewhere in most of these states. The summary given is for the major part of the highway traverse that has been adjusted through November 1959. The average correction to a length should not be considered an absolute criterion in the evaluation of the accuracy of the Tellurometer, since errors in the triangulation observations also affect this quantity. It should be noted that in the assignment of relative weights to the directions and lengths, a standard error of 1.5 sec on an angle and a standard error in the Tellurometer lengths of about one part in 40,000 was assumed. The 840 Tellurometer lengths have an average correction of one part in 50,000. This would indicate that the original assumption of the relative accuracy of the Tellurometer lengths, for the average length of line being measured, was reasonable.

Although the Tellurometer was designed to give an accuracy of one part in 100,000 over lines of length from 10 to 25 mi, the instruments have been employed for measurement of lines much shorter than that which the instrument was designed to measure. Therefore, since an accuracy of one part in 50,000 was obtained for 840 lines of an average length of 2.9 mi, the Tellurometer can be considered an excellent instrument for second-order highway traverse.

Less than 1 percent of the lines measured by the Tellurometer has been rejected as unsatisfactory. The shortest lines measured by the instrument were just over one-half mile in length. In general, lines of length of 2 mi or more give much better results than those under 2 mi.

CONCLUSIONS

Surveys by Tellurometer can be made with a considerable saving of time and expense. In the summer of 1959, in a period of time just over 2 months, a single Tellurometer party operating in Southeast Alaska established 45 stations and measured about 720 mi of Tellurometer traverse. This area from Prince William Sound to Lituya Bay, Alaska, is very rugged with high-mountain peaks and glaciers covering a large part of it. Some of the traverse stations were established on glaciers. It was necessary to use helicopters to move men and equipment to the stations since the area was practically inaccessible by any other means of transportation.

In the establishment of highway control surveys, the Tellurometer can be used to speed up operations and reduce costs. Fewer steel towers are necessary than in triangulation, and station sites can often be selected to entirely eliminate the use of towers. A study of the results of Tellurometer traverse in 8 states shows that second-order accuracy can be attained by Tellurometer traverse, even over comparatively short lines.

All the traverse points established during the highway surveys which are summarized in the enclosed table have been permanently monumented. Two reference marks have been established at each station and an azimuth mark has been established at those stations where topography permits. Geographic positions, descriptions, and state plane coordinates are available for these highway control points.

The Tellurometer is a very useful geodetic tool which can be used in many places in which conventional triangulation or traverse is difficult or impossible.

Tellurometer Use in Control Surveys for Mapping by Photogrammetric Methods

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Results of use of the Tellurometer in control surveys for mapping by photogrammetric methods for highway survey purposes over a wide range of temperature and humidity, over a variety of topography with various types and intensities of ground cover, and away from and near traffic, are reported. Special tests and remeasurements made to determine the effectiveness of the equipment, while the control surveys work was accomplished, are also reported. Slight modifications in operating techniques were adopted to admit of more efficient use of the equipment under specific conditions. Included are a report on maintenance required during evaluation, the training given personnel, minor modifications made in the equipment, and a program for electronic computation of slope distances from Tellurometer data.

●THIS PAPER is based on field use of the Tellurometer, an electronic distance measuring device, in Arizona for a period of 14 months. The equipment was procured and field work conducted in cooperation with the U.S. Bureau of Public Roads.

The scope of the Tellurometer research program, as approved for Arizona, covered evaluation over wide variations of temperature; near heavily traveled highways and in remote areas; over terrain varying from plains through rolling hills to mountains; under a variety of ground cover; and in surveys to determine adaptability to location and coordination of section corners and picture points for use with photogrammetric techniques. In addition, other items encountered were investigated and included as matters of general interest and usefulness. Examples of such items are the programming of Tellurometer field data for electronic computation and the development of field and office techniques. In several instances, although no apparent cause was determined observed data were recorded for possible later evaluation by this or other agencies. The Tellurometer was used to establish control for photogrammetric mapping projects and on evaluation tests, all conducted throughout the state under a variety of field conditions. Each of these projects on which the equipment was used was a live photogrammetric mapping project and as such, the results were used to compile photogrammetric maps. Problems or unique conditions encountered were usually remeasured and in a number of instances these lines were made the subject of special evaluation tests in an effort to determine a relationship between the conditions encountered and the readings obtained. Field work on these projects required the transportation of the equipment for thousands of miles on highways and over extremely rugged terrain. Short and long distances were measured, however, most were less than one mile in length.

An attempt has been made to cover most phases of Tellurometer usage in the field, including field procedures and results. Little is said about the electronic principles of the equipment since that aspect has been well covered in numerous other publications. It is hoped that results and procedures covered in this paper may be of value to other agencies in the use of electronic distance measuring devices for surveys requiring rapid accurate measurement of longer distances.

As can be seen on the Arizona Tellurometer Projects Map (Fig. 1), the Tellurometer was used throughout the state over a wide range of elevations along and away from major highways. These projects also offered a variety of ground cover, terrain, and meteorological conditions. Ground cover varied from none to heavy timber; terrain from flat desert, to rolling hills, to rugged, rocky mountains; and meteorological conditions from cold wet weather to dry desert heat. Numerous remeasurements were made on some projects and later special studies were made to determine the consistency of readings under varying meteorological conditions.

In establishing control for the photogrammetric mapping projects on a statewide basis, field work was successfully accomplished under virtually all conditions existing in Arizona. Measurements were made with the instruments at elevations ranging

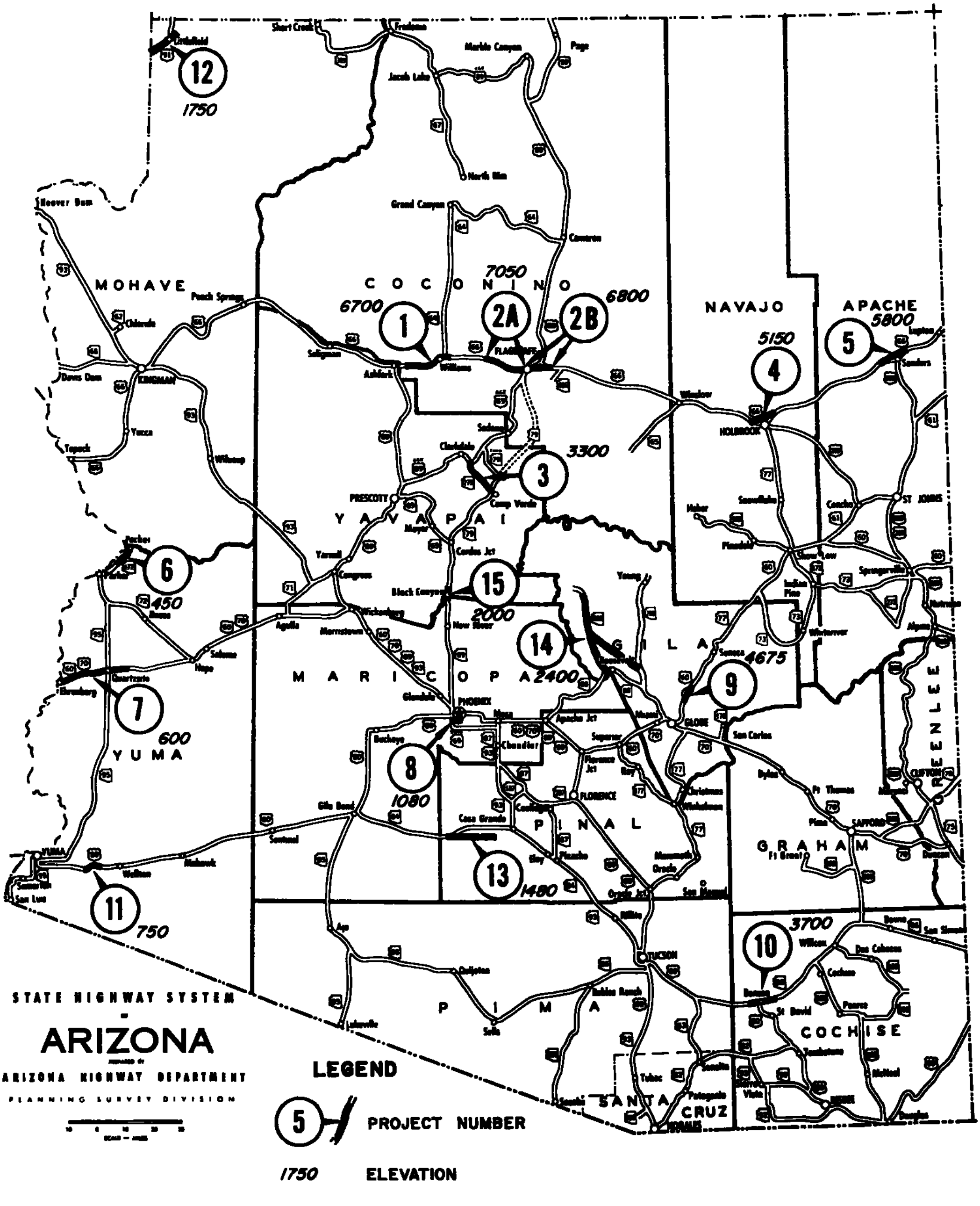


Figure 1. Tellurometer projects map.

from 200 ft to 9,200 ft above sea level, humidity varied from 11 to 95 percent and temperatures ranged from 16 F to 115 F.

The only problems encountered under these conditions were due to temperature. In cold weather, equipment warm-up required more time than the measurements. In hot weather, crystal synchronization was difficult over 90 F. Each of these problems was solved through use of a cold weather kit modification which kept crystals at a constant 50 C, plus or minus 1 C, and resulted in automatic crystal synchronization. Late in the research program, warm-up time in cold weather was again considered excessive, over 20 min, and on many occasions manual synchronization was necessary. These problems are not considered major, and minor additional modifications will undoubtedly improve the equipment in this respect.

Terrain varying from flat desert to rolling hills, canyons and mountains on which ground cover ranged from none to a dense growth of timber were encountered and successfully surveyed. In a few instances erratic measurements were obtained and the survey point had to be moved. No difficulty was experienced in finding a substitute point nearby, from which normal instrument readings could be obtained. Selection of points was made first for location in respect to position for control purposes, second for intervisibility, and third for minimum interference from brush and trees, or man-made obstacles very near the line of sight and measurement. An ideal Tellurometer line has ground sloping down between the instruments with no intermediate grazing conditions (line lying close to ground or skimming tops of trees) or flat reflective surfaces to adversely affect measurements, yet lines over ground with these characteristics were often difficult to measure.

The optimum conditions need not be present to obtain accurate results but the probability of encountering troublesome readings or results is reduced by selecting such lines. Successful measurements were made in Arizona from points in the immediate vicinity of microwave stations, radio antennas, across and under high voltage transmission lines, and in one instance an accurate measurement was made between non-intervisible points. A line on which very good results will be obtained cannot be definitely determined prior to actual field measurement. Also, lines which do not appear to be satisfactory for measurement may yield excellent results. In the case mentioned regarding non-intervisible points, the stations were visually separated by a low hill. Later work revealed an angle check within one second of arc between trilateration computation and the angle turned in the field.

The Tellurometer party, equipped with a master and two remote units plus a theodolite and level, normally consisted of 5 persons. This assumes packing to about one-half the survey points. Two men were at the master station, two at one remote and one at the other. Although two men are usually needed to carry the equipment, one man can easily operate a remote unit, therefore stations accessible to driving or to short walking and packing were handled by one man.

Several persons experienced in surveying have been trained in use of the Tellurometer. In a relatively short period of time they have become proficient in operating the instrument as well as in performing the necessary field checks and computations. It has been found that a person with surveying experience can be trained in one day to operate the master and remote units, record notes, and perform the necessary computations. With two or three weeks of practice he can then become proficient in these operations.

A minimum of maintenance has been required by the Tellurometer units operated in Arizona. Routine checks have been made every 2 to 3 months by the Highway Patrol Radio Shop to check crystal frequencies, detect weak tubes, and make necessary replacements. During the report period, three tubes were replaced, an A-crystal which drifted off frequency had to be replaced and two fuses burned out. No other replacement items were needed. A routine periodic check of the equipment is considered necessary in order to be assured of best results and a minimum of "down time."

Included in these periodic checks is a general check of all small screws and fittings to insure against loss. Excessive maintenance was required of the tripods furnished with the equipment and their use in the field was discontinued. Wild IIIb tripods have been substituted.

The psychrometer is now the item requiring most maintenance, in that the thermometers are easily broken during its use. Over 24 thermometers were broken accidentally during the report period, some of which broke when exposed to sun temperatures during hot weather tests. Breakage was reduced somewhat during the latter part of the report period to a rate of approximately one thermometer every three weeks.

Batteries were recharged on the average of 2 times per week. With this amount of recharging the water level and acid strength of the battery were checked regularly.

The most undesirable characteristic of the wet cell batteries, has, of course, been the acid. Batteries, battery cases and cable clips should be kept clean to minimize acid damage. Care must be taken at all times in handling these batteries to avoid spilling acid on personnel, clothing, and equipment. A supply of soda and water carried in each vehicle can be used to reduce damage after accidental spillage.

As in any type work standardization of procedures results in the saving of much time and effort. The adoption of several standard procedures for Tellurometer operation has reduced the time required to measure a distance to less than 15 min.

A reconnaissance of the project is made first to select and set station markers at the control points on sites which meet mapping control requirements and are suitable for making Tellurometer measurement. The sites selected are relatively free of brush and trees, at least in the direction of measurement. Grazing lines are avoided and brush immediately on line 100 to 150 ft in front of either instrument is removed. By careful site selection, a minimum of brushing was done during the report period, even though surveys were made through heavily wooded areas.

Brush or high grass in front of either instrument made observations difficult during windy weather. The movements caused a blurred or oscillating pattern on the master cathode ray tube which could not be accurately read.

In selecting places for station markers and instrument points, a distance of less than 2, 000 ft between measurement points was avoided. Distances were kept long to reduce an accumulation of small measurement errors in the survey which could occur if a large number of short distances were a part of the primary traverse. In many instances, the topography of Arizona has permitted horizontal control to be easily established along a straight line. A few high points along the line were used as the master stations and remote units occupied all other points on line. Checks were made by adding or subtracting the lengths of various segments of the measured traverse. This procedure not only reduced field time but computations were also greatly simplified, base sheet layout was faster and azimuth control in steroscopic compiling instruments was easily maintained.

Only crystal warmup time, which varied from 3 to 30 min, was the most frequent reason to increase measurement time. The warmup time was greatest for the first measurement in cold weather. On subsequent measurements it was usually less, since some heat was retained in the insulated crystal chamber from the previous measurement.

One of the most important items in reducing time losses was the use of one cavity tune number for initial tuning to establish contact. The Arizona Highway Department uses the 3 setting on the remote cavity tune dial. This setting (usually referred to as channel 3) is always used. The remote operator sets the cavity tune dial to channel 3, brings the milliamp reading to maximum and waits for the master to tune to his remote. The master always tunes to the remote. If at any time contact is broken the units return to channel 3 setting to re-establish contact.

The observer soon could tune and read the master unit faster than the recorder could record clear legible figures. The speed at which readings were taken was then governed by the recorder's ability to record neat legible information. The repetitious nature of Tellurometer readings was used by the recorder to detect an erratic reading almost as it was read. If several erratic readings were obtained during a measurement a careful check of all readings was made before moving the equipment.

Motorcycle batteries weighing 16 lb were used successfully on pack stations in rough country. They were used to measure up to three distances without recharging. Regular 6v automotive batteries were used on all drive or short pack stations. These batteries will last one to two days before a recharge is needed, depending on observation time. During the research project a maximum of 25 distances were measured in one day without a battery charge. Equipment was turned off after each measurement.

A slow battery charger which can be plugged into a regular 115v outlet to recharge three batteries connected in parallel proved to be very satisfactory. A rotation system whereby batteries were used every other day seemed the best solution to keep charged batteries on hand at all times.

Mirror signals between stations served to conserve batteries to a great extent. As was usually prearranged, the operator at each station signaled by flashing a mirror when ready. Equipment was not turned on until these signals were received, unless a long warmup time was anticipated. Battery life was thus lengthened. Long measurements requiring an indefinite travel or pack time were frequently made earlier than expected when an operator arrived at his station sooner than anticipated, and signaled the other station. Signals from a small shaving mirror have easily been seen at a distance of over 20 mi. Mirrors used in Arizona have saved much time and effort. The preponderance of sunny days in this state has undoubtedly aided this procedure.

Evaluation of the Tellurometer under hot, dry desert conditions was made on several mapping projects and by special hot weather tests. The mapping projects were successfully completed with no difficulty experienced in obtaining accurate results. Special hot weather tests, which will be described in some detail, were designed to study the effect of high temperatures on the procedure of distance measurement with the Tellurometer.

The technique followed in conducting these tests was to measure several distances (one per day) a number of times through the heat of the day keeping most variables constant. The equipment was set up in umbrella shade to begin measurements at 9:00 a.m. and then measure again each hour on the hour from that time through 6:00 p.m. On a few occasions the readings were taken each half hour. Temperatures were usually above 95 F at 9:00 a.m., rose to a high between 105 and 115 F near 4:00 p.m. and dropped to near 100 F by 6:00 p.m. The equipment was not moved during the day except to move the umbrellas slightly to maintain a shaded condition. Shade temperatures near 110 F frequently indicate temperature in the sun has reached 150 F and it was assumed these sun temperatures would have a much greater effect on personnel than equipment, therefore no sun tests were made. It was occasionally necessary to wait for the crystals to cool to the 122 F temperature maintained thermostatically by the internal heaters.

No difficulty was encountered in reading, tuning or operating the equipment during the hot weather tests. All electronic components functioned properly as far as could be ascertained by experienced operating personnel. Although no effect on readings was apparent, later checks of the readings determined that a majority of the variation in measurement was due to small variations in the fine readings. The cause of these small variations was not determined; however, the computed effect of the change in atmospheric conditions as it in turn affects signal transit time, did not account for a variation of the magnitude encountered.

As an example of graphs prepared to analyze test results, Figure 2 was prepared to represent an average case. Wet bulb depressions were slightly less than average but the curve of readings is normal. Relative accuracy encountered is indicated on the right. Since measurements varied by 0.36 ft under these test conditions, with intervening ground characteristics and instrument setup remaining constant, a measure of accuracy to be expected under these conditions has been obtained. Similar results were found on the other lines measured during the hot weather tests. It is believed that the equipment will produce satisfactory results on surveys under these conditions, keeping in mind of course that minimum length of measurements would be governed by the magnitude of variation and accuracy desired.

Remeasurements of some of the same lines made during cooler weather checked each other from 0.03 to 0.15 ft and thus, if more accurate work were required, better results should most probably be obtained during cooler weather.

An interesting phenomenon was encountered in obtaining wet bulb temperature readings under hot dry conditions. With the relative humidity under 15 percent, the normal method of wetting the wet bulb wick and twirling the thermometers to obtain a low reading did not produce a true low temperature. Water evaporated from the wick very rapidly and did not allow sufficient time for the wet bulb temperature to drop the necessary 40 F or more. A depression of this magnitude was routine during the tests.

To overcome such conditions, the psychrometer was not twirled immediately. The wet bulb wick was kept wet and normal evaporation in a slight breeze soon cooled the thermometer to the approximate low point. With the wick wet near the low temperature reading the usual method for obtaining a low reading was employed to obtain accurate results.

In the course of measuring many lines it was necessary to tilt the master and/or remote unit to overcome the difference in elevation between the master and slave instruments and to avoid reflective surfaces, or to minimize the effect of slightly grazing lines by tilting each instrument up in the direction of measurement. Since the plumb bob is not suspended from the measurement center of the Tellurometer any tilting introduces an eccentricity to the setup which can be easily measured as shown in Figure 3.

This eccentricity was expected to be the same at each unit in most instances, however, the difference can amount to more than 0.03 ft per unit. It is usually much greater than the crystal temperature correction and, therefore, all work should take into account the eccentricity in each instrument setup. (Theoretically the eccentricity should be measured parallel to the line of measurement. In this instance, such a minute difference is involved that measurement along the top edge of the side panel of the instrument, as shown in Figure 3, is considered satisfactory.)

Figure 4 is a graphical comparison between the results obtained with a line, with obstacles near one end, is measured twice, once with the master unit at each end. In this instance, a point was to be established on the median strip of a deck-type bridge. The bridge had metal handrails on each side. The line of sight was almost perpendicular to the bridge centerline and just cleared the handrail. Measurement started with the master unit on the bridge and the remote unit approximately 2,000 ft away. After measurement, the units were switched in position and the line was measured a second time. Similar results were obtained on other lines and as a result, in order to reduce the effect of such obstacles, the master unit has since occupied the more open site. Open

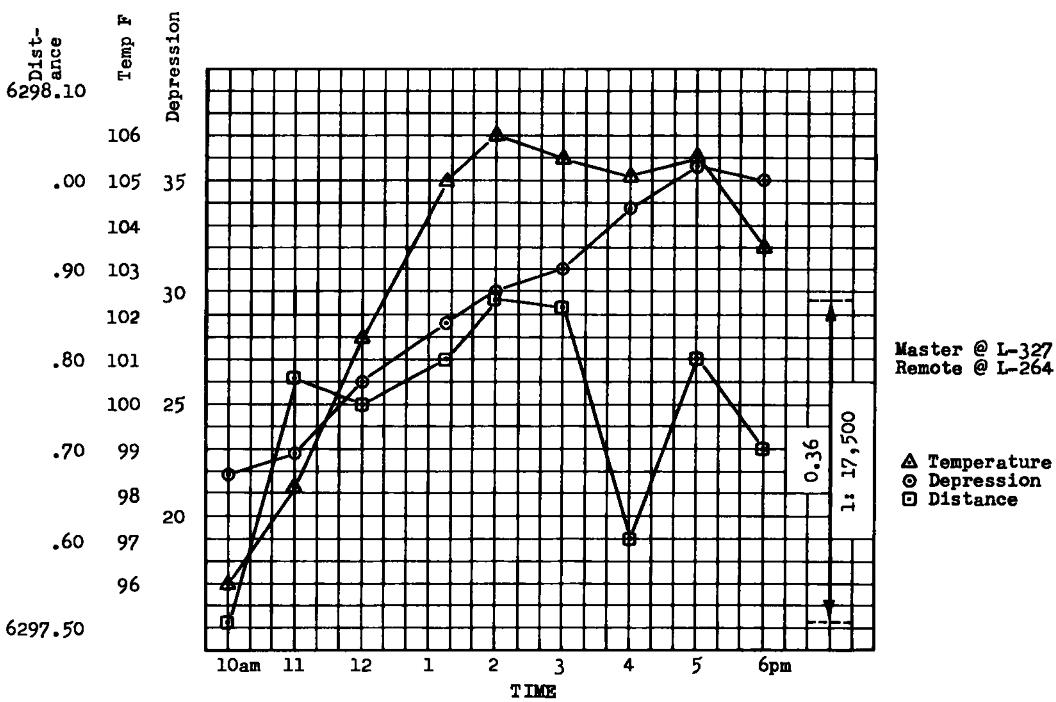


Figure 2. Hot weather measurement.

sites with nearby highly reflective surfaces such as water, pavement, walls or buildings are not used when the incoming signal may reflect from these surfaces to the receiving antenna. Another site with more acceptable characteristics is selected in such cases.

Through use of the Tellurometer, control was successfully established for photogrammetric mapping in all areas of the state. Accurate measurements were obtained with a minimum of operational difficulty and under normal field conditions, 15 to 18 measurements were made each day. The number of lines which can be measured per day is primarily dependent upon travel time to occupy stations. Average accuracy for traverse closures was near 1:25,000 and ranged from 1:17,000 to 1:88,000. The equipment proved to be well designed for field use and is sufficiently rugged to be transported in survey vehicles with the same care given other survey instruments.

The special evaluation tests revealed a variation in measurements slightly in excess

C = Instrument Center

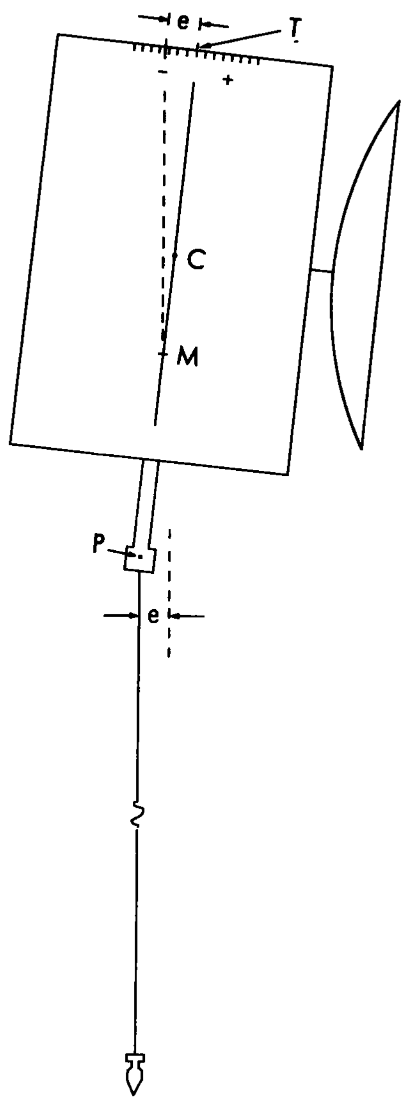
P = Point of plumb bob suspension.

T = Center of top edge of side panel.

M = Plumb line point to be marked on side panel.

e = Eccentric introduced by tilting instrument.

CP = TM



Procedure

Mark top edge of side panel in 0.01' graduations from "T" (ahead +, back -)

Mark point "M" on centerline of side panel so that TM = CP.

Hold plumb line alongside side panel so string passes through "M" and read eccentricity on top edge of panel.

Report + or - eccentricity in remote units to master for record. Example: A negative eccentricity indicates a short line measurement.

Figure 3.

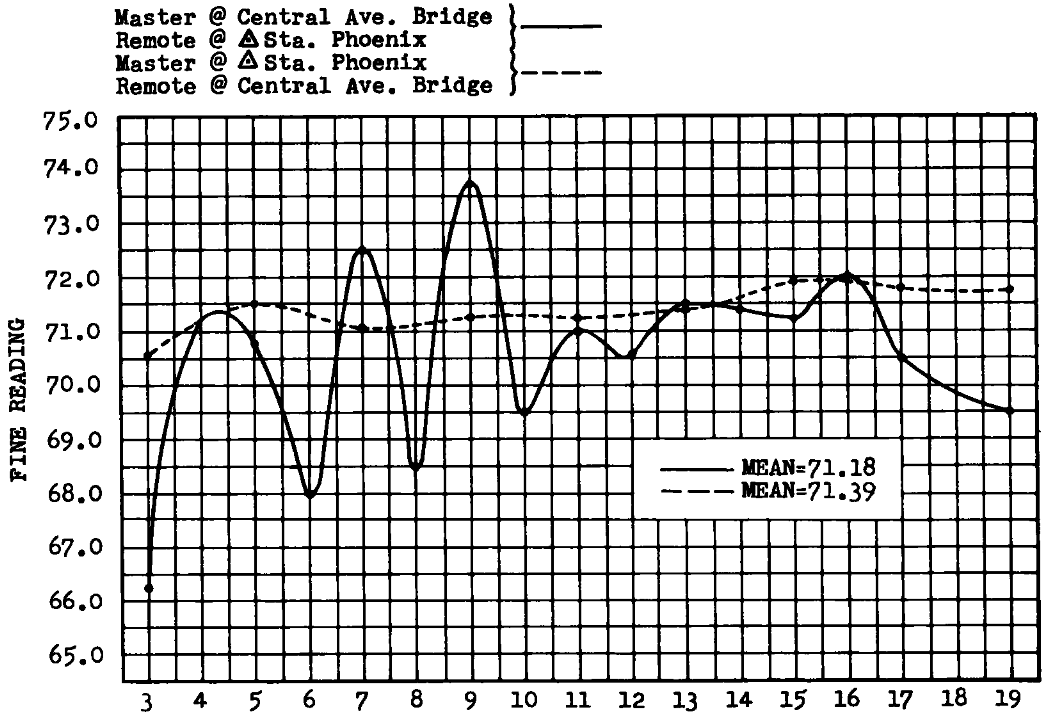


Figure 4. Channels.

of the expected results. With the variation known, however, it has served to increase the minimum distance to be measured in a few cases in order to meet accuracy requirements for the project. Electronic measurement devices are considered essential to photogrammetric mapping projects in the establishment of primary nets of basic horizontal control upon which maps and other survey data can be based. The Tellurometer has proved to be very satisfactory in this respect.

Evaluation of the Tellurometer for Highway Survey Control in Maryland

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A brief description of the field procedure and use of the Tellurometer in Maryland is presented. Results obtained, as affected by topography, land use, traffic, wind, and temperature, are reported, together with the efficiency of the Tellurometer as compared to surveys by chaining in certain regions of Maryland.

●THE BUREAU of Control Surveys of the Maryland State Roads Commission was established in 1939 to provide a central depository for information concerning horizontal and vertical control established locally by Federal Government, state agencies, and private engineering concerns. The Bureau's field survey party is continually engaged throughout Maryland extending USC&GS control to areas of eventual highway construction designated by the Highway Location Division.

In March 1958, this Bureau, in cooperation with the U.S. Bureau of Public Roads, began a period of testing and evaluation of the Tellurometer for making control surveys relevant to highway surveys and design. The contents of this paper are based on 18 months of field operations completed in October 1959.

Most engineers are familiar with angle and distance measuring in making traverse surveys. Consequently, a detailed account of field survey procedure and traverse surveying will not be given, but a few pertinent facts will be mentioned. Traverse surveys with the Tellurometer are less restricted by topography, land use, and ground cover than are traverse surveys by conventional methods. In control surveying with the Tellurometer, it is advantageous for a two man reconnaissance party to explore the most suitable routes for traverses with respect to sight distances and positioning of permanent control stations. Since most of the distance measurements are made by ground-to-ground observations without the aid of towers to elevate the instruments, the thoroughness of this preliminary field work can have an important bearing on the results attained on a particular project. Permanent station markers to serve as survey monuments are positioned by the reconnaissance party at desired intervals of from 1 to 3 mi, and at major highway junctions.

Angle measurements are made with a Wild T-2 Theodolite. For traverses with average sight distances of 1 mi or less, 8 readings of each angle measurement are made, four direct and four reverse. Where longer courses are measured, 12 to 16 readings of the angle measurements are made depending on the average length of sight between the measurement stations. Vertical angles are observed from each end of the measured course. The mean of a direct and reverse angle reading is used for determining the correction to be applied to the slope distance measured with the Tellurometer.

For distance measurements, 12 Tellurometer readings are obtained on successive frequencies for each course. Occasionally, one or two readings of a set will appear erratic, and then additional readings are obtained. For reduction of Tellurometer readings to State plane coordinate distances, a form used by the USC&GS has been adopted. A slight revision of this form permits all machine computations for each course, including reduction to datum of the State plane coordinate system and application of the scale correction factor, to be completed on one sheet.

As mentioned before, most of the field work has been completed with ground-to-ground observations. As a result, the topography and ground conditions have had a great influence upon the degree of accuracy and the efficiency to be obtained for each project. Maryland affords three distinct types of topography over which the Tellurometer has been utilized with varying degrees of success. The most consistent results have been obtained in central and northeast Maryland, where high, rolling hills permit sight distances averaging from 3,000 to 7,000 ft with little or no clearing of lines. Of the 31 traverses completed in this area, an average closure of 1 part in 56,000 has been obtained.

The mountainous region of western Maryland has permitted very good results particularly during the spring and fall of the year. The numerous fire towers of this area have been used with great success to extend control into portions of this region where no USC&GS control previously existed. Three nets, totaling 112 mi of traverse, were recently established in this area with average closures of 1 part in 115,000. To position permanent stations at desired intervals and at major highway junctions, approximately 45 mi of secondary traverses were established from these nets. These traverses have average closures of 1 part in 43,000. The differences in the accuracy of these closures are due to average length of lines used for each type of traverse; the accuracy of shorter lines being limited by the ± 2-in. error that may occur with each measurement.

Results have shown that the relatively flat ground in southern Maryland and in the Eastern Shore areas is not as suitable for Tellurometer surveying as the topography in other regions of Maryland. The closures obtained thus far in flat ground areas, however, have been satisfactory for highway work. The frequent large wooded areas and the predominance of agriculture in this region have confined most of the traversing to highway and railroad rights-or-way, thus necessitating shorter lines and in several cases the inclusion of chained distances. Whenever possible, sight distances have been lengthened by occupying fire towers, church belfries and roof tops. Of the four traverses completed in this area, closures have averaged 1 part in 23,000.

During the field demonstration and instruction period, prior to the operations with the Tellurometer, ideal ground conditions for measurements, such as depression of ground between stations and light vegetation to minimize reflected waves, were described. Realizing that these conditions would be impossible to obtain in certain regions of Maryland, the first two traverses were established in areas with conditions similar to those which would prevail throughout the projects. The closures obtained were 1:27,000 and 1:48,000, respectively. From the adjusted courses of these traverses, triangles were projected over and through various types of ground cover to simulate conditions likely to occur in future work. Intervisible courses were measured from within a wooded area to a point on open ground, over fields of wheat and low brush, and with trees or obstructions adjacent to the line of sight.

The closures of these triangles indicated little or no adverse effects resulting from these conditions. Terrain conditions were also altered between several of these base courses by chaining eccentric points. Readings were taken with the intermediate terrain rising adjacent to the line, and again satisfactory results were obtained. While all of these simulated conditions permitted satisfactory results, it should not be concluded that all intervisible lines will permit accurate measurements. On several occasions, courses were measured where no apparent cause for reflective interference existed, and yet the readings were scattered, with high and low readings differing as much as 6 to 8 ft. On still other intervisible courses, weak and unstable signals were encountered from which readings could not be obtained. Fortunately, these instances occurred so infrequently they did not constitute a hindrance or weakness in the overall performance of the Tellurometer.

Prior to establishing ground control for the Potomac River Crossing of the Washington Circumferential Highway near Alexandria, Va., several overwater tests were conducted. Computed distances, between first-order USC&GS triangulation stations established along the shores of the Magothy River in Anne Arundel County, Maryland, were used for base courses. The height of the instrument above the water surface varied from 10 to 25 ft, and the distances measured ranged from 4,000 to 11,000 ft. Closures from 1:14,000 to 1:58,000 were obtained indicating that satisfactory results could be expected under these conditions.

To determine what adverse effects might result from the motion of vehicles and the reflective surfaces of roadways, a series of tests were conducted along US 40, west of Baltimore. At the time and place these tests were made, the average daily traffic for this section of divided highway was 11,000 vehicles.

Using a base course previously established by first-order traverse, quadrilaterals were projected to select test courses on and near the roadway. Measurements were made parallel, diagonal, and perpendicular to the flow of traffic. In each of these tests, comparison of the measured and triangulated distances gave closures of 1:18, 000 and better, indicating practically no adverse effects from these conditions. It was concluded that in most cases, where the flow of traffic did not pass through the direct measuring signal, very little delay occurred while obtaining the readings. When vehicles passed near the direct line being measured, the reading trace of the oscilloscope had a tendency to expand and contract, but the value of the phase shift was not affected by this interference. Thus a trained instrument operator could continue reading without delay.

When measuring where the flow of traffic passed directly through the measured signal, delays could not be avoided. The amount of delay, in each case, depended on the volume of traffic, and the acuteness of the angle between the measured line and the direction of the traffic movement. The least delay occurred when measurements were being made perpendicular to the direction in which traffic was moving.

When measuring on, or across paved roadways, care should be taken to watch for erratic readings, as certain frequencies may be affected by reflected signals. In extreme cases, certain frequencies may be affected so much as to preclude readings being made. This seldom occurs for more than one or two frequencies for any group of readings. If necessary, additional readings may be taken at other specified frequencies to obtain the desired number of readings, with little, if any, effect on the final result.

Ideal meteorological conditions for making Tellurometer measurements, such as dry and clear weather with light breezes, are not considered when scheduling the measurements. The average length of courses used in the majority of the work permits little variation of temperature and vapor pressure throughout the intervening terrain. Psychrometer and barometric readings are recorded at both the master and remote units and the arithmetic mean of these values is used when applying the meteorological corrections.

Experience shows that light to heavy winds can cause considerable delays when measuring near trees and foliage. Light breezes will permit readings if foliage is not adjacent to the measured line, but winds greater than 10-15 mph will cause interference from moving foliage a considerable distance from the line. Delays that would be caused by continually prevailing winds have been avoided by scheduling angle measurements at other times.

The Tellurometer, Model MRA-1, has not been adapted with the cold weather conversion assemblies perfected by Tellurometer, Inc. By jacketing the instrument to retain the internal heat, it was possible to operate it satisfactorily at temperatures above freezing. The greatest disadvantage of operating in cold weather is the 20- to 30-min warm-up period necessary before making any measurements. Test measurements over pre-established courses at temperatures below freezing have resulted in inaccurate distances and difficulty in synchronizing the crystals. Winters in Maryland, with the exception of western Maryland, are relatively mild and sub-freezing temperatures seldom prevail for more than one or two weeks. Operational delays have been avoided by scheduling angle measurements at these times. No attempts have been made to determine the effects of rainfall or snowfall on measurements, nor has there been occasion to measure during extremely high temperatures.

From experience in establishing horizontal control by chaining methods, it was estimated that the daily rate of traversing for six men was 1 mi; with probable closures of 1:10, 000 to 1:35, 000. This figure includes clearing of lines, positioning of permanent station markers, and making the angular measurements.

From records kept by the field party, covering 84 mi of traverse over various types of terrain, the daily rate of Tellurometer traversing was estimated to be 2. 1 mi. Closures of from 1:10, 000 to 1:180, 000 were obtained. The rate of traversing, if estimated to include the entire 18 months of operations, would average or exceed 2. 5 mi per day.

As mentioned before, when traversing with the Tellurometer by ground-to-ground measurements, character of topography and type and intensity of ground cover govern the rate of traversing to be expected on a project. When short lines (less than 1, 500 ft) can be avoided, with a minimum of brush cutting and packing of equipment to remote points, traversing should exceed 3 mi per day. When adverse conditions cannot be avoided, the rate of traversing may be less than 1, 5 mi daily. Greater efficiency may be obtained if the work in these difficult areas is scheduled with respect to the seasons of the year, thus minimizing hindrances attributable to farm crops and heavy foliage.

During the 18-month period covered by this report, 608 linear miles of traverses have been completed to position permanent station markers forming a network of horizontal control along 354 centerline miles of primary and secondary highways. Second-order closures and better have been obtained throughout. Of the 36 control survey projects completed thus far, 119 mi have been of second-order closure. The remaining 489 mi have closed 1 part in 25, 000 and better. The best adjusted closure obtained thus far has been 1:264, 000.

A cost analysis was not computed for any of the aforementioned projects as the daily rate of traversing is too variable on individual projects to provide useful cost-per-mile basis.

Based on a six man field party, utilizing two carryall trucks, the present daily cost of operations is $140 to $160 depending on the travel distance to and from the work area. Assuming that 60 percent of the traverse mileage is actually for centerline control, our average daily rate of centerline control is 1. 5 mi. This would put the approximate cost per centerline mile at $100. The unit cost, however, would vary from $70 to $150 per highway mile depending on the frequency and location of existing basic control, and the character of the topography throughout the survey area.

The Tellurometer system of microwave distance measurement has not only proven its effectiveness in making horizontal control surveys for highways, but also, as compared to previous chaining results, it has reduced cost and time for traversing by at least 50 percent, improved the quality of work, permitted traversing of basic control into sparsely controlled regions which would have been impractical by chaining methods, and eliminated practically all field operations to which most errors of distance measurements are attributed.

Evaluation of the Tellurometer in Highway Horizontal Control Work

H. H. McBRIDE, Field Operations Engineer, Photronics Development Division, Mississippi State Highway Department

From July 1, 1958, through September 1, 1959, the Tellurometer was used in Mississippi for establishing control over about 439 route miles of highways in 218 working days. Throughout summer and winter operations, a variety of weather conditions and a large range in temperatures were experienced. The measurements were made over all types of topography, throughout sparse and intense land use areas, and along heavily traveled highways.

Based on results attained, the Tellurometer can be relied upon for the establishment of horizontal control to second-order accuracy. Such use of the Tellurometer reduced costs of control surveys to less than 50 percent of the costs of such surveys by conventional triangulation and traverse methods.

●THIS WORK was done by the Photronics Development Division of the Mississippi State Highway Department under the supervision of I.W. Brown. This paper covers a period of 13 months (July 1, 1958 to September 1, 1959) and was initiated under the Bureau of Public Roads and financed with the Highway Planning Survey funds for research projects.

The research has been concerned with the practical application of the Tellurometer and not with its theoretical aspects. The purpose of these research projects was to evaluate the Tellurometer in (a) horizontal control with permanent survey markers established in the State plane coordinate system; and (b) horizontal control for photogrammetric work. These two phases are closely related and for all practical purposes the field methods and operations are the same. Only the cost per mile and coverage are separated into distinct parts for this report.

Some of the field party operations in Mississippi are outlined briefly in this paper. They have been well covered in previous detailed reports. Horizontal control work in Photronics Division is accomplished by five separate operating groups:

1. A reconnaissance party, consisting of either two or three men. It is the responsibility of these men to locate, identify, write a description of and make an overlay plat of all control points to be used in the survey. This includes the location of tower points and selection of the height of tower to be used. All of the surveys are tied to USC&GS triangulation stations which must be found on the ground. The recovery notes for the station markers are sent to USC&GS.
2. A tower party of five men. This party erects and tears down the four Bilby Aluminum towers (two 24 ft and two 37 ft) as required, and sets the permanent survey markers. A 24-ft tower can be built in about 2 hr and a 37-ft tower in about 3 hr. Tear down time averages about 1½ and 2 hr, respectively, for the 24- and 37-ft towers. Towers and station markers are used only on the main scheme centerline surveys.
3. The Tellurometer party of five men, comprising a master operator, two remote operators, a recorder, and a utility man. The utility man drives the truck, and helps hand carry the equipment and set it up and tear it down where required.

4. Two theodolite parties, each consisting of three men, an observer, a recorder, and a light keeper. One party works on main scheme second-order control surveys and the other on third-order supplemental control for photogrammetric mapping operations. These parties use Motorola P-17 portable radios for communication. Much time is saved by the observer having this voice contact with the light keeper, especially when long measurements are being made. Long measurements have ranged up to 35, 000 ft; consequently, some type audible communication must be used.

5. Electronic computations staff. All mathematical computations and adjustments are programmed for and computed by an IBM 650 computer.

These five operating groups were briefly mentioned, as the cost per mile of survey is directly dependent upon the effectiveness and efficiency in which each group performs its part of the work.

The Tellurometer in Mississippi has been used in all parts of the State, covering open farm lands, pastures, densely wooded swamps, tree farms, along and across heavily traveled highways, industrial areas, and thickly populated sections.

It was found that the most difficult and time consuming areas were along the U.S. highways, and at the existing and proposed interchange areas of the larger cities where the traffic counts were as high as 24, 000 vehicles per day. With the use of the Bilby towers, however, the operating time was cut considerably in these areas. One control survey loop along and across US 80 was measured on the ground in 12 field hours and the same loop with the aid of towers was measured in 8 hr.

Throughout the 13 months of Tellurometer operation, the weather conditions varied from bright, sunny, hot days to cold, foggy, overcast days with light mist and rain. Two of the interchanges of I-55 within downtown Jackson were control surveyed at night with good results. Field temperatures ranged from maximums of 16 to 99 F and from minimums of 5 to 22 F, during this period. Probably the most noticeable difference in operational procedures between the extremes of temperature was the instrument warm-up time which increased from the short time of 2 to 3 min in hot weather to as long as 15 to 20 min during the winter months. Another noticeable problem in cold weather was the freezing of the wet bulb of the sling psychrometer and the amount of time required to dissipate the ice before a normal reading could be taken. From such experience it became evident that some work should be done in this field perhaps with alcohol tables.

The work week for the control surveys was five 8-hr days, including all travel time, maintenance time, time lost due to weather, holidays, etc. A period of approximately two weeks covering Tellurometer familiarization, operation, and instrument calibrations was not charged as productive time and is not carried in this report. A man can operate the Tellurometer units after about one day of instruction, but it requires considerable experience on field operations before he is able to select the best sights for optimum operation and to be aware of the capabilities of the instrument. Accuracy and speed of operation are gained with experience. During the past summer, Thomas J. Kennedy, Jr., of the Bureau of Public Roads visited the field crews and timed the Tellurometer operations, when the duration of making several separate set-ups ranged from 12 to 15 min for each one.

The Tellurometer was calibrated once a month and each time maintenance work was performed on it. To accomplish the calibration, two courses are used. One course had been laid out by USCE and is 1, 400 ft long, and the other course is between two first-order triangulation stations 9, 304 ft apart. The instrument measurements of these test courses repeated fairly closely to the correct distances, even under severe weather conditions. Over the 9, 304-ft course the error in Tellurometer measurements ranged to 0. 21 ft and all distance readings were longer than the actual distance. The accuracy of measurement ranged from 1/11, 000 to 1/58, 000, with a mean of approximately 1/26, 000. At the present time a correction of -0. 20 ft is being used for each distance measured between two station markers.

The Tellurometer personnel, with the exception of the utility man, have at least attained a Junior College education and electronic experience in the armed services or civilian electronic occupations. This experience is especially valuable, not from the instrument operation aspects, but for making minor repairs to the instrument in the field. Field maintenance work and down time have been held to a minimum. It is felt that the background of the instrument operators has contributed greatly in this respect.

The Tellurometer has been used for approximately 218 work days. Roughly 75-80 percent of this time has been charged to the Interstate System and the remainder to primary and secondary roads, route relocation, and river control. During this period, approximately 439 highway miles have been control surveyed. All basic horizontal control established by these methods for use in highway centerline staking has been according to specifications set forth by USC&GS for second-order basic control, and for third-order control which is used to control the aerial photographs in photogrammetric work.

For second-order work, 2 coarse and 12 fine readings are taken. Under certain operating conditions such as taking a reading in a deep railroad cut, it was found that certain frequencies tend to "drop out." These readings are omitted and other frequency steps are read.

Permanent survey station markers have been set along approximately 232 mi of highways and all of the 439 mi of project surveys have been control surveyed for mapping photogrammetrically with the Kelsh stereoplotters. Actual traverses measured total 844.85 mi, for an average of 3.87 mi per day.

In accomplishing the horizontal control surveys, a total of 2,555 points were occupied of which 514 were measured to second-order accuracy and 1,169 to third-order accuracy with the Tellurometer, and 872 points were surveyed to third-order accuracy by chaining. The average distance measured between points in the second-order control surveys was 3,641.36 ft, and in the third-order was 2,082.51 ft. The average distance measured by chain to third-order accuracy was 177.43 ft. There was an average of 11.7 points occupied per day or 1.47 points per hour.

The accuracy attained was well within second-order limits, the average being about 1/22,000. The best accuracy achieved with the Tellurometer during these project control surveys was 1/192,000. During October, however, one loop closed to an accuracy of 1/805,000. It should be noted, at this point, that the distance measurements were generally fairly short due to trees and other growth and that the accuracy is very satisfactory. When measuring long distances under optimum weather and topographical conditions, it was found that the Tellurometer is a potential first-order instrument. Good second-order accuracy may be attained under all of the operating conditions encountered so far.

The total cost of the 13 months operation was $107,700. Some of this cost was for non-recurring items such as observation tents, additional tribrachs for the T-2, tripods, tower and ground signal lights, etc, but these items were not deducted and are therefore included in the average cost per mile. Breaking down the total cost between the basic control for centerline staking and supplemental control for photogrammetric mapping is somewhat difficult because there was overlap and duplication of effort in the two separate types of control surveys work. All travel, bad weather, and maintenance time was prorated between the two types of control according to the percent of the total time spent on each. Although the mileage for each type is approximately the same, 69 percent of the total cost was charged to the supplemental control and 31 percent to the basic control. This may seem ambiguous, but several factors enter into these differences in total cost. The objects or ground patterns of which images were selected on the aerial photographs to be position surveyed on the ground as supplemental control points were generally difficult to reach. Instrument pack-in time was increased which reduced the number of instrument set-ups that could be made each day. Also, in all supplemental control surveys work the length of the average distance measurement was approximately 60 percent as long (2,081.51 ft as compared to 3,641.36 ft) as the distance measured in the basic control. Moreover, many of the supplemental control survey measurements were made by chaining distances of less than 500 ft. Thus, $74,300 was charged to supplemental control for an average of $169 per mi; $33,400 was charged to basic control for $76 per mi. The over-all average cost of establishing both basic and supplemental control for 439 linear highway miles was $245 per mile. This cost is less than 42 percent of the average cost of $589 per mile which was incurred in similar control surveying, by conventional triangulation methods, along 74.5 mi of proposed Interstate Route 10.

CONCLUSIONS

1. The cost per mile of Tellurometer surveyed control is approximately 50 percent that of control surveyed by conventional methods.
2. The speed and accuracy with which horizontal control surveys can be accomplished with the Tellurometer are especially advantageous in making surveys for highways.
3. The Tellurometer can be used under practically all weather, topographic, and land use conditions.

The Tellurometer as Used for Highway Control Surveys in Virginia

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This paper contains the operational procedure of the Tellurometer in Virginia for Highway Location and Ground Control Surveys, and a discussion of the results obtained through use of the Tellurometer under varying topographic and atmospheric conditions.

●THE VIRGINIA Department of Highways first became interested in the Tellurometer in the fall of 1957 and immediately began to investigate the possibility of using this instrument for the ground control surveys in the photogrammetric section which was being organized at that time. It was apparent from the beginning that this instrument would add flexibility to surveying which would combine the best features of traversing with those of triangulation. As in traversing, the strength of figure would not be very important; and as in triangulation, the character of the terrain between stations would be of very little importance so long as the stations were intervisible. The Department has used the Tellurometer since August 1, 1958, for ground control surveys and for some of the interstate location surveys.

When the Department first acquired the Tellurometer, one master and two remote units were purchased which were loaned to the USC&GS for establishing horizontal control points at intervals of 3 to 4 mi along the interstate highway routes in Virginia. During this time, the Tellurometer was borrowed from the Coast Survey for a few days at a time and measured the more difficult courses on the ground control traverses. At times an entire traverse would be measured where the terrain was unfavorable for traversing by conventional methods. It later developed that the Coast Survey was using only one remote unit due to a shortage of personnel. Another master unit was purchased and this system was turned over to the ground control survey parties. The Coast Survey completed the horizontal control along Virgina's interstate routes in July 1959; and since that time, two Tellurometer systems have been used on a full time basis.

To date, meteorological conditions have had very little effect upon the accuracy of the work. Lines were remeasured which were suspected of containing an error using the Tellurometer, and the results have agreed with the initial reading although several weeks may have elapsed between the time the two readings were taken. These lines would later be taped and found to contain an error of from 1.0 to 1.6 ft. The greatest errors are generally in short lines of less than 1,500 ft and over highly reflective surfaces or where the ground clearance was only a few feet throughout the line. In most cases, the tape-measured distance has been less than the Tellurometer distance. This would indicate that reflections were causing some of the trouble. The instruments are not equipped with crystal ovens. This has caused some trouble in synchronizing the crystals in cold and in hot weather; however, it is felt that this does not affect the accuracy of the work. Some of the best closures have been obtained in cold weather when it was necessary to warm the remote unit, by keeping it in a vehicle until ready to measure, in order to synchronize the crystals.

The Department tried to use the Tellurometer to obtain the secondary control for the 50 ft to 1 in. scale topographic mapping in urban areas, and this is where the greatest difficulty was had. These lines were short and over highly reflective surfaces. It was found by taping these lines that over 90 percent of the Tellurometer measured distances agreed with the taped distances; however, there was no way of predicting which of the Tellurometer measured distances would contain an error. This traverse was originally set up as a Tellurometer traverse due to the heavy traffic in this urban area, which was running both parallel and normal to the traverse lines being measured. The interference from traffic in this urban area was less than expected, and the break was relatively still and could be read very fast during those brief periods when the line was not actually blocked.

The Tellurometer was previously used in rural areas on much longer lines which were parallel to the road, and traffic had slowed down the reading due to the fact that it would cause multiple circles; and the break in the circle would be very unsteady. It seems that this interference in caused by reflections from vegetation along the road which is disturbed by the air currents from the passing vehicle as the multiple circles continue after the vehicle has passed.

Recently the Department has been traversing between the P.I.'s on the interstate location surveys. First, the survey party hubs the line through and establishes the P.I.'s. Then the Tellurometer party traverses between P.I.'s along the most convenient route. This survey is tied into the U.S. Coast and Geodetic Survey's horizontal control stations and adjusted. The adjusted position is then held to as the correct position and is used throughout the survey. The survey information P.I.'s, P.C.'s, P.T.'s, etc. is then calculated; and several survey parties may start work on establishing the actual survey centerline on the ground from several places along the line at the same time. The survey party running in the centerline is expected to check the calculated length. Using this approach on a project 23 mi in length, one of the distances between P.I.'s was found to be short by 1.7 ft. This tangent, 6,500 ft in length, was measured in two courses along the centerline; one course of 2,300 ft and the other 4,200 ft; and the measurements had been made on two different days. The traverse closure was 1:39,000; and the adjustment had shortened this course by 0.2 of a foot, while the actual distance was found to be 1.49 ft longer than the original measurement. This line was twice checked by horizontal taping along the centerline, once by remeasuring the Tellurometer measured distance using the original traverse points and twice by measuring the Tellurometer measured distances using different or new traverse points. These distance measurements along a different route were made on different days; once when there was about an inch of snow on the ground and later after it had melted. There were five check measurements along this line, and the maximum spread was 0.3 ft. The error in the first course of this line was 1:4,591; and 1:4,309 in the second course. For the original length by the Tellurometer to check, the refractived index would have to be 0.064 per thousand feet. In Virginia, the refractived index is normally between 0.27 and 0.33 ft per thousand feet. This traverse was in what is considered to be Tellurometer country—rolling pasture land with very few trees, where the line of sight was from 100 to 150 ft above the ground in the high places. This is the only line ever remeasured where the Tellurometer failed to check its original measurement within 0.3 of a foot. In fact, on a later traverse in the same area where a mistake was made in computing the closures and six courses were reread, the difference in distances varied only from 0.01 to 0.1 of a foot.

In the normal traverse work with the Tellurometer where it is necessary, due to wooded areas, to traverse along a heavily traveled road, it is not always apparent that the Tellurometer is affecting an increase in efficiency, for it sometimes takes longer to measure some courses with the Tellurometer than by chaining. However, at the end of the traverse it is realized that good progress has been made since the number of angle points has been reduced by as much as 50 percent; and this means not only the time saved in not having to occupy these points but also the time saved by not having to reference and describe them. It was also found that fewer men have been required because there were no flagmen used nor was the flow of traffic interrupted, and the men have worked from a much safer and more comfortable position.

In traversing in areas where it is possible and convenient to get away from the road, the Tellurometer is good from the standpoint of public relations, as it does not leave any tracks or tear down any fences; and most of the property owners are unaware that a survey party is working in the area.

The instrument, as now constructed, was intended primarily for geodetic surveying with long lines and few setups, rather than the relatively short lines which are normally employed; and although the design is excellent for an instrument that is only one model away from the prototype, the design could be improved to make it more convenient for the Department's purposes. It is believed that the barometer and psychrometer should be built into the Tellurometer case and the Tellurometer circuit should be built around the reflector as some television sets are built around the cathode ray tube so that it would not be necessary to put this reflector up every time a new station is occupied. The Department expects to measure 12 courses a day, and any saving in setup time is important. The transistorized power pack is a step in this direction.

Some simple method of elevating the antenna at least 5 ft above the present instrument for use in traffic is desirable. This would probably also increase the accuracy of the instrument on short lines with low ground clearance. Also, it would be desirable to have a swivel-type mount on the instrument so that it could be pointed and leveled more readily.

It was found that it is easy to train good Tellurometer operators from among the youngest men on the survey parties, as these men are anxious to learn to use the instrument. In fact, the Tellurometer has been well accepted by all survey party personnel, and they use the instrument at every opportunity.

On some projects, the Tellurometer has reduced the cost of horizontal control by 70 percent, if calculated on the basis of comparable accuracy by some other method of control.

HRB:OR-352

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