USE OF ELECTRO-OPTICAL DISTANCE MEASURING INSTRUMENTS*

Submitted by the Government of the United States of America

At the present time the widespread use of electronic distance measuring equipment in the practical operations of surveying has just about replaced chains and tapes for measuring precise distances. When these instruments were first introduced on the market, about 20 years ago, many surveyors and engineers were skeptical about their practical use in survey operations. However, the accuracies obtainable with these instruments today, when they are used properly, are probably superior to results obtained from taping. The National Ocean Survey uses electro-optical distance measuring instruments in various types of survey operations, such as, the transcontinental traverses, co-operative projects with other agencies, crustal movement studies, and various special purpose surveys. The results obtained from some of these survey operations are discussed below under the particular type of survey involved.

High-precision transcontinental traverse surveys

A program for establishing high-precision traverse surveys in the United States was started by the Coast and Geodetic Survey, now the National Ocean Survey, in the latter part of 1961. At the start of this program the primary requirement of these surveys was to position satellite tracking cameras at several places along the east coast of the U.S. north and south of Cape Kennedy, Florida. In order to fulfill this requirement and to meet the increasing demands for high accuracy surveys, a system of transcontinental traverses was planned. Also, plans were made to extend the high-precision traverses to connect the BC-4 network of satellite triangulation stations.

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The network of high-precision surveys which has been planned for the conterminous United States consists of eight closed loops formed by three east-west and five north-south traverse lines. The total distance to be covered by these surveys is approximately 22,000 kilometers. Figure 1 shows the traverse sections which had been completed at the end of July 1972, the total network which has been planned, and the BC-4 satellite triangulation stations.

During the first six years of this program, the traverse net consisted of elongated triangles as indicated in Figure 2A. Sides of these triangles ranged from 8 to 15 km and each side was measured on different days with different electro-optical instruments. The required check between the two measurements was to be within 1.7 cm plus one part per million of the distance. Very few remeasurements were necessary in order to meet the required check.

After the electro-optical instruments were equipped with a laser light source in 1966, the practical operating range was increased to 25 to 35 km. Many of the figures in the traverse net are now observed as shown in Figure 2B. In these triangles, the two short sides are measured with the same instrument and the long side is measured with a different instrument on another day. The required projected check is the same as mentioned above, that is, 1.7 cm plus one ppm of the distance.

The section of traverse extending north-south through the State of Wyoming, accomplished from May to August 1972, was performed as a single-line traverse as indicated in Figure 2C. The requirements for the single-line traverse are that each line be measured with different instruments on different days. The required checks between the two measurements are given above.

In these high-precision surveys, Laplace stations are established at 20 to 30 km intervals. Also, directions and azimuths must be observed with different instruments on different days. Results to date indicate that internal accuracies on the order of, or better than, one part per million have been obtained. The computed position closure of the large closed loop in the western part of the U.S., approximately 8,000 km in length, was six meters. Closures of the two loops in the eastern U.S., each about 4,500 km in length, were five meters for the most easterly loop and 1.5 m for the adjacent loop. The small loop 1,200 km in length, inside the adjacent eastern loop, had a closure of 1.2 meters.

In order to maintain the high-precision required in the electro-optical distance measurements, each instrument is calibrated at periodic intervals and tests are made over taped base lines. Results obtained from several instruments over two base lines are given in Tables 1 and 2.
<table>
<thead>
<tr>
<th>Date</th>
<th>Geodimeter Model &amp; No.</th>
<th>Distance (m)</th>
<th>Mean Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/20/69</td>
<td>4 236L</td>
<td>4</td>
<td>13,948.416</td>
</tr>
<tr>
<td>12/04/69</td>
<td>4 304L</td>
<td>4</td>
<td>13,948.422</td>
</tr>
<tr>
<td>9/15/70</td>
<td></td>
<td></td>
<td></td>
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<td>9/16/70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9/17/70</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>9/17/70</td>
<td>4 150L</td>
<td>2</td>
<td>13,948.421</td>
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<td>9/24/70</td>
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<td>4</td>
<td>13,948.427</td>
</tr>
<tr>
<td>9/16/70</td>
<td>4 284L</td>
<td>4</td>
<td>13,948.422</td>
</tr>
<tr>
<td>9/17/70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9/24/70</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>9/15/70</td>
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<td>4</td>
<td>13,948.417</td>
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<tr>
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<td></td>
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</tr>
<tr>
<td>9/24/70</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>9/15/70</td>
<td>4 441L</td>
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<td>13,948.412</td>
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<tr>
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<tr>
<td>9/08/70</td>
<td>8 80020</td>
<td>3</td>
<td>13,948.402</td>
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<tr>
<td>9/16/70</td>
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<td>4</td>
<td>13,948.406</td>
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<tr>
<td>9/17/70</td>
<td>8 80030</td>
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<td>13,948.410</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>13,948.419</td>
</tr>
</tbody>
</table>

(A). Number of complete measurements.

(a), (b), and (c) are simultaneous measurements made from each end of the base.

The refractive index corrections applied to these measurements were based on temperatures and pressures taken at instrument and reflector height, approximately 30 meters above the marks.

* This taped result is based on measurements made in 1933 with three 50-meter invar tapes. The tapes were calibrated by the U.S. Bureau of Standards just before and after the measurements.
Table 2: Geodimeter Results: Holton South Base to Holton North Base

<table>
<thead>
<tr>
<th>Date</th>
<th>Geodimeter Model &amp; No.</th>
<th>(A)</th>
<th>Distance (meters)</th>
<th>Mean Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/14</td>
<td>4 155L</td>
<td>6</td>
<td>5,500.581</td>
<td>5,500.581</td>
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<tr>
<td>7/15</td>
<td>4 155L</td>
<td>5</td>
<td>5,500.581</td>
<td>5,500.581</td>
</tr>
<tr>
<td>7/14</td>
<td>4 441L</td>
<td>5</td>
<td>5,500.580</td>
<td>5,500.581</td>
</tr>
<tr>
<td>7/15</td>
<td>8 80030</td>
<td>4</td>
<td>5,500.584</td>
<td>5,500.583</td>
</tr>
<tr>
<td>7/20</td>
<td>4 284L</td>
<td>4</td>
<td>5,500.582</td>
<td>5,500.585</td>
</tr>
<tr>
<td>7/21</td>
<td>4 288L</td>
<td>4</td>
<td>5,500.586</td>
<td>5,500.587</td>
</tr>
<tr>
<td>7/20</td>
<td>4 246L</td>
<td>4</td>
<td>5,500.583</td>
<td>5,500.584</td>
</tr>
<tr>
<td>7/21</td>
<td>8 80020</td>
<td>3</td>
<td>5,500.583</td>
<td>5,500.584</td>
</tr>
</tbody>
</table>

(A) Number of complete measurements.

The refractive index corrections applied to these measurements were based on temperatures and pressures taken at instrument and reflector height, approximately 30 meters above the marks.

* This taped result is based on various measurements made with steel tapes in 1891. The measurements were made over a wide range of temperature conditions, day and night, over an interval of about three months. This value is the mean result of all steel-tape measurements.

During the same time interval in 1891, five meter iced bars were also used to measure the base. The result of these measurements was 5,500.563 meters.

It is interesting to note that this is the first base measured with 100-foot steel tapes by the Coast and Geodetic Survey. A discussion of these measurements is given in C&GS Report of 1894, Appendix No. 5.
Co-operative surveys with city, county, and state agencies

Figure 3 shows a typical horizontal control network of stations which is established on a co-operative basis with city, county, and state agencies. The spacing of stations in these nets is on the order of 4 to 8 km and electropho- 

tical distance measurements are planned in every third or fourth triangle as indicated in Figure 3. In surveys of this type, the number of Laplace stations will depend on the total extent of the area and the number of stations in the network. The example net shown in Figure 3 indicates the approximate spacing of Laplace stations which would be planned with stations spaced at five km.

The specifications for these surveys are that relative accuracies on the order of one part in 100,000 be maintained between stations in the net. Direction and azimuth observations are made to first-order specifications and electropho-
tical distance measurements are made on one night. Each night's result consists of the mean of four complete measurements of a line. Also, the required length check between consecutive distance measurements is one part in 100,000.

In some surveys of this type, where angle observations have been made from the tops of buildings, problems have been encountered in obtaining the required first-order triangle closures. These problems have been resolved by measuring the distances of all sides involved in the problem areas.

The results of these surveys provide high accuracy control for the local breakdown surveys in urban areas.

Special purpose surveys

The National Ocean Survey performs, on a co-operative basis as requested, special purpose surveys for other federal and state organizations. A particular survey of this type is shown in Figure 4. This survey was requested by the Department of Transportation to establish high-precision control stations at intervals of approximately 800 meters around an oval track about 35 km in length. The purpose of this control was for the construction and maintenance of a track to be used for testing trains at speeds up to 800 km per hour.

This survey consisted of six basic stations on the east, west, north, and south sections of the track as indicated in Figure 4. The specifications stated that all horizontal directions were to be observed on two nights, with the average triangle closure not to exceed 0°7. In addition, each triangle side was to be measured on one night with electro-optical distance measuring instruments. The checks between the measured and computed sides of the triangles were seldom to exceed one part in 200,000. A second set of control stations positioned by traverse methods and spaced at intervals of about 800 meters were to be established between the six basic stations. The linear closures of the traverses between basic points were not to exceed 2.5 cm. Also, the perpendicular closures of the traverse loops, involving triangles with the two short sides about 800 meters in length, were not to exceed six millimeters.
In order to obtain the specified closures of loops involving distances of 800 to 1600 meters, distance measuring instruments using an infrared light source were used. These instruments have a maximum range of about two km; however, repeated field tests by the National Geodetic Survey had shown that accuracies within two or three mm could be obtained over lines up to about 1600 meters in length.

Many of the distance in this survey were measured five to ten times. The consistency of the results are indicated below for measurements in the triangle 5-5E-6.

<table>
<thead>
<tr>
<th>Side</th>
<th>Measured Distance (meters)</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 - 5E</td>
<td>1,031.2750</td>
<td>1,031.2740</td>
</tr>
<tr>
<td></td>
<td>.2720</td>
<td></td>
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<tr>
<td></td>
<td>.2764</td>
<td></td>
</tr>
<tr>
<td></td>
<td>.2725</td>
<td></td>
</tr>
<tr>
<td>5E - 6</td>
<td>554.1438</td>
<td>554.1473</td>
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<td></td>
<td>.1472</td>
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<td>.1510</td>
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<tr>
<td>5 - 6</td>
<td>1,578.2327</td>
<td>1,578.2334</td>
</tr>
<tr>
<td></td>
<td>.2321</td>
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<tr>
<td></td>
<td>.2332</td>
<td></td>
</tr>
<tr>
<td></td>
<td>.2355</td>
<td></td>
</tr>
<tr>
<td>Projected distance = 1,578.2385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perpendicular closure = 1.4 mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The computed position closure of this 35 km loop was three cm and the angular closure was less than one second. The overall results obtained in the survey were well within the specified limits.

**Surveys for crustal movement studies**

Geodetic surveys for monitoring deformation of the earth's crust along the San Andreas fault system of California were started by the Coast and Geodetic Survey about 65 years ago. After the San Francisco earthquake of 1906, the primary triangulation networks in the area were observed to determine the extent of horizontal movement. The original surveys in this area were accomplished during the period from 1875 to 1885. Results obtained from the 1906 resurveys formed the basis for a systematic program of special pattern surveys established at various places along the San Andreas fault system. This program was started in the 1920's and resurveys have been performed at intervals of 5, 10, or 20 years.

In recent years, these resurveys have been supplemented with electro-optical distance measurements. The combined triangulation-trilateration observational data has enabled us to detect small movements over a much shorter time span than was possible with angle observations only.
The maximum annual rate of horizontal movement along the San Andreas fault is in an area between Stone Canyon and Parkfield. This annual rate, 35 mm, is based on the results of triangulation surveys performed in 1944 and repeated in 1962. During the 10-year interval from 1960 to 1970, electro-optical distance measurements repeated at intervals of about one year showed about the same annual rate of movement.

In 1964, a co-operative program was started with the California Department of Water Resources to monitor movements in areas where a proposed aqueduct would cross the major fault zones. Figure 5 shows typical nets which were established in various areas across the faults. Each net consists of 6 to 8 stations with sides of the figures ranging in length from 200 to 600 meters. Resurveys have been made at intervals of one or two years; and in areas where systematic movements have been disclosed, the results have provided valuable information for construction of the aqueduct.

Each resurvey of these small nets, performed during the last two years, has consisted of combined triangulation-trilateration observations. All sides of each net are measured with infrared distance measuring equipment on at least two days. These precise distances furnish redundancy to the angle observations; and with the combined data, movements of two or three mm can be detected in a time span of about one year.

Summary

The use of EDM equipment in survey operations has simplified the problem of introducing scale into the network. If long range electro-optical instruments are kept in good operating condition, very little difficulty should be encountered in obtaining results on the order of one part per million over lines at least 10 km in length. Numerous tests have shown that short range instruments, equipped with an infrared light source, will give accuracies better than one cm.

In order to obtain high precision results with any type of EDM equipment, it is imperative that the instruments be calibrated at periodic intervals. The uncertainty in the meteorological data is one of the largest sources of error in the measurement of distances with electronic instruments. An error of 1°C will produce a change of about one part per million in the results. When high precision results are required, temperatures should be taken about 10 meters above the ground at the terminal stations. Various tests have shown that temperatures taken during the day, one to two meters above the ground, generally are 2° to 3° greater than those at a height of about 10 meters. During night observations, the reverse is true, that is, temperatures near the ground are less than those 10 meters above the station.
CONFIGURATION OF TRANSCONTINENTAL TRAVERSES
SCHEMAS DE CHEMINEMENTS TRANSCONTINENTAUX

Figure 2A

Figure 2B

Figure 2C

* Laplace station

Approximate distances
A - 10 to 20 km
B - 20 to 35 km
C - 25 to 35 meters

* Point de Laplace

Distances approximatives
A - 10 à 20 km
B - 20 à 35 km
C - 25 à 35 mètres
EXAMPLE OF CO-OPERATIVE TYPE SURVEY
EXEMPLE DE LEVE EXECUTE EN COOPERATION

Figure 3
EXAMPLE OF SPECIAL PURPOSE SURVEY
EXAMPLE DE LEVE À USAGE SPECIAL

Figure 4
EXAMPLE OF FAULT CROSSING FIGURES SIDES, 200 TO 600 METERS IN LENGTH
EXEMPLE DE MAILLES TRAVERSANT UNE FAILLE, COTES DE 200 A 600 METRES DE LONGUEUR

Fault Line
Ligne de faille

Figure 5