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A Geodetic Measurement of Unusually High Accuracy
By Captain Garner
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LANDSCAPE FROM EAST BASE SHOWING OTHER STATIONS

A Geodetic Measurement of Unusually High Accuracy

CAPTAIN C. L. GARNER (Retired)
U. S. Coast and Geodetic Survey

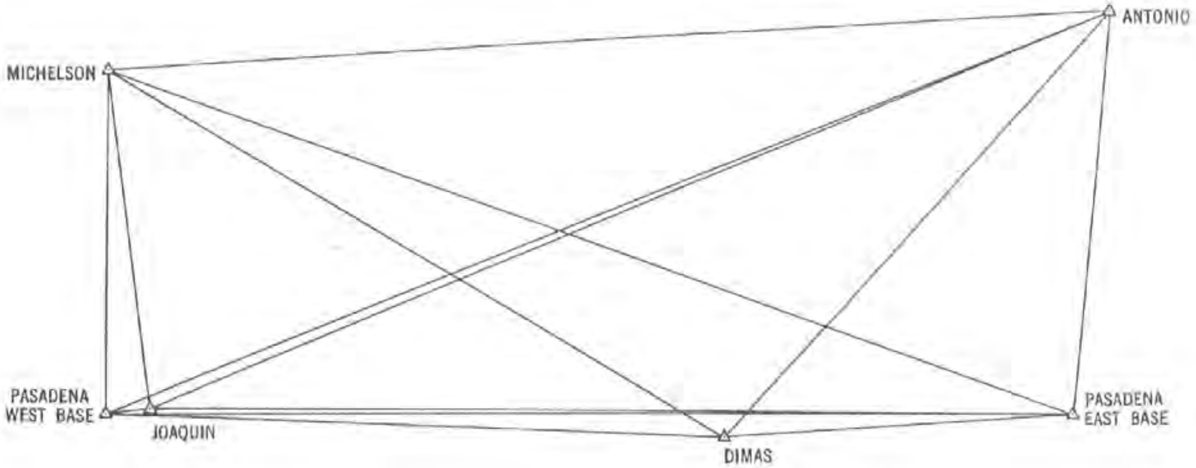
THE DETERMINATION of the velocity of light has been a problem of intriguing interest to physicists and astronomers since the latter part of the 17th century. Dr. Michelson, himself, made at least three determinations under as many conditions, the last one being at Santa Ana, California, in 1931. Because of its long experience in the precision measurement of base lines, the Coast and Geodetic Survey was requested to undertake the necessary observations and measurements. The Pasadena Base for the Mt. Wilson project was measured in the winter of 1922-23; many and varied difficulties were encountered in its 22-mile length. The Santa Ana Base was only 1 mile long and presented no unusual problems.

Michelson's experiments on Mt. Wilson involved only two stations: one on Mt. Wilson near the astronomical observatory of the Carnegie Institution of Washington (station MICHELSON) at an elevation of about 5,600 feet; and a second (station ANTONIO) on a spur or shoulder of San Antonio Peak ("Old Baldy"), 23 miles east of Mt. Wilson at an elevation of about 7,500 feet. The air line distance between the two stations was desired. (This is the Michelson Line whose length was determined indirectly from the Pasadena Base.) There was very rugged wooded terrain between these stations, thus making it entirely impracticable of direct measurement. Obviously, the distance had to be determined through the process of triangulation from a measured base to be somewhere in the valley to the south, and preferably of about the same length and as near the mountain line as possible.

The ideal form for a base line is a straight line and clear visibility between the ends over level or nearly level ground, a condition which the early reconnaissance proved impossible of attainment. A straight line, however, is not absolutely essential. Base lines with certain departures from a straight line, usually referred to as "broken bases," can be measured with a high degree of accuracy, provided, of course, that these departures are properly determined in angular measurement so that the straight line distance between the two end stations can be determined with requisite accuracy. The Pasadena Base was of this type. The length of the base was 21.5 statute miles, about a mile shorter than the line to be determined, nearly parallel to it and at an average distance from it of a little more than 8 miles. The base line was largely along public roads and over reasonably level ground except for about 1/2 mile. Considering the length of the base very little clearing was required.

The reconnaissance conditions sought were that all of the main stations should be intervisible, that the lines should clear the earth sufficiently to avoid the effect of lateral refraction due to currents of hot air or smoking from chimneys or other sources, that lines should not graze sloping surfaces, and other minor requirements.

When these conditions are ordinarily obtained there is need for only two stations at the base ends. The situation on this project required an interior station (DIMAS) because of a jog in the



MICHELSON BASE NET

east-west roads (which followed the land sectionalization) along which for the sake of economy it was necessary to carry the measurements. And an extra station (JOAQUIN) was established near WEST BASE in order to have a series of base lines from which to make several determinations of the length of the line MICHELSON-ANTONIO. Topographical conditions generally vary so much from place to place that this identical pattern would not be encountered elsewhere.

ACCURACY REQUIRED

It was desired that the distance between Michelson's mountain stations (about 23 miles) be determined so that the length would not be in error by more than 1 part in 500,000. This is a severe requirement, for 1/500,000 part of 23 miles is about 3 inches. The direct measurement of a length with this accuracy is routine procedure by geodetic field parties, but to measure a base and from it through triangulation obtain a length with that accuracy is quite another matter. The chief difficulty is due to the constantly varying characteristics of the air covering the earth. The air moves and is not uniform in temperature, humidity, or pressure, particularly along rays of sight as on triangulation over terrain ranging from sea level to 7,000 feet mountains. These changing characteristics cause horizontal as well as vertical refraction, the former often seriously affecting triangulation observations.

In the measurement of first-order bases by the Bureau it is required that the probable error shall not be more than 1 part in 1,000,000 and that procedures be followed to insure that there will be no actual error in the length of the base due to any one cause, such for example as, alignment, grade correction, etc., in excess of 1 part in 500,000.

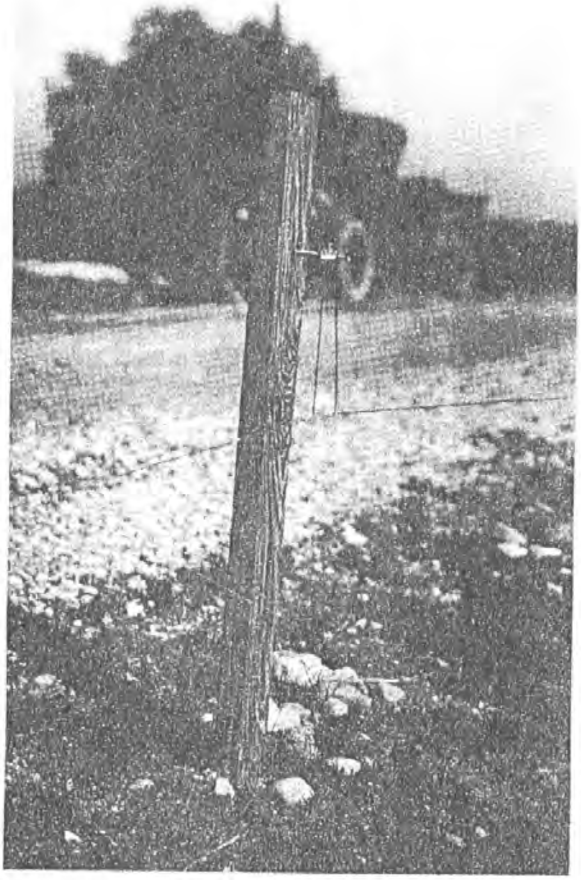
Obviously, then, these specifications had to be drastically tightened in order to obtain the accuracy of measurement required for the Michelson project.

BASE MEASUREMENT PROCEDURE

All sections of the Pasadena Base were measured with at least four different tapes, and additional measurements were made when the discrepancies between the various measurements differed by more than 4 mms. times the square root of K, where K represents the distance in kilometers. From long experience in first-order triangulation, the laws of probable errors of measurements, with which we can and do deal, are understood and have been successfully applied to many practical problems of this kind. In general, when the probable error is held sufficiently low the actual error cannot exceed certain reasonable amounts, if no systematic errors are present.

The following are some of the most serious sources of error to be encountered and which were guarded against in the measurement of the Pasadena Base:

1. ALIGNMENT.--Naturally each individual measurement on a base must be along a single straight line between

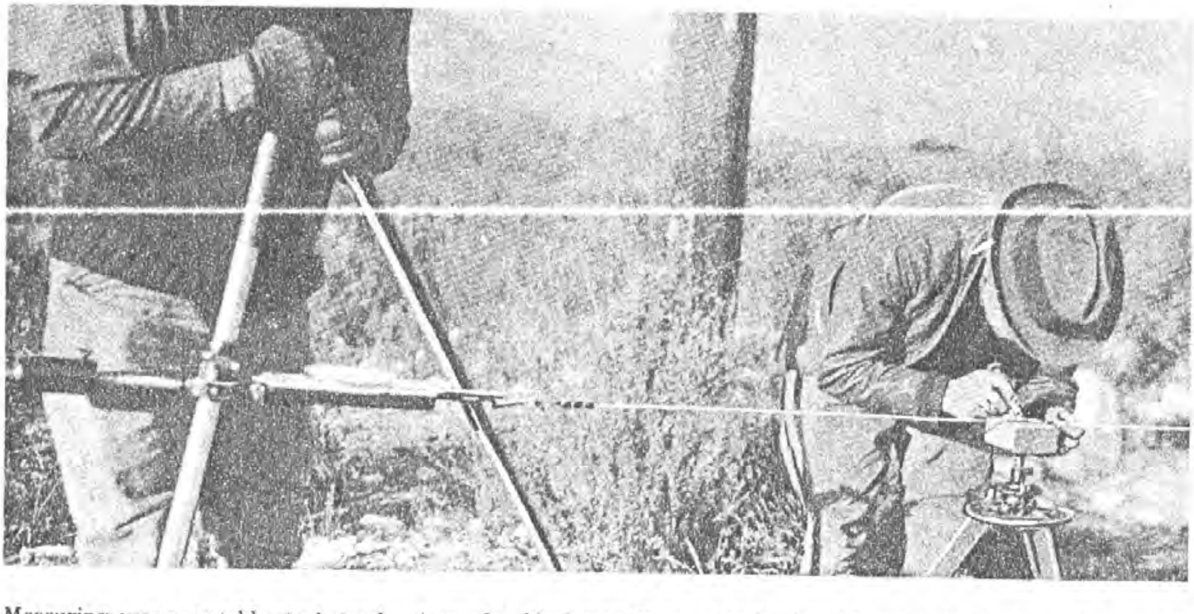


Center tape support. A wire loop was pivoted on a nail to prevent possible friction.

the end stations--if not, the amount the measurements are out of alignment must be known and corresponding corrections applied.

2. CORRECTION FOR GRADE.--Since in field measurements all tape supports are never at the same elevation, it is necessary that the differences in elevation of the tape ends be determined by spirit leveling in order to obtain the inclination for each measurement. The necessary corrections are then applied to the measurements to reduce them to the horizontal.

Over fairly level ground the determination and application of this correction is not at all difficult but it becomes progressively critical as the inclination or slope of the base line increases. For this reason base measurements of this type are limited to slopes of less than 10 percent because the determination of the correction with requisite accuracy for steeper slopes is too involved. Obviously, the steeper the slope, the more critical becomes the measurements of differential elevations. Sometimes, as on the Pasadena Base, short sections of excessive slopes are unavoidable. On this base there was about 1/2 mile where the slope of the ground exceeded 10 percent. This difficulty was overcome by making the measurements to the tops of towers which were built to a height such that the grade along the line of measurement

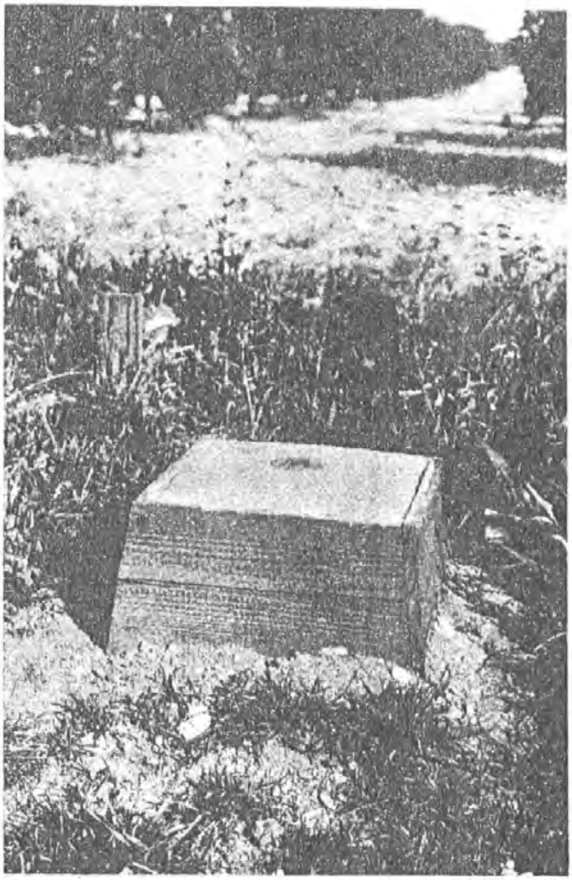


Measuring over a portable steel stand. A wooden block was fastened to head and brass strip set on top for contact.

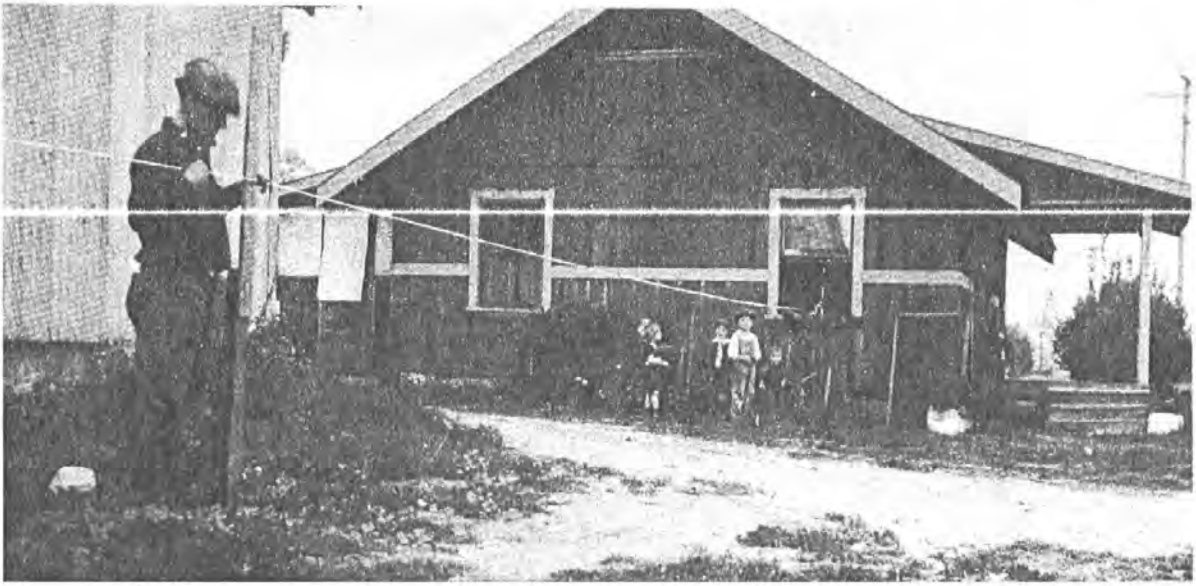
was less than 10 percent. Naturally, the heights and numbers of such towers depend on the particular conditions encountered. Every effort was made in the reconnaissance to select a route where such building was not required.

3. CORRECTION FOR TEMPERATURE.--All base tapes are standardized at the National Bureau of Standards for length, temperature coefficients, etc., before and after each base measurement. In the field measurements temperatures are recorded for each tape measurement and corrections applied for the coefficient of expansion due to the difference from the standardization temperature. Invar tapes, 50 meters long, are used for the measurement of bases. Invar has a coefficient of expansion of about 1/12 that of steel or 0.000001 per degree centigrade. This makes it practicable to measure base lines in sunlight.

4. TENSION.--Base lines are measured with a tension of 15 kilograms (about 33 pounds) applied to the tapes. In Europe and other countries it has been the custom to apply this tension by suspending a standard weight from a wire which is passed over a frictionless pulley and attached to the base tape or wire. This method is ideal for accuracy but is very slow and cumbersome. The practice in the Coast and Geodetic Survey is to use a type of spring



Typical station marker extending 4 or 5 feet below the surface and bulged at the bottom.



Measuring through a house. The base was selected so as to pass through a window in each end of the house.

balance which has a dial graduated in grams. This is tested three times each day to maintain proper control and accuracy.

5. CONTACTS.--The contacts at all tape ends must be made with utmost caution to prevent parallax or any systematic errors.

6. FRICTION.--There must be full 15-kilogram tension throughout the length of the tape. This requires extra precautions at both ends and at the center support to prevent friction.

7. OTHER ERRORS.--For measurements of this class, it is necessary to study carefully all classes of contact, accidental or systematic errors, and to devise methods that insofar as possible, will eliminate them. Much of this is accomplished by making measurements forward and backward, reversing the positions of the contact men and alternating conditions re the changes in temperature. For example, where a forward measurement is made in the forenoon with rising temperatures the backward measurement would be made in the afternoon with falling temperatures.

SPECIAL PROBLEMS ENCOUNTERED

In one case the slope was prohibitive and the line was diverted through an orange grove to avoid it--thus presenting a further difficulty of measuring over the grove. The trees were well developed with heavy limbs and foliage from the ground to the top and measurement under or through the trees was out of the question. This required that the measurements be carried over towers built a little above the trees for the tape end and center supports. Scaffolds surrounding these supported the party personnel.

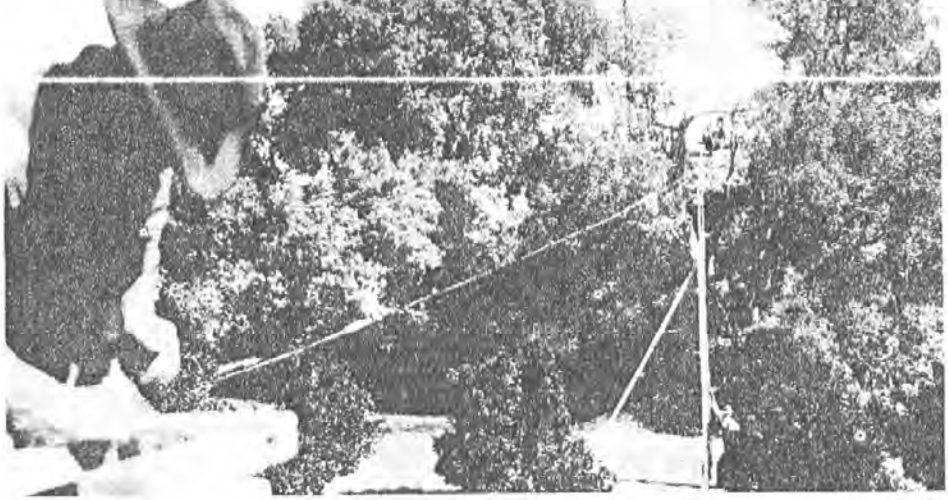
One dwelling house was on the line. Fortunately it was possible to plan the base line to pass through windows and doors thus presenting no measurement difficulties but some little disturbance to the household when carrying measurements through the house.

Serious lateral refraction was encountered in the horizontal angle observations at EAST BASE station and it was necessary to wait a period of more than 2 weeks in order to obtain better conditions of wind and air and thus eliminate this difficulty.

TRIANGULATION OBSERVATIONS

It is customary on first-order triangulation to complete the observations at a station under favorable conditions in only one night. Reference already has been made to the danger of lateral refraction on triangulation observations. Under erratic or abnormal conditions, rays of light between triangulation stations may change direction by several seconds of arc in a few hours of time. This is particularly true under rapidly changing meteorological conditions and especially so when there is a radical change in the temperature gradient and the direction of the wind.

The records of the Bureau over the years show some phenomenal changes of this nature. In one case the direc-



Measurement from top of stand to summit of grade. The line passes through the top of a tree.

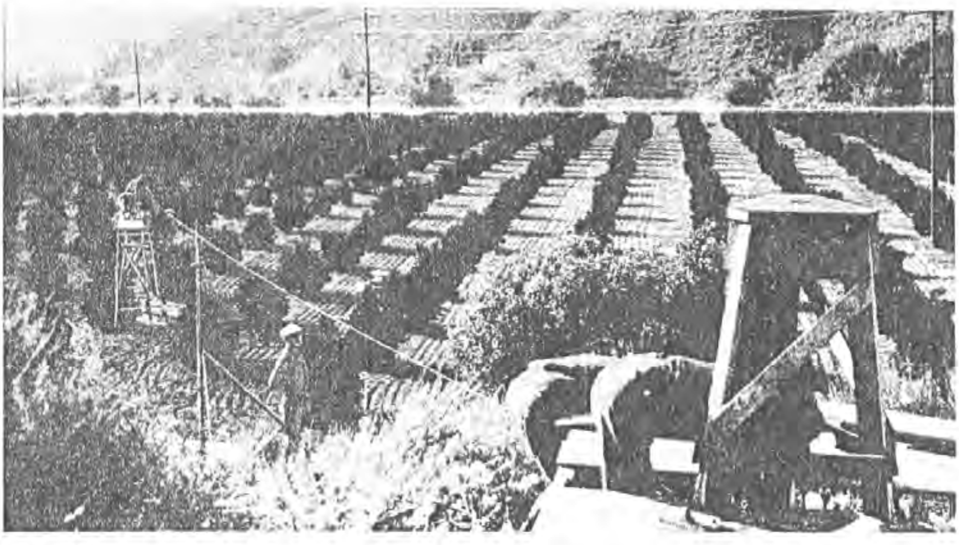
tion of a line changed more than 7 seconds of arc. This is cited merely to emphasize the need for a program of observing which insofar as possible will eliminate systematic and personal errors in both the triangulation observations and base measurements and at the same time provide checks which will indicate unacceptable discrepancies. Fortunately the trigonometric process is self-proving and doubly so when several methods of determining the length of triangle sides are provided as with the Michelson Line.

Undoubtedly lateral refraction is the source of the worst errors. That being so one may question how the observer may know whether or not his work is not subject to serious error of this class. But for the checks and balances the problem would be difficult indeed. Under routine operations, as for first-order triangulation, an experienced observer generally recognizes abnormal conditions by "flaring" signal lights or "wandering" objects; by large and erratic changes in the directions; and by other "telltale" phenomena which are noted during the course of the observations. Thus, through experience one becomes a good judge of conditions and is guided thereby. On projects requiring unusual accuracy the only safe way is to make observations at each station over a sufficient length of time to cancel out errors due to abnormal conditions. On the Michelson Line, observations were made on three nights at each station, but at station EAST BASE even this proved to be insufficient.

The specifications for the work required also that the average triangle closure should not exceed one-half second of arc, the maximum closure to be not more than 1 second. Another requirement was for reciprocal vertical angle observations to all stations. This was for the purpose of determining the height of the various stations above mean sea level. Due to the variability of vertical refraction, trigonometric elevations are liable to be rather seriously in error for work of this class except where the observations are made at both ends of the line--that is reciprocally. Sometimes, as on the Michelson Line, it is necessary that they be simultaneous and reciprocal--the ideal condition, but one which requires much more time and for that reason is not often specified except for special projects.

A further refinement was that stride level readings be taken for the directions to all stations for which the vertical angle (slope angle) exceeded one-half degree. These data made it possible to reduce errors due to the inclination of the horizontal or telescope axis. It is to be noted that on geodetic work of this scale and accuracy the plumb lines at all stations are not parallel. Each is subject not only to the variations due to the general configuration of the earth as an ellipsoid of revolution but is also influenced by any nearby mountain masses, deep valleys, or buried structure.

The astronomic latitude, longitude, and azimuth at each station were also observed on at least two nights each. These data provided both astronomic



Stands built for the purpose of gaining the summit of a small bluff on a 10 percent grade.

and geodetic longitudes, latitudes, and azimuths at all stations and made possible the computation of the deflection of the vertical at each station. This permitted further refinement to the inclination correction.

FINAL RESULTS

The probable error of the measured base line was about 1 part in 11,600,000 and the probable error of the desired line--that is between stations MICHELSON and ANTONIO--was approximately 1 part in 5,000,000.

Exactness in measurement, of course, is impossible and the probable error of a measurement is the best obtainable expression of accuracy. This and the experience of the Bureau in the measurement of some 300 first-order bases in the United States in its more than 130 years of existence are sufficient to justify the belief that the actual distance was correct at least to 1 part in 500,000, which met the requirements contained in the original request.

Caution Lights for Leveling Vehicles

LT. COMDR. EDWARD B. BROWN, JR.
U. S. Coast and Geodetic Survey

MUCH OF THE LEVELING that is being done follows highways over which there is considerable traffic. This creates a problem of protecting personnel and equipment from traffic hazards. The observing unit moves along at such a rate that caution signs placed along the pavement would not be practical unless in constant attendance. The use of flagmen also necessitates additional personnel. The system of using a truck on which red flags were secured was tried with some degree of success, but during periods of low visibility the flags could not be seen and during periods of good visibility they were not effective in slowing traffic.

The use of blinker lights on the observing vehicle was found to be an effective method of affording the desired protection. Lights were installed so they could be seen from the front and the rear. One light was mounted on the left front fender and the other on the left rear fender. The lights used were a pair of common fog lights with a flasher installed in the circuit. The cost of the equipment was $12.20 plus $1.50 for installation.

The system was tested in California during a period of considerable fog. At such times as the observer could see the rods, the blinkers could be seen by the oncoming traffic. As a general rule the traffic slowed down so as not to seriously endanger the personnel and equipment. During cloudy days the equipment had its maximum effect; all trucks and buses slowed down and many of the private automobiles exercised proper caution. Such a system is at its greatest disadvantage on clear bright days when the lights can be seen only at short distances--but they do have some effect. There is also the disadvantage that many states, California among them, have laws which prohibit the use of blinkers on all but emergency vehicles. Before the blinkers were installed, however, many law enforcement officers were contacted, and they were all of the opinion that no officer would question their use. Some even suggested the use of a red blinker on the rear of the truck and an amber blinker on the front. That system would probably be more effective but would depart further from state laws.