DISTANCE MEASUREMENTS,

ONE MILLION A SECOND

(Paper by Milton E. Compton of Berg, Hedstrom & Co., Inc., New York.)

You may have heard or read in the past five years of a revolutionary new device for direct measurement of distance. This new instrument is called the GEO-DI-METER from GEOdetic-DIstance-METER. It is the result of 15 years of research in the electronic and optical field. Distances are measured with the GEODIMETER* by projecting a highly collimated, modulated light beam to a distant reflector. Light is reflected back to the instrument and, by special electronic techniques, a phase comparison is made between the modulated light being projected and that being received. The measuring technique was conceived by a Swedish Scientist, Dr. Erik Bergstrand, to obtain a better value of the fundamental constant, the velocity of light. Measurements of this constant made with the larger and more precise version of the GEODIMETER are presently universally accepted as the "best" known value. The AGA Company, one of Europe's largest optical-electronic manufacturers, redesigned the earlier instrument into a family of distance measuring instruments of the highest precision known for practical measurements. The larger versions, the Model 1 and Model 2 GEODIMETERS are presently in use by many countries for acceleration of their mapping programs as well as for other specialized scientific applications. The latest addition to this instrument family is the Model 3 GEODIMETER. Before discussing this new instrument, let us briefly review design considerations and the method.

WHY LIGHT IS USED

A conventional Radar measures range to a target by transmitting pulses of radio energy to the target and determines the time required for the loop transmission path. Since electromagnetic propagation velocity is a constant, time is readily converted to distance. Radar measurements are accurate enough for the location of a ship or aircraft, but surveying and mapping distance requirements demand far greater precision. For this reason the GEODIMETER uses light as the propagating agent.

The use of light as the carrier permits a well defined light beam to be projected from the instrument to a distant reflector. This is of utmost importance since at all times the propagation path is precisely known. Unlike radio or radar methods, there are no multiple paths to combine in vector additions and cause phase interference resulting in anomalous observations. Beam confining is not possible at radio or radar frequencies. For example, a radar system operating at 10,000 megacycles per second, would require a dish antenna 10 miles in diameter to have the same optical efficiency of the one foot diameter GEODIMETER mirror. Hence, in radar methods, the signal

* GEODIMETER is a registered trade name, REG. US PAT OFF

strikes surrounding objects resulting in measurements that are difficult to rationalize into precise distances.

INFORMATION ON A LIGHT BEAM

Light is used in the GEODIMETER as the transporting agent. The measurement intelligence is superimposed on the light beam as very rapid sinusoidal flashes of intensity. The device that imposes this high frequency "blinking" on the steady output of a normal lamp is an electronic shutter and is called a Kerr-cell. The Kerr-cell system, which is precisely controlled by a crystal oscillator, forms variations in intensity or "blinks" on the light and the optical system projects these light variations to a distant reflector of special design that returns the light variations to the receiving portion of the GEODIMETER. Light returned to the receiver is collected and focused as a spot on the cathode of a photo-multiplier tube. In this tube light on the cathode surface causes electron emission which is amplified to the order of one million times by secondary emission technique, and appears at the output of the tube as an electrical current.

THE ELECTRICAL TECHNIQUE

The following hypothetical device will permit a clear understanding of the method. Suppose we have a Kerr-cell modulator that is modulating a light with a signal of sinusoidal waveform. Then being projected out in space to a distant reflector and returned is a series of maximum and minimum light intensities in accordance with the amplitude of the sine wave modulation. Let us now have a photo sensitive device, the photomultiplier tube, located alongside the light projection system and in conjunction with this light receiver a suitable optical system to gather light and bring it to focus on the photomultiplier tube. See Figure 1.

"In Phase"

Now we connect to this light receiver a meter that will indicate light intensity in terms of current. We also connect the Kerr-cell modulator to the light receiver in a synchronous manner so that when the out-going light intensity is maximum the sensitivity of the receiver is maximum. If we detach this receiver portion from the transmitting portion and carry it along the outgoing projected light beam, we shall observe meter deflections of maximum and minimum on the meter in carrying the receiver along the light path. This simplification necessarily assumes the sensitivity connection between the projector and photo sensitive receiver has zero time lag. Now the intensity as indicated by the meter if plotted vs distance would appear as Figure 2. It may be observed that where maximum or minimum occurs there is not a sharply defined position on the distance scale because the rate of change of a sine curve is minimum at these points.

"Out of Phase"

Let us modify the receiving portion and add another photomultiplier tube whose sensitivity is maximum when outgoing light is a minimum. We now observe an intensity vs distance curve displaced 180° in phase with the first arrangement. See Figure 3. This arrangement also has the same deficiency of having relatively undefined maximum and minimum points vs distance.

A "Difference" Device

Now, however, if we feed the currents from the two receivers into an indicator that will register the difference currents of the two systems, we have an extremely sensitive device, for the points of zero current will be well defined. The difference current will be zero in the points where the rate of change is maximum. See Figure 4. To utilize a two tube receiver practically, would require both tubes be identical which is difficult, for even if initially identical different ageing characteristics would destroy the function of the circuit.

A Single Integrating Detector

A much more unique solution is to use a single photomultiplier receiver and alternately switch its sensitivity from maximum when outgoing light intensity is maximum to minimum when outgoing light intensity is maximum and feed the two currents so derived in opposition to a current meter.

In the GEODIMETER, we modulate the light at two frequencies, a high frequency which is the measuring frequency, and a very low frequency derived from the power line that provides the switching function. In a half period of the power frequency or 1/120 of a second with a 60 c/s supply. and if the high frequency is 1.5 megacycles per second, 12,500 "blinks" will be passed for a half period in one direction through the null detector circuit, and in the next half period 12,500 "blinks" in the opposite direction. Each blink or sine wave is a measurement contribution. An integration of their effect is compared on alternate half periods of the switching frequency. In a one second period 1,500,000 differential measurements have been made and compared. See Figure 5. Thus, measurements of an unknown distance are literally made millions of times per second, and in the time required for a complete distance measurement, a statistical result consisting of billions of individual measurements or phase comparisons are made.

Null Technique

Measurements, in general, can be made directly or indirectly. The direct method is limited by the design sensitivity of the instrument. The indirect or null method, however, is practically unlimited in sensitivity since two signals are fed in opposition to each other and by means of amplifiers and coarse and fine reading steps any desired amount of sensitivity may be employed. The null method is also desirable from the operators point of view, since all that is required to make a measurement is to adjust coarse and fine control knobs until a meter or other indicator reads zero, and read the setting of the knob.

SUMMARY OF THE METHOD

We may summarize the measuring technique: Modulated light is projected to a distant reflector which returns the modulated light. Since a finite time is required in the loop transmission, light being received will be displaced in phase (by a number of wavelengths depending on the frequency and distance) from that being transmitted. The receiving detector cannot well define the maximum or minimum points on a sine wave so the receiver has its sensitivity alternately switched from maximum sensitivity when outgoing light has maximum intensity to maximum sensitivity when outgoing light intensity is a minimum. Currents derived from these two conditions are subtracted from each other to accurately define points between the GEODIMETER and reflector of zero current. These "zero" points in space are a quarter wavelength of the modulating frequency apart between the GEODIMETER and the reflector.

THE NEW MODEL 3 GEODIMETER

The newest member of the GEODIMETER family functions on the principles discussed. The method is basically that of the larger Model 1 and Model 2 types. The larger versions have a built in calibration path permitting a direct calibration of electrical delay. The instrumental uncertainty of the Model 2 is one half inch with a maximum range of 30 to 50 miles. The smaller Model 3 is the answer to the requests of many American Surveyors and Mappers to make a lighter and more portable instrument of lesser accuracy than the "first order" models but with sufficient accuracy for most conventional applications. This has been achieved by elimination of the calibrated light path, use of smaller projection optics, light magnesium alloy castings, and a lower measuring frequency. These changes reduce the weight to approximately 50 pounds. Range and accuracy are reduced somewhat, the instrumental uncertainty being about four inches and the range on the order of 20 miles. Since the calibrated light path is eliminated, the electrical delay may be directly calibrated as distance.

HOW THE DISTANCE IS DETERMINED

When measuring a distance with a tape, we first measure the distance to the first tape length then count the number of tape lengths. Like-wise, with the GEODIMETER, distance measurements are in two parts. We determine the distance from a reference point on the instrument to the first point of zero current in space. Secondly, we determine the number of zero points between the instrument and the reflector at a distant point. Since the determination of an unknown distance involves two steps let us discuss them in order.

The Distance to the First Zero Point

The determination of the distance from the reference point of the GEODIMETER to the first zero point requires inspection of a generalized schematic of the instrument. See Figure 6. We may see in the schematic that a crystal controlled frequency is applied to the light modulator as well as to the light receiver. The control signal passing to the receiver, however, goes through an electrical delay line graduated in coarse delay steps and also a fine delay. Now as explained previously the current in the null meter indicates zero only at well defined points in space separated by a quarter wavelength of the modulating frequency. Therefore, it is necessary to determine how far away the reference point on the instrument is from the first zero point. In measuring, the delay in the instrument is adjusted to make the null indicator read zero. Since any delay in the instrument is equivalent to distance, introducing an artificial delay amounts to measuring the distance from the instrumental reference to the first zero point. The coarse and fine delay are directly calibrated in distance. See Figure 7. The distance on the coarse scale plus the distance on the fine scale represents the distance to the first zero point. In the Model 3 each coarse step represents 5 meters and the fine scale 5 meters with 100 divisions, readable to 1/10 division, and if we observe coarse 6 and fine 55.0 then 6 x 5 = 30 meters, and 0.05 x 55.0 = 2.750 meters, and then 30 + 2.750 = 32.750 meters to the first zero point.

Determining the Number of Zero Points

It is now necessary to determine the number of zero points between the GEODIMETER and reflector. This is relatively easy. If the GEODIMETER could be moved forward toward the reflector, it would discriminate between an odd or even number of quarter wavelengths. This is true because of the nature of the null meter reading the difference of a 180° phase displacement with respect to the outgoing modulation intensity. In the odd quarter wavelength the minus current intensity sensitivity exceeds the positive current intensity sensitivity as can be observed from Figure 4. Likewise, the indicator will deflect to the positive portion of the scale in an even quarter wavelength. From this then we need to know the distance being measured to within plus or minus a quarter wavelength or ± 50 meters. If we introduce a second frequency 2.5% higher than the first frequency, and measure with this frequency, then we shall have two measurement equations and two unknowns, and we only need know the distance to ± 2000 meters or ± 1-1/4 miles. The effect is that of a vernier in space. There are two "light" measuring tapes of slightly different lengths between the terminal points being measured. Since one "light" tape is shorter than the other only at certain points will the "markings" coincide. We must know the distance to ± one "marking."

LEARNING TO OPERATE THE GEODIMETER

Operation of the GEODIMETER is easy. A person who operates a transit, level, or theodolite in survey operations can quickly learn the procedure. One week of training measurements are normally sufficient to produce a competent observer. No observer personal errors have been observed with trained operators.

Using the Model 3 GEODIMETER

The Model 3 GEODIMETER is placed on its tripod which is set-up over one terminal point of the line to be measured. See Figure 8. A small gasoline engine generator, supplying the power required, 115 volts-60 c/s, 80 watts, is connected to the instrument. An assistant, at the reflector site on the other terminal point of the line being measured, shows a signal light toward the GEODIMETER. The GEODIMETER operator, upon seeing the signal, directs the GEODIMETER by using a coarse sight provided. Then by swinging an eyepiece in position normally occupied by the lamp, and using the projection system as a powerful telescope, the pointing on the distant light is finalized. The lamp is swung into position, and the well collimated light beam will be directed on the reflector site. The reflector assistant upon seeing the light from the GEODIMETER replaces the signal lamp with a prism system consisting of a group of tetrahedron prisms. See Figure 9.

The prism reflector consists of an easily transportable unit of seven prisms, individually mounted. The angular tolerance of the individual prisms is less than two seconds. The design of the housing and containers is such as to minimize the formation of condensation. Each unit may be used on a conventional tripod. On long lines, or under poor light conditions, the units may be mounted on the tripod as two or three units. Three units form a system of 21 prisms. The prism system has the property to return light parallel to that projected upon it. Angular pointing and stability are not important with this system. There are two other types of reflector systems available, a spherical mirror system and a plane mirror. These systems have special applications, and generally the prism system is the most desirable.

With the pointing complete the measurement is begun. The GEODIMETER is zeroed by a knob adjustment, and the coarse delay push buttons are pushed one at a time beginning with zero and the null meter is observed. The null meter will be off scale to one side or the other. The buttons are pushed quickly in succession, and depending on the distance, one of the buttons will cause the meter to stand "on scale". When this selection has been made the fine delay is adjusted to hold the null meter on zero. After about one minute of adjustment of the fine delay, the operator is satisfied of the null condition and reads the fine delay scale. This is phase measurement. It is necessary to repeat the fine delay adjustment in three additional phase switching positions to eliminate systematic errors. This requires about five minutes. The zero set is again checked.

A measurement has now been completed on frequency number one. Normally the frequency is now changed to the second frequency by means of a switch and the four phase measurements are again repeated. If measurements are being made on an existing triangulation arc or distance that is known to ± 50 meters the single frequency measurement is sufficient. Otherwise, the second frequency is necessary to reduce any possible distance ambiguity. The total measurement time requires approximately 20 to 45 minutes depending on visibility. Pre-computed tables are furnished to make the observed distance immediately available in the field. The instrumental uncertainty of such a measurement is about 10 centimeters or 4 inches. Since measurements are made in the atmosphere, on longer lines say over 10 miles in length, temperature and pressure measurements should be made and corrections applied by means of the furnished pre-computed tables

ACCURACY OF THE MODEL 3

The average accuracy of a GEODIMETER measurement may be stated as ± (10 cm + 2 millionths of the distance). We may tabulate expected accuracy in terms of fractional ratios as follows:

Range Miles	Nominal Fractional Ratio
1	1/16,000
2	1/30,000
5	1/70,000
10	1/120,000
15	1/160,000
20	1/190,000

If maximum accuracy is desired, so that a better fractional ratio may be obtained, then as tabulated, a tape length of approximately 50 meters may be established at the GEODIMETER site and direct calibration of the electrical delay may be made. Tests indicate instrumental uncertainty may be ± 5 centimeters or less using this method. The fractional ratio on a one mile line is then 1/30,000.

THE RANGE OF THE GEODIMETER

The range or maximum distance the Model 3 GEODIMETER can be expected to measure will vary with atmospheric transmission. Loop visibility is required since the light must travel twice the distance to be measured. Actually slightly better than loop visibility range can be measured since the GEODIMETER can detect and measure on light reflection so faint that the reflected image cannot be detected with binoculars. Under "good" conditions the range will be 10 to 15 miles. Under "excellent" conditions it may exceed 20 miles.

APPLICATIONS OF THE MODEL 3 GEODIMETER

Mapping engineers and surveyors that have distance requirements greater than approximately one mile will find great application for this speedy method of distance determination. Mapping control thinking may well be revised by such a device since distances may now be established between any two visible points. The following are a few applications:

Triangulation Arcs

Baselines other than first order are quickly established. Triangulation arcs can be directly measured. Any suspected erroneous arcs can be proven in short order.

Traverse Surveys

Traverse surveys are easily performed since the Model 3 GEODIMETER is light and portable enough to employ two reflector crews, and by measuring fore-sight and back-sight as in leveling to perform a fast, long legged direct traverse. The GEODIMETER need occupy only every other station.

Photogrammetric Application

Since ground distances between prominent photo points can be measured directly, large scale mapping of unexplored areas employing photogrammetric techniques will be expedited.

Hydrography

Base-lines can easily be established along shore points so that an off-shore hydrography vessel may be positioned by theodolite from the ends of the base line.

Highways and Pipeline Surveys

Surveys for new or existing highways can be completed with great savings of time and manpower. Cross country pipe line surveys are particularly easy since point to point distances are measured directly.

Geophysical Surveys

Intensive and accurate nets can be made over land or water for the requirements of geophysical locations. Ties between existing locations are made directly.

Mine Surveys

The GEODIMETER has been successfully used in Sweden to tie together existing mines each having its own survey net not previously combined into a single controlled survey due to difficult terrain.

Radar Calibration

Calibration of radar-ranging devices and navigational instruments and layout in remote areas of ranges with intensive control is an easy job for the GEODIMETER.

CONCLUSIONS

GEODIMETERS of the Model 2 high accuracy type are now in use by nearly all major countries for acceleration of their mapping programs. The Model 3 GEODIMETER provides a readily portable fast and accurate instrument to satisfy most distance requirements and supplements the measurements of First order baseline accuracy by the larger Model 2. The two instruments provide accurate distance measurement coverage in the range of one to approximately 50 miles. There is no existing practical device presently known with such utility and accuracy.

- - - -

The instrument is mounted on it's own tripod with a turnable and tiltable head for slope measurements when required.

FIGURE 7 — THE MODEL 3 GEODIMETER

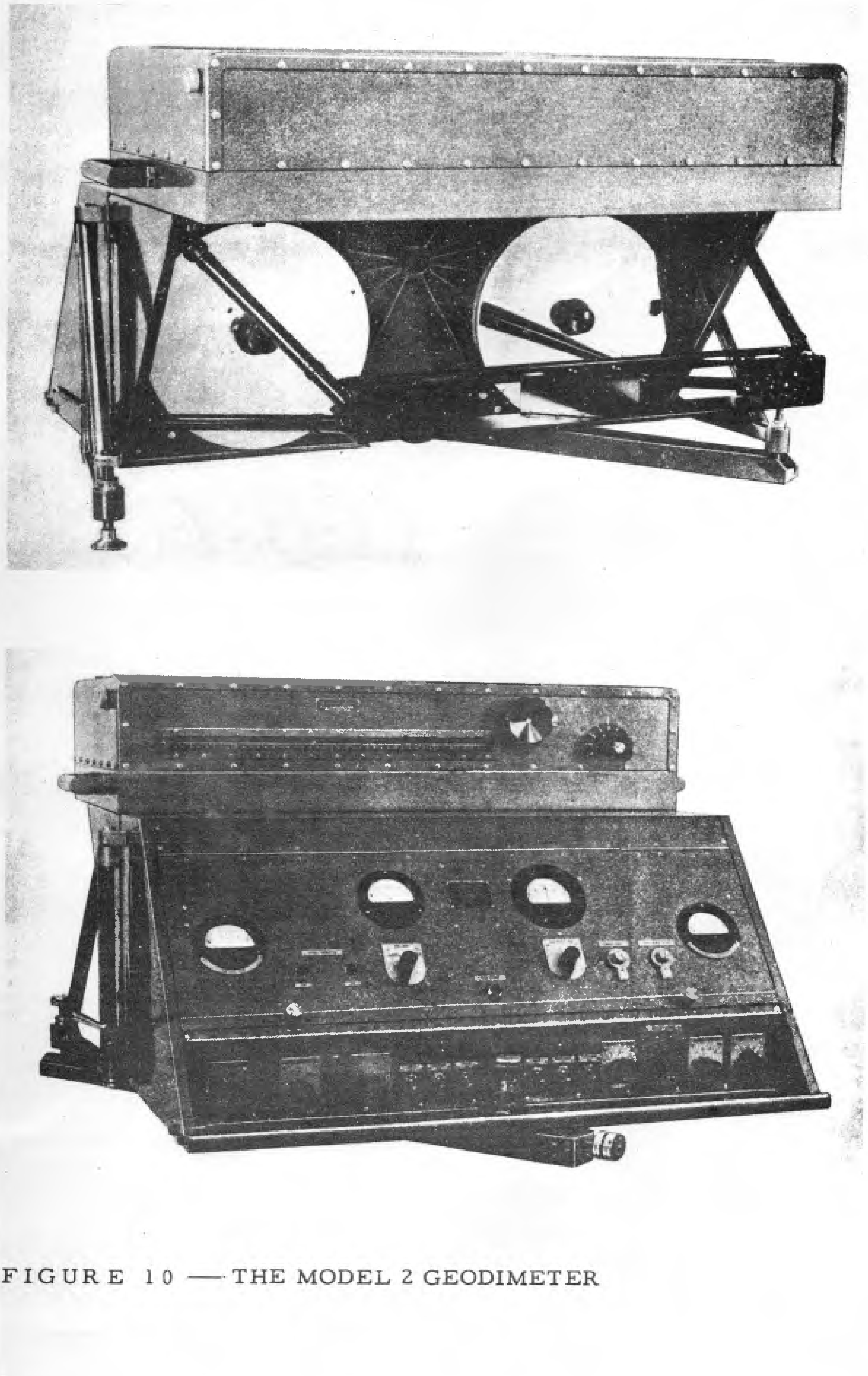

FIGURE 10 — THE MODEL 2 GEODIMETER