RESULTS OF TRIALS ON THE CONDITIONS UNDER WHICH THE TELLUROMETER IS USED

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IHB Note. — Ingénieur géographe DECK, a former student of the *Ecole polytechnique,* is head of the Department of Electronics and Chronometry of the French National Geographic Institute's Study and Manufacture Service.

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Mr. DIDEY is a State Geographical Works engineer. After appointment to the Photogrammertic Service, he was put in charge of the laboratories under Mr. DECK's direction.

Since 1958 the French National Geographic Institute has carried out various experimental operations with the tellurometer, with the main object of ascertaining the best working conditions for the instrument. Approximately 30 sides and 4 bases have thus been studied. In addition to these tests, current use was made of several tellurometers in the Sahara, where over 1 000 km of traversing was done.

The sum total of these measurements has enabled the rules set forth in the present article to be derived. The results obtained, moreover, are indicated at the end of the article.

Number of measurements, series or ½ days required

— A measurement is defined as a set of 4 readings (+ A, — A, — A reverse, + A reverse).

— A series is defined as a set of 16 measurements made either on frequencies 3, 4 .... 18 (up scale series), or on frequencies 18.5, 17.5 .... 3.5 (down scale series). Up scale and down scale series are obtained alternately.

— Temperatures are measured before and after each series; pressure before and after each ½ day.

— To ensure the validity of a series, temperature should not vary by more than a few tenths of 1° C. The rule is to *eliminate any series* in which *one* of the 4 temperatures (dry or wet at master or remote) *varies by more than 0.5° C.*

— Two valid series suffice to supply an accuracy of 10 cm up to 10 km, or of 1×10^{-5} beyond. A higher accuracy rate requires additional series, but *it is useless to obtain more than 6 valid series* (up or down scale) *per ½ day*, as temperature conditions do not have time to vary enough for effective repeat observations.

— The various ½ days do not have the same value: everything depends on wind. Temperature measurements are significant only when there is good air circulation, that is, if there is wind. The rule is to attribute to the various ½ days the weights:

3 if the wind is moderate, moderate to strong, or strong;
1 if the wind is slight, or slight to moderate;
0 if the wind is nil, or nil to slight.

Note : If wind is nil, or nil to slight, it is useless to begin measurements. Wait until wind is favourable.

— For routine work, observations are taken during two ½ days (if possible an evening and a morning); for highly accurate work, during about ten ½ days (balancing if possible the number of mornings and evenings), each ½ day counting with its weight.

Height of signals

— Regardless of the desired accuracy, the height of the signals must satisfy two requirements :

(1) Line-of-sight conditions should be met;

(2) Additional clearance should be available above flat areas parallel to the measurement. The minimum height of clearance above the ground depends on the length of the graze area, and has the following approximate values:

3 m over 0.5 km
5 m over 3 km
7 m over 10 km
12 m over 18 km

Such clearances enable avoidance of the lower layers, which are subject to temperature disturbances, and especially prevent absorption of the waves by the ground; when height is too low, the automatic volume control is generally under 40 (or 35 in some instruments), the circle is fuzzy (*), and the break in it is difficult or impossible to read (figure 1).

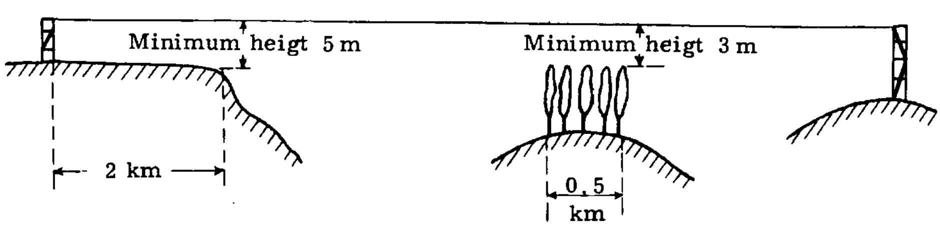


FIGURE 1

(*) *IHB Note.* — The outline of the circle presents a fuzzy appearance.

Notes :

— Wooded areas constitute an obstacle similar to the ground; the above clearance conditions hence apply to the tops of trees. Isolated trees cause no inconvenience, however.

— In certain regions, such as the Sahara, visibility varies according to the time of day; both of the above conditions must be met at the time of observation.

Antenna clearance

— In the case of observation from a pillar, the instrument should be placed on a board projecting out from the handrail, and not in the centre. Otherwise a signal-centre error amounting to as much as 10 cm may result (figure 2).

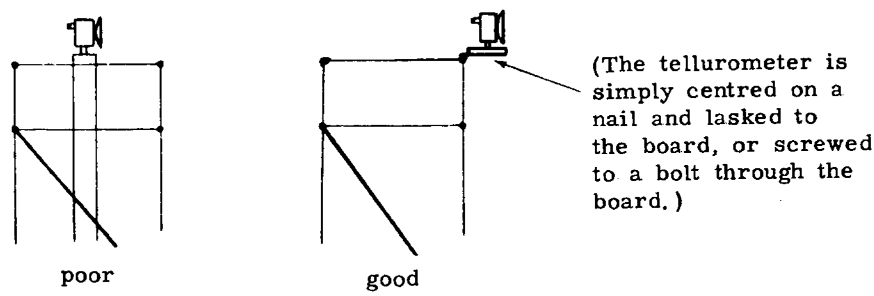


FIGURE 2

— When measurements can be made on the ground, two cases may arise:

(1) If the ground falls away rapidly in the direction of measurement (slope in excess of 10 per cent over at least 50 m), tripod observations may be made (figure 3).

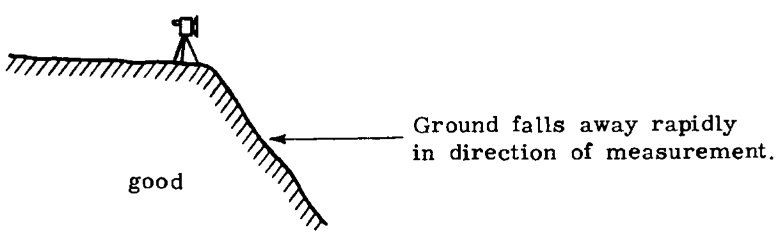


FIGURE 3

(2) If the ground is relatively flat in the direction of measurement, *a pillar at least 4 m high* should be erected. This elevation is required in order to eliminate ground error, which can reach 10 cm, and enable correct temperatures to be taken (figure 4).

— These precautions are essential for accurate work. Signal-centre and ground errors are all the more dangerous inasmuch as they pass

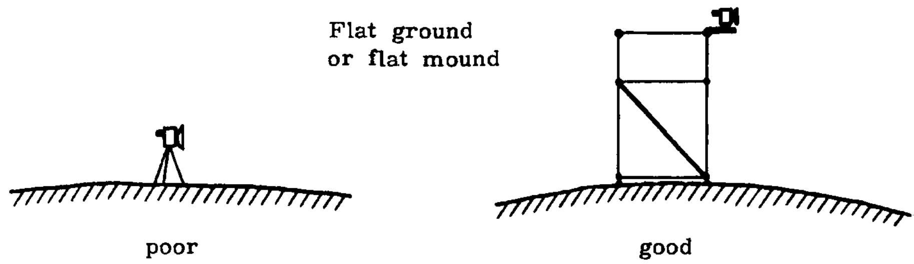


FIGURE 4

completely unnoticed. They have been clearly shown up on several occasions.

Elimination of significant parasite reflections

— Significant parasite reflections should be avoided. These reflections show up as curves of large amplitude. A measurement is poor when the curve is both nonsinusoidal and of a larger amplitude than 4 units (*), and the average of such a curve has little meaning (figure 5).

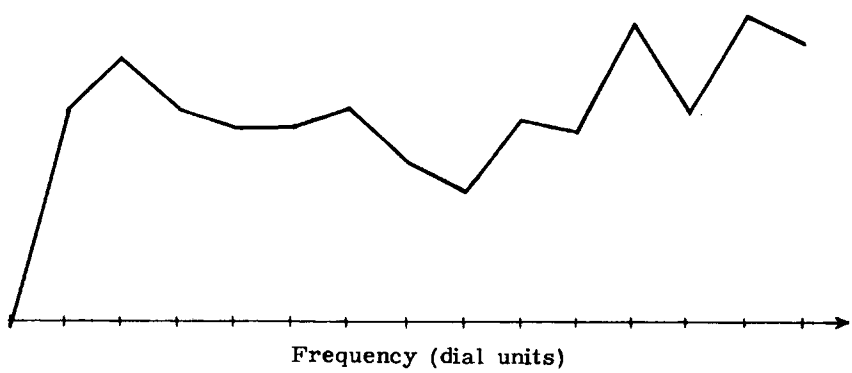


FIGURE 5

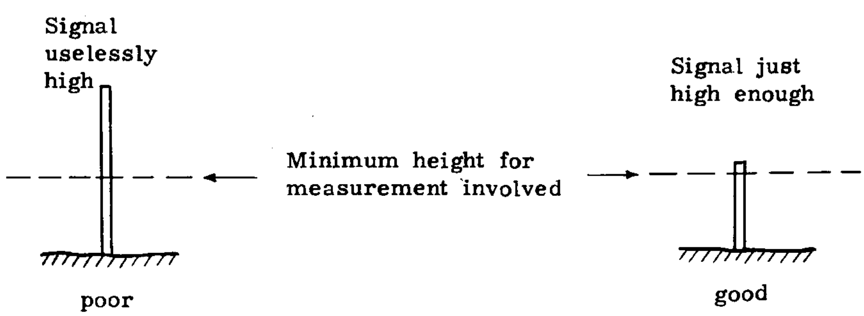


FIGURE 6

(*) 1 unit corresponds to 1 millimicrosecond and about 15 cm.

— The first rule is to observe systematically the *minimum height* compatible with the other conditions, since intensity of reflection increases with clearance (figure 6).

— Reflections are caused by flat areas or water surfaces surrounding points where reflection is possible, by the tops of rounded mounds below the line measured, and by slopes near the ends of the line. The fewer the obstacles and the more conductive the ground at the point of reflection, the stronger the reflections. (An area covered with brush or hedgerows, or very dry ground does not reflect the waves.) (figure 7)

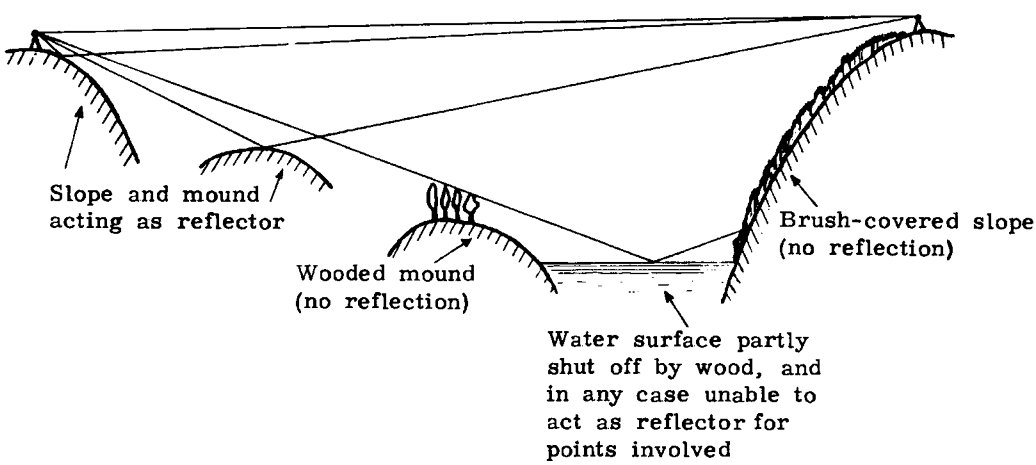


FIGURE 7

— These established facts lead to the following remarks :

— Slopes may occasionally be avoided by shifting the position to the edge of the slope, as far as possible near an obstacle (such as a hedgerow or rocks) acting as a screen for the reflected ray. Connection is then made (by stadia rod, for instance) (figure 8).

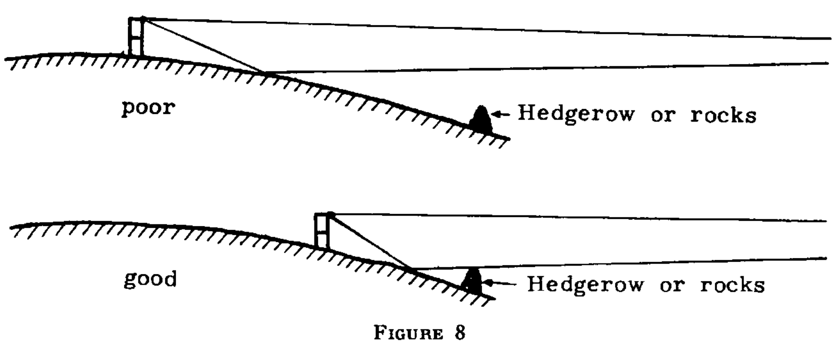
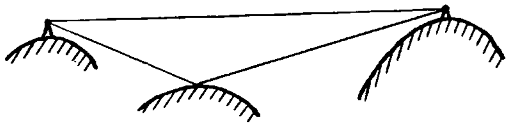
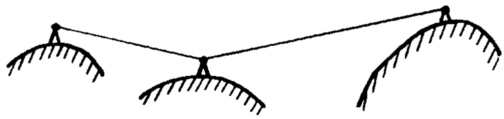


FIGURE 8

— In the case of a rounded, smooth hilltop, it may be desirable to change the line or split it. This method of division can also be used in the case of reflection on a flat area (figure 9).



poor



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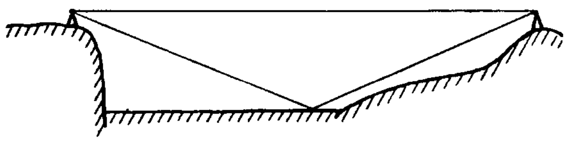

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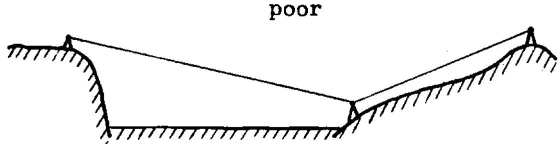
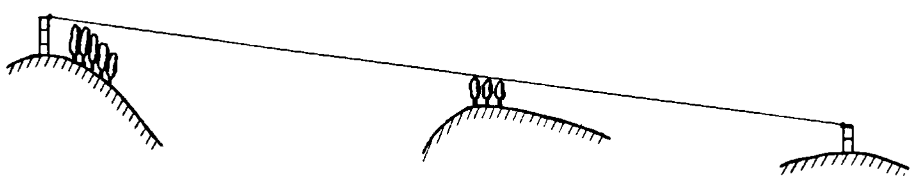


fairly good

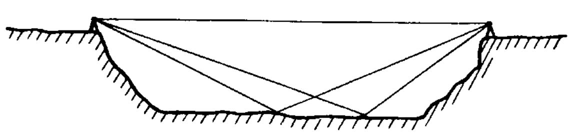
FIGURE 9

— When one or more intermediate crests exist, advantage must naturally be taken of the fact by measuring from heights such that the line passes immediately above the crest or crests (allowing as necessary for absorption); no reflected ray can then pass. (Ex: Châlons base) (figure 10).

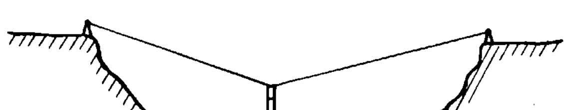


excellent

FIGURE 10



poor



good

FIGURE 11

— A line with good clearance throughout (such as between two mounds rising above an intervening plain), however, is subject to strong reflections. It may be desirable to split the line (figure 11).

Additional remarks:

— When reflection takes place at sea, a change in the altitude of the reflector due to swell or tides results in curves of large amplitude which vary considerably from one series to the next.

— In the Sahara, conductibility of the ground is low and reflection is slight; hence they may usually be disregarded.

— If a single side (base or control) is measured, the side offering optimum conditions for the elimination of parasite reflections should be chosen.

— In the preliminary study of a line, an approximate profile of the terrain is useful.

— Preliminary study is not conducive to absolute certainty; a measurement which may seem initially satisfactory sometimes results in a curve of large amplitude, or inversely. One cannot be really certain that a measurement is good until an initial series of measurements has been made and the corresponding curve has been plotted. If it is poor, the line must be changed. Fortunately unpleasant surprises seldom occur if the problem has been studied correctly.

Homogeneity of lines

— Since temperatures are measured only at the ends of the lines, it is desirable that the lines be homogeneous. This homogeneity applies to height above the ground, the nature of the areas crossed, and symmetry of the ends. An attempt will be made to avoid as much as possible:

— Lines which partly graze and partly show large ground clearance;

— Lines passing over a broad valley, or a forest, where the air is more humid;

— Lines between the edge of a tableland and a point located on the plain below.

— The remedy consists in dividing up the line into homogeneous sections.

Meteorological equipment

— For pressure, use ordinary, good-quality barometers, but calibrate them at least once a week, and oftener if possible, with an accurate instrument.

— For temperature, use ordinary thermometers and not psychrometers, as in these instruments the thermometers are perturbed by radiation of the case.

— Check thermometers for quality and for breaks in the columns.

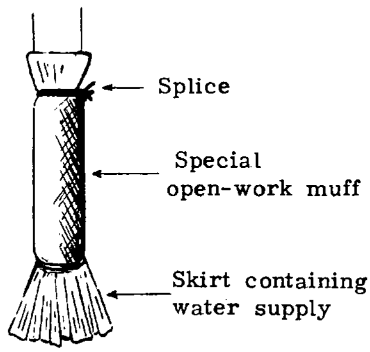


FIGURE 12

— For wet bulb temperature θ', use a special muff (figure 12). Do not use gauze (which dries before balance is achieved) or cotton wool (which becomes like felt and prevents balance).

— Use only distilled or rain water; the muff should of course be clean.

— To obtain accurately the difference $\theta - \theta'$ (*), use a double support (figure 13); this is the only way to measure θ and θ' at identical times and under identical conditions.

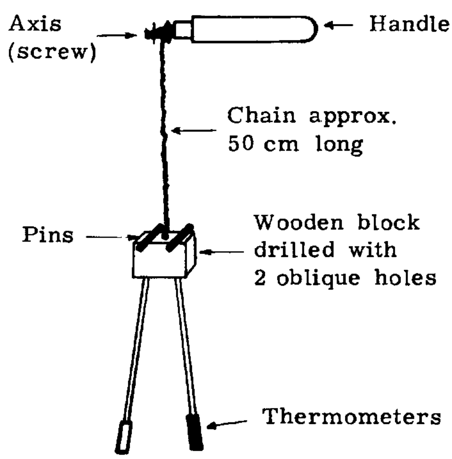


FIGURE 13

Method of obtaining temperatures

— On flat ground, temperature measurements and consequently observations should be made on pillars in order to avoid ground radiation and the effect of the lower layer. (A height of 4 m suffices.) Measurement on the ground is only possible if the position possesses natural clearance (edge of tableland, summit, or sharp-topped mound) (figure 14).

(*) Vapor pressure is mainly a function of θ' and $\theta - \theta'$; the temperature θ itself is of minor significance.

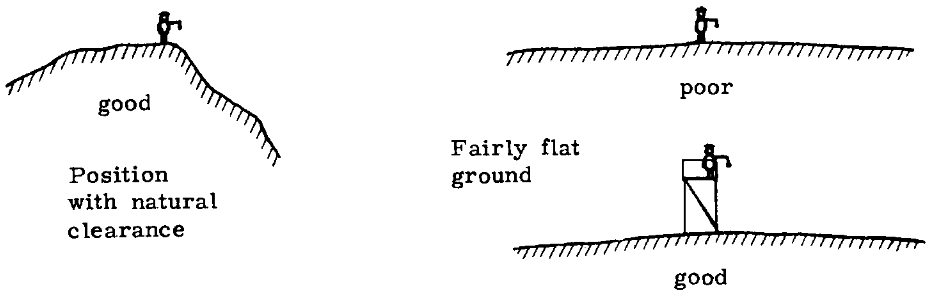


FIGURE 14

— The thermometers should of course not be exposed to the sun.

— Whenever there is a slight wind, *the thermometers should not be swung*. Hold the thermometers by their support, at arm's length, in the shade of the body, facing the wind as far as possible, and outside the guard rail. Or hang the thermometers in the shade of a board lashed to the outer part of the rail or under the floor. On the ground use a vertical tube about 2 m long (figure 15).

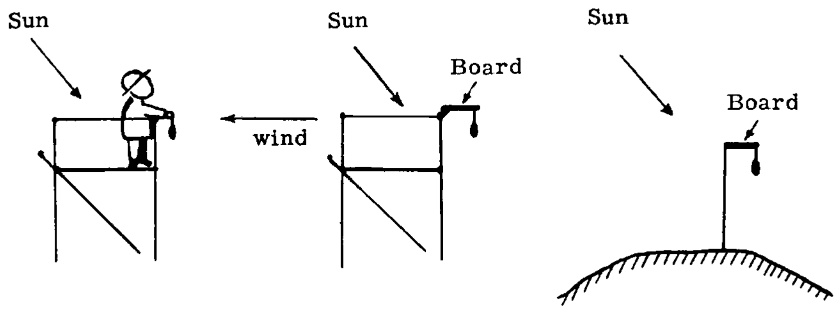


FIGURE 15

— In the case of an irregular wind, attempt to make the most of each gust to take temperatures.

— If wind is nil no accurate work can be undertaken. In any case thermometers must be swung. This requirement becomes evident if lower temperatures are obtained by swinging rather than by holding the thermometers at arm's length. But there should be no sun (early morning, late afternoon, or cloudy weather). If the weather is both sunny and windless, there is no way of obtaining correct temperatures.

— Readings should in all cases be taken rapidly, first the θ value, followed by the θ', as heat radiated by the face causes a rise in the indicated temperatures, especially in the dry thermometer. Balance can only be considered to be attained after two identical readings.

— Make sure the wet thermometer is still wet at the end of the measurement; and wet it again immediately after measurement in order that balance may be practically reached at the outset of the next measurement.

Calibration of crystal

— The 10-Mc/s crystal of the master station should be calibrated and adjusted before and after each survey.

Computations

— The *formulae* used are those indicated by the manufacturer :

$$p_v = p'_s - 0.00067\ p_a\ (\theta - \theta')$$

$$N = \frac{103.46}{T}\left(p_a + \frac{4744}{T}\ p_v\right)$$

where:

p_v :	vapour pressure	in mm Hg
p'_s :	saturation vapour pressure	»
p_a :	atmospheric pressure	»
θ :	dry bulb temperature	in °C
θ' :	wet bulb temperature	»
T :	absolute temperature 273.15 + θ)	»

— To facilitate computing, two tables have been worked out by electronic computer.

Table 1 :

Entries:
(1) Difference $\theta - \theta'$ between dry temperature θ and wet temperature θ' for successive tenths of a degree (one entry per page).
(2) Wet temperature θ', for successive degrees — linear interpolation.

For each entry, the table supplies

$$\frac{1}{2} V_0 \quad \text{and} \quad \frac{1}{2}\left|\frac{\partial V_0}{\partial p_a}\right|$$

whence half the wave velocity, in km/s:

$$\frac{1}{2} V = \frac{1}{2} V_0 - \frac{1}{2}\left|\frac{\partial V_0}{\partial p_a}\right| \times p_a$$

Table 2 enables a checking operation to be carried out.

Entries:
(1) Wet temperature θ' for successive tenths of a degree.
(2) Dry temperature θ for successive degrees — linear interpolation.

For each entry the table supplies two values λ and μ whence a *pseudo-index* ν is derived by the formula:

$$\nu = \lambda + \mu\ (p_a - 500)$$

The approximate distance d' is obtained by taking the wave velocity as V = 300 000 km/s.

The exact distance is obtained by dividing the approximate distance by the *pseudo-index* ν :

$$d = \frac{d'}{\nu}$$

Results

— Four bases were measured, maximum precautions being taken. Each measurement lasted about 10 days. Results were as follows:

Base		Tellurometer error
— Saint-Michel	(9.4 km)	+ 36 mm
— La Rochelle	(9.5 km)	+ 41 mm
— Châlons	(11.6 km)	+ 31 mm
— Crozon	(7.9 km)	+ 48 mm

It will be noted that the error varies but slightly: the maximum difference with respect to the mean (4 cm) is less than 1 cm, or 1×10^{-6}. The mean error of 4 cm was considered to be a type of instrumental calibration error, at least as regards lengths in the neighbourhood of 10 km.

This calibration error appears to be of definite significance and to be constant. The Châlons base was measured again a year later with the same instrument, and this time an error of + 28 mm instead of + 31 mm was found.

The calibration error varies by several centimetres from one instrument to the next, and principally with respect to different remotes. Comparison is easily effected, on a selected side: the two instruments are placed side by side on a board at each end of the line, and alternately used for measurement (*). Two series (one up scale and one down scale series) suffice for obtaining the calibration difference; temperatures need not be measured.

An important feature was to determine whether or not the calibration error of an instrument varies according to distance. All the measured bases were about 10 km long and we could not be sure that the error found was valid for bases of other lengths.

But no bases 20 km long or over are available in France. The solution consisted in calibrating long sides by means of the tellurometer itself, either by dividing them up into sections, or by adding a sliver triangle. (In this case possible angular errors have practically no effect.) This device is moreover the conventional method for studying length standards by means of comparators.

Several long sides between 15 and 35 km in length were thus calibrated and then measured directly, enabling 5 closure equations to be set up of the type "long side = sum of sections" or "long side = sum of projections of short sides of sliver triangle". All necessary precautions were taken for these measurements, which lasted two months.

The result is as follows : even allowing for the calibration error of + 4 cm at 10 km, the sum of the sections or projections was systematically longer than the direct measurement, by amounts varying between 4 and 16 cm.

It was believed that this might be explained by a decrease in the

(*) The *idling* instrument is set on speak and the crystal current set to zero.

calibration error according to distance. The simplest solution was to assume a linear decrease, or in other terms an error of the form 40 mm $- K\ (d - 10)$, (d in km), and to compute K by means of each closure equation.

The 5 values of K obtained were:

$$\left.\begin{array}{l} 6.2 \\ 5.9 \\ 6.7 \\ 8.4 \\ 4.3 \end{array}\right\} \text{mean } 6.3 \text{ mm/km}$$

Scatter is relatively slight (mean square error: 1.5 mm/km). This small scatter seems to indicate the constancy and accordingly the existence of a constant K not equal to zero. The calibration-error formula would hence be :

$$40 \text{ mm} - 6.3\ (d - 10),\ (d \text{ being in km})$$

for the instrument used. By applying this formula, the measurements on the long sides approach to within a few centimetres, and even along bases where the distance varies but from 7.9 to 11.6 km, application of the formula improves results.

It is not known whether the formula is valid for other instruments, but it is proposed to investigate this situation by comparing the initial instrument with others over a number of distances.

Under 8 km, four sides measuring between 4.5 km and 600 m were studied. The following results were obtained:

— Although the error due to temperature decreases in proportion to distance, scatter between series does not diminish. At 4.5 km and at 600 m it still amounts to 8 cm, as at 10 km (*); hence as many measurements as at 10 km should be made.

— The *calibration* error of the tellurometer appears to be greater than at 10 km, but no definite law became evident; it varied from 4 to 6 cm for the tellurometer used (instead of 4 cm at 10 km).

— The ground error (i.e. the error obtained when observing on the ground) may be considerable over short distances. At 3.5 km, errors were obtained between points on the ground varying from 10 cm to 20 cm according to the point sites. Observations should therefore always be made from pillars, unless the ground falls away rapidly in the direction of the line.

As regards long distances, a line 62 km long was measured without difficulty, and it is likely that the instrument can still operate satisfactorily beyond this distance. But temperature measurements then increasingly lose their significance and there is a rapid drop in accuracy. The limit beyond which scatter between series is appreciably greater than 1/150 000 is approximately 25 km in France and 40 km in the Sahara. (This difference is due to the dryness and homogeneity of the air.)

To sum up, the following errors may be assumed, provided observa-

(*) Beyond 10 km it amounts to approximately 1/150 000 of the distance.

tions are carried out during ten ½ days or so (*) and *after calibration* of the instrument:

1 to 2 cm	under 10 km
1×10^{-6}	between 10 and 25-40 km according to area
2 to 3×10^{-6} beyond.	

In ordinary work, observations usually only take place during two ½ days (preferably one evening and one morning). The above errors are then approximately doubled.

Use of instrument

In surveyed country, the obvious application is the measurement of bases or various sides. In unsurveyed country, the most rational method seems to be traverse: angles are measured by theodolites of the Wild T3 type, and sides by tellurometer. To ensure satisfactory accuracy, observations for each side should be spread out over at least two days (such as 6 valid series during the afternoon of the first day and 6 other valid series the following morning).

The only problem in the case of such traverses is closure. In secondary traversing no difficulty arises, since closure is effected at a previously known point. In primary traverse, several methods may be adopted, including:

— Double traverses which connect up every two or three hilltops or so;
— Simple traverse with chain of triangles;
— A combination of these methods. (Depending on the terrain, one method is easier than the other.)

The accuracy obtained by this method is a good as with conventional geodetic chains, or better where retention of scale is concerned. Thus, in the Sahara, length closures of the order of 1/500 000 were obtained between double traverses approximately 100 km long.

(*) By balancing, if possible, the number of mornings and evenings, each ½ day counting with its weight. Thus : two ½ days with weight 3 and four ½ days with weight 1.