"THE FIELD CALIBRATION OF INFRA–RED DISTANCE MEASURERS"

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Summary

Trinidad now possesses a facility for the field testing and calibration of electronic distance measurers (E.D.Ms.) used in cadastral and engineering surveying. Explanations are given of the theory (§2), location (§3), design (§4,§5,§6) and use (§7) of this development.

1. INTRODUCTION

The modern land surveyor would seem just as ill-equipped without his electronic distance measurer as he would without his theodolite. 'E.D.Ms' are now ubiquitous. A typical device mounts on a theodolite, and, using infra-red radiation, can measure at least 2 km to an accuracy of a few millimetres at-the-push-of-a-button'. So impressive is the specification for modern instruments that one might doubt the worth of testing them at all for common applications where lesser precision suffices. In defence of creating a testing facility, the following points may be made:

(a) The surveyor may be modern, but his E.D.M. may not be, and a device that has seen several years of service could well be out-of-adjustment.
(b) Systematic errors in distance measurement of several centimetres can occur simply through using an E.D.M. with a reflector of different make, and a correction must be determined.
(c) Uncalibrated equipment may serve satisfactorily for common applications, but one day the undetected systematic error will show up in a critical observation, such as the measurement of a bridge span.

A project to create an E.D.M. test site was launched in April 1985 by the author on behalf of the new U.W.I. Department of Land Surveying. December 1985 saw the completion of a seven-pillar calibration line at Piarco International Airport.

2. THE FIELD TESTING OF ELECTRONIC DISTANCE METERS (E.D.Ms.)

Modern E.D.M. instruments used in surveying are capable of the following 'root mean square errors' in measuring distances:

± 5 mm in resolution
± 5 mm per km, due to uncertainty in measuring wavelength.

These figures define likely random error. The three types of systematic error (Fig. 1) that may be present are:

1. Scale error, due to frequency drift.
2. Zero error, due to discrepancies between the measurement point, within instrument or reflector, and the position of mounting fixture.
3. Cyclic error, due to interference between reference and measuring signals.

In theory, if measurement 'i' is free of random error, true distance 'i' may be defined as follows:

$$\hat{D}_i = s\,D_{oi} + z + f(\Delta\,\phi) \qquad (1)$$

where $\hat{D}_i$ = true distance i

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D_{oi} = measured distance i

s = scale correction

z = zero correction

$f(\Delta\Phi)$ = a function of measuring phase difference, $\Delta\Phi$, typically + or — A sin $\Delta\Phi$, where A = amplitu cycle error.

Quantification of s, z and $f(\Delta\Phi)$ would permit the determination of a true distance from a measurement. Ran error modifies equation (1) thus:

$$\hat{D}_i = s\,D_{oi} + z + f(\Delta\Phi) + v_i \ldots\ldots$$

where v_i is the random residual in measurement 'i'.

The field testing of an E.D.M. on a multi-pillar baseline can isolate the three components of systematic error indicate likely random error in a measurement, i.e. instrumental accuracy. An early explanation of the theory was gi by Schwendener [1]. A practical approach demands initial modification of equation (2).

Firstly, scale correction, s is dropped, so that $\hat{D}_i$ is redefined as 'true distance subject to scale correction'. Sec dly, cyclic correction, $f(\Delta\Phi)$, is assumed to be small and with a properly designed test base can be considered to randomly; this latter point will be discussed in section 6. The term is therefore dropped, and any cyclic correction form part of residual v_i. Investigation of scale and cyclic errors is not overlooked, but postponed to later in the exerc

We thus have

$$\hat{D}_i = D_{oi} + z + v_i \ldots\ldots$$

The Piarco Base consists of seven co-linear instrument pillars, spaced at irregular intervals, spanning a total distan of 1.16 km. Each pillar has a standard screw thread protruding from the top capable of receiving either E.D.M. reflector, thereby forcing the device into a fixed position in space. Fixed distances can thus be measured between a two pillars. Seven pillars provide twenty-one different distances for measurement, in this case ranging from 28.4 m 1160.3 m. A calibration exercise consists of the measurement of all twenty-one possible distances with the sa E.D.M./reflector combination. The subsequent analysis of inconsistencies between observations yields estimates of ze and random error.

In equation (3), $\hat{D}_i$ and z are considered unknown, and the terms are rearranged thus:

$$(\hat{D}_i - z) - D_{oi} = v_i \ldots\ldots$$

This is the classical format for a 'least squares' adjustment of observations, whereby' best estimates' of $\hat{D}_i$ and z a obtained when the sum of the squares of the residuals is minimized. Only six distances need be specified to define t relative pillar positions, so those measured from pillar 1 to the other six pillars were deemed 'unknown' together wi the zero correction, z.

The solution of the normal equations yields the seven unknowns, from which the residual for each measureme may be found. An indication of the accuracy of the E.D.M. is the observing standard error estimated from the residual viz.

$$\sigma_o = \sqrt{\sum_{1}^{m} v_i^{\,2} / (m-n)} \ldots\ldots$$

where m = observations, i.e. 21 and

n = unknowns, i.e. 7

With the foregoing analysis complete, cyclic and scale errors are reconsidered. A measurement is based upon th exact phase difference between outgoing and incoming pattern waves. Cyclic error may be investigated provided tha the twenty-one phase differences are spread around the measuring cycle of the E.D.M. Residuals are plotted agains phase difference (or equivalent distance), whereby any significant cyclic correlation should be revealed. (Fig. 2)

Scale error determination requires a high accuracy 'standard' measurement of at least one of the longer inter-pillar stances, with which to compare the 'best estimate' of the E.D.M. under test. Unfortunately, discrepancies may also be ie to pillar movement, inaccurate temperature measurements and random error, thereby making error the most difficilt error to quantify.

SITE SELECTION

The initial determinants in the selection of a site to locate the pillars were as follows:

) Accessibility from U.W.I. to the site.
) Ground of even slope for a distance of at least 1 km.
) Minimal likelihood of disturbance from future development.
) Security for both pillars and personnel.

The international airport at Piarco seemed to offer the best prospects for meeting these requirements. The airport located about 10 km and a 20–minute drive from U.W.I. along good roads. Naturally any airport offers relatively flat ound. At Piarco there is a considerable acreage of open land on either side of the 3 km long runway. The airport mpound is surrounded by a high chainlink fence and all gates are attended by security guards. Special permits are uired by anyone wishing to enter the compound. In the light of other survey department's experiences of pillar idalism, such security would be welcome.

The manager of planning, engineering and construction at Piarco Airport was approached for permission to use a within the compound fence. Airport development plans have included construction of a new terminal building, air go and maintenance areas, and a new taxiway to the north side of runway [2], so permission was granted for an estigation of a piece of land between the runway and Caroni North Bank Road (Fig. 3) approximately 1400 m x 200 This was carried out with consideration given to:

Access to and between pillars.
Soil stability.
Ground profile, drainage and obstructions to line-of-sight.
Aircraft safety.

hicle access is provided along the length of the strip by a road inside the perimeter fence. At certain points there are ss-tracks leading to the runway, which proved especially valuable, as the presence of a batching plant prevented pillar cement close to the perimeter road.

Soil surveys had already been carried out in connection with airport development plans [2]. Test pits had been dug 000 foot intervals along both runway edges to depths of 10 feet. Typically a one foot thick top-soil of sandy silt lies ve a deep layer of silty clay, "rust brown" with "high plasticity" and "very stiff". This type of clay has high er-retaining characteristics, however it is not an expansive clay, prone to liquifying when saturated. Whilst some lement of pillars might occur, wide symmetrical footings would minimise this and tend to prevent tilting. Regarding stability, considerable comfort may be drawn from the fact that the site was chosen for an airport runway.

The questions of ground profile and aircraft safety are discussed in section 5.

PILLAR DESIGN

Each survey pillar was required to provide a stable instrument platform, featuring forced centering, from which ervations could be made comfortably from any side. Furthermore, it was intended that all pillar tops should be ically-aligned, so that all distances would be measured along the same line in space. This would necessitate varying r heights to accommodate the ground profile, and it was proposed that the height range should not exceed.

1.20 m ± 0.20 m (4 feet ± 8 inches)

A typical theodolite measures 0.24 m from base to trunnion axis, so the range of observing heights would be

1.44 m ± 0.20 m (4'9" ± 8")

was considered comfortable for the majority of people.

Steel pipes 340 mm in diameter donated by Amoco Oil Co. formed the basis for a pillar. Steel was preferred to concrete, as the pipes could initially be cut to lengths greater than required, set in the foundation holes, and then cut t a calculated level to align the tops (Fig. 4).

A reinforced concrete pedestal surrounding the pillar was built which in combination with the blinding laye should prevent tilting, as well as providing dry hard — standing for observers.

The instrument fixture was located in wet concrete in the pipe. This consisted of a circular aluminium plate screwed down onto the thread of a section of ranging pole. The thread protruded through the plate to take a standard instrument tribrach. Anchorage in the concrete was provided by rods set in plate and ranging pole (Fig. 4).

5. ALIGNMENT AND 'COARSE' SPACING

Constraints on the approximate positioning of the pillars could be stated as follows:

(a) Safety regulations stipulated that no solid structure should be constructed within 500 feet (152.4 m) of the runway centreline and also a 'safe' distance from a helicopter pad at the western end of the site.
(b) The tops of pillars should be vertically-aligned and intervisible, whilst not exceeding the pillar height range of 1.2 m ± 0.2 m.
(c) Access to pillars should be optimised.
(d) The 21 inter-pillar distances should be evenly distributed to a maximum of about 1 km and incorporate bays of 30m, 50 m and 100 m for measuring tape standardisation.

A site survey established that the line could be placed midway between runway edge and the perimeter road, just to the north of some old soil and gravel tips (Fig. 5) A ground profile surveyed in the vicinity (Fig. 6) served as a basis for deciding pillar spacing. It showed that the ground surface remained within ± 0.25 m of a line of constant slope for a distance of 1.2 km with the exception of a 1.5 m deep depression between chainages 1 + 75 and 5 + 50. Vehicle access was available at chainages 0 + 00, 9 + 20 and 11 + 90. The positions decided (Fig. 6) exploited these features and gave the following approximate spacings:

PILLAR	COARSE INTER—PILLAR DISTANCE (m)					
1						
	50					
2		150				
	100		545			
3		495		890		
	395		840		1135	
4		740		1085		1165
	345		985		1115	
5		590		1015		
	245		620			
6		275				
	30					
7						

Not only does this configuration enable E.D.M. testing over a veriety of ranges up to 1165 m, but also it provides suitable short distances for tape standardisation.

6.'FINE' SPACING

Having determined the approximate spacing of the pillars, a separate exercise was conducted to fix the 'exact' spacing with a quite different criterion — that of the effect of possible cyclic error.

As discussed in section 2, cyclic error is systematically related to phase difference, $\Delta\phi$, or the 'surplus distance over a multiple of the measuring unit'. For example, when a distance of 78.5 m is measured with an E.D.M. using a 10 m unit, the 'surplus distance' is 8.5 m, and $\Delta\phi = 0.85$ of a cycle. With a 5 m unit, surplus = 3.5 m and $\Delta\phi = \frac{3.5}{5}$ cycles = 0.7 cycles.

In section 2, it was assumed that any cyclic error would have an approximately random effect in the least squares analysis. For this to be so, the pillar spacings must be finely adjusted to meet two requirements:

(a) A set of 21 phase differences evenly spread over one cycle when using any common measuring unit, viz:

10 metres, e.g. Modern Aga and Kern instruments
5 metres, e.g. Aga Geodimeter 6
2 metres, e.g. Tellurometer MA100

This ensures that cyclic error in the distances is not predominantly positive or negative thereby biasing the determination of zero error. It also enables inspection of residuals over the full cycle in establishing the existence of cyclic error.

(b) No correlation between surplus distance and overall distance. If a correlation exists, error would appear cyclic when plotted against overall distance. Analysis will interpret this as the combined effect of zero and scale error, thereby distorting the determination of both (Fig. 7).

It was the computer that provided a set of surplus, or 'fine', distances to meet these requirements. Random combinations of six distances between 0 and 10 metres were generated. The 21 fine distances (within 2—, 5— and 10—metre ranges) resulting from each combination were calculated. A 'perfect spread' would give a straight line when the distances are plotted in order of size. Each set of fine distances was tested by calculating the sum of the squared departures from the perfect distribution (Fig. 8). A total of 310 random combinations were investigated in this way, and one selected on the basis of having 'significantly lower-than-average' correlation indices.

In the light of this computer search, inter-pillar distances were set out as follows:

PILLAR	PRECISE INTER—PILLAR DISTANCE (m)					
1						
	47.52					
2		145.55				
	98.03		541.23			
3		493.71		887.27		
	395.68		839.75		1131.92	
4		741.72		1084.40		1160.34
	346.04		986.37		1112.82	
5		590.69		1014.79		
	244.65		619.11			
6		273.07				
	28.42					
7						

7. FIELDWORK AND RESULTS

Electro-optical distance measurements on the base are accompanied by observations of air pressure and temperature, in order to calculate refractive index and hence a scale correction for atmospheric conditions. An aneroid altimeter, reading to 5 feet is used to measure pressure. A pressure change equivalent to 100 feet will only alter a distance measurement by 1 mm in 1 km. Temperature recording is more critical. The same effect upon distance measurement, 1 p.p.m.), results from a temperature change of only 1°C. Thus it is standard practice to read thermometers at both ends of a bay being measured.

Both the atmospheric corrections and the adjustment of distance observations are carried out by computer. Two

E.D.Ms. belonging to U.W.I. have each been calibrated three times. Agreements between different calibrations of th same instrument have been good. Taking one example of each:

The Wild D14L instrument returned a small constant (—10.4 mm) and an implied accuracy of ±6. 7 mm whic agrees with expected figures quoted in section 2 (Table 1).

The Aga 220 instrument appeared to be faulty from the initial analysis (Table 2). Of particular concern was th accuracy of only ±18.5 mm, well outside specification. However, when it was noticed that agreement between th observations taken in different exercises was very good, suspicions arose regarding the validity of the results. Comparison was made between the Aga 220 observations and adjusted distances derived from the Wild D14L calibration

(Table 3). A very striking pattern emerges. With the exception of the five ranges over 1000 m, differences are very similar suggesting a true additive constant of about —38 mm. The exceptions average +21 mm, a difference of 59 mm.

The five suspect observations were omitted from the adjustment, resulting in a dramatic improvement in results (Table 4). The new constant of —34.5 mm may be largely due to using a Wild reflector with the Aga E.D.M., rather than maladjustment. The accuracy of ±3.4 mm now betters the Wild D14 L. Clearly the instrument is performing within specifications.

What caused a shift of about 59 mm in five of the 21 observations? It was suspected that in these cases, part of the signal was reflecting off the top of an intervening pillar, thereby interfering with the direct ray, and causing a spurious phase shift. The Aga 220 has a wider cone of signal propagation than the Wild D14L, namely 25 cm width at 100 m, as against 12 cm width at 100m. This characteristic does appear to open the possibility of reflections from pillar 4 in particular (Fig. 9).

Rayleigh's Criterion holds that a surface will reflect radiation if the 'depth of roughness',

$$R < \frac{3.6\ \lambda}{\Theta}$$

where λ = wavelength of light, and

Θ = incident angle in degrees [3].

In this case, $\lambda = 9.1 \times 10^{-4}$ mm and $\Theta \simeq 0.03°$

$\therefore$ For reflection to occur, $R < 0.1$ mm

Thus the aluminium plate in the pillar top may well be flat enough to cause reflections.

The theory had to be tested, and a permanent solution found. In fact, this came by 'hooding' pillars with rough sacks, a perfectly convenient solution (with the added advantage of protecting the pillar tops from bird droppings!).

8. CONCLUSION

It is expected that the Piarco Base will provide a focus for calibration work and research into measurement science. For professional surveyors to engage in high accuracy work, such as structural and seismic monitoring, and industrial metrology, instrument calibration is vital; the means is now available. For students of surveying, the methodical field operation of measurement instruments will be encouraged at the Base, where, with computer support, performances of operator and device are most clearly perceived.

In the future, satellite position fixing with sub-centimetre resolution will replace much terrestrial measurement. Will this mean an end to the usefulness of the base? The site survey of the distant future may involve the fixing of every detail point by satellite methods, thereby removing distance measurement, but in the mean time the expectation is that just the control points on the site will be 'satellite-fixed' whilst detail will still be surveyed by electronic theodolite and E.D.M. [4]. High precision E.D.M. with sub-millimetre capability will certainly not be replaced for a very long time. Recent developments such as the Com-Rad Geomensor and Kern Mekometer ME5000 illustrate the healthy interest in this field. The resolution of satellite positioning methods could actually be tested at the Base in the future, when accuracies demand the precise location of the receiver in space for testing.

Other applications for the pillars are under consideration. In the field of research, some of the possibilities are:

(a) the measurement of light path curvature through the atmosphere under tropical conditions for comparison with current theories on the relationship to vertical temperature gradient [5].
(b) a comparison of techniques for precise distance measurement up to 150 m, e.g. E.D.M., precise taping, subtense bar, for application in precise setting-out, structural monitoring and industry.
(c) the calibration of a north-seeking gyro owned by U.W.I. from a precise astronomic determination of the geographical azimuth of the Base.

E.D.M. CALIBRATION: WILD DI 4L/ Wild circ.

OBSERVED DISTANCES	(metres)	RESIDUALS (mm)
1 to 2	47.5304	—.4
1 to 3	145.5722	—8.0
1 to 4	541.2327	+1.8
1 to 5	887.2702	+11.5
1 to 6	1131.9349	—4.2
1 to 7	1160.3439	—.6
2 to 3	98.0541	—9.5
2 to 4	493.7134	+1.5
2 to 5	839.7547	+7.4
2 to 6	1084.4096	+1.5
2 to 7	1112.8250	—1.3
3 to 4	395.6823	—1.7
3 to 5	741.7300	—2.2
3 to 6	986.3851	—8.3
3 to 7	1014.7948	—5.4
4 to 5	346.0572	+.4
4 to 6	590.7051	+1.5
4 to 7	619.1194	—.2
5 to 6	244.6506	+8.8
5 to 7	273.0636	+8.4
6 to 7	28.4238	—.8

(21 OBSERVATIONS)

ADJUSTED DISTANCES	(metres)
1 to 2	47.5196
1 to 3	145.5538
1 to 4	541.2241
1 to 5	887.2713
1 to 6	1131.9203
1 to 7	1160.3329

ADDITIVE CONSTANT	—10.4 mm
STANDARD ERROR OF OBSERVATIONS	6.7 mm
STANDARD ERROR OF CONSTANT	3.0 mm
STANDARD ERROR OF DISTANCE 1 TO 7	6.2 mm

Table 1

E.D.M. CALIBRATION: AGA 220 / Wild circ.

OBSERVED DISTANCES	(metres)	RESIDUALS (mm)
1 to 2	47.5626	+13.1
1 to 3	145.5826	+4.6
1 to 4	541.2602	−13.6
1 to 5	887.3111	−22.7
1 to 6	1131.9027	+13.9
1 to 7	1160.3096	+4.7
2 to 3	98.0640	+6.2
2 to 4	493.7365	−6.9
2 to 5	839.7897	−18.3
2 to 6	1084.3759	+23.8
2 to 7	1112.7891	+8.3
3 to 4	395.7070	+11.2
3 to 5	741.7592	+.8
3 to 6	986.4126	−24.3
3 to 7	1014.7628	+23.2
4 to 5	346.0781	+22.5
4 to 6	590.7376	−8.7
4 to 7	619.1496	−23.0
5 to 6	244.6886	−1.5
5 to 7	273.1010	−16.2
6 to 7	28.4534	+3.1

(21 OBSERVATIONS)

ADJUSTED DISTANCES	(metres)
1 to 2	47.5169
1 to 3	145.5284
1 to 4	541.1878
1 to 5	887.2296
1 to 6	1131.8578
1 to 7	1160.2555

ADDITIVE CONSTANT	−58.8 mm
STANDARD ERROR OF OBSERVATIONS	18.5 mm
STANDARD ERROR OF CONSTANT	8.3 mm
STANDARD ERROR OF DISTANCE 1 TO 7	17.3 mm

Table 2

	WILD D14L ADJUSTED DISTANCES (m)	AGA 220 OBSERVED DISTANCES (m)	DIFFERENCE (mm)
1 to 2	47.5196	47.5626	−43.0
1 to 3	145.5538	145.5826	−28.8
1 to 4	541.2241	541.2602	−36.1
1 to 5	887.2713	887.3111	−39.8

1 to 6	1131.9203	1131.9027	+17.6
1 to 7	1160.3329	1160.3096	+23.3
2 to 3	98.0342	98.0640	−29.8
2 to 4	493.7045	493.7365	−32.0
2 to 5	839.7517	839.7897	−38.0
2 to 6	1084.4007	1084.3759	+24.8
2 to 7	1112.8133	1112.7891	+24.2
3 to 4	395.6703	395.7070	−36.7
3 to 5	741.7175	741.7592	−41.7
3 to 6	986.3665	986.4126	−46.1
3 to 7	1014.7791	1014.7628	+16.3
4 to 5	346.0472	346.0781	−30.9
4 to 6	590.6962	590.7376	−41.4
4 to 7	619.1088	619.1496	−40.8
5 to 6	244.6490	244.6886	−39.6
5 to 7	273.0616	273.1010	−39.4
6 to 7	28.4126	28.4534	−40.8

Table 3

E.D.M. CALIBRATION: AGA 220 / Wild circ.

OBSERVED DISTANCES	(metres)	RESIDUALS (mm)
1 to 2	47.5626	−4.1
1 to 3	145.5826	+3.5
1 to 4	541.2602	+1.4
1 to 5	887.3111	−.8
1 to 6	NO OBSERVATION	
1 to 7	NO OBSERVATION	
2 to 3	98.0640	−1.9
2 to 4	493.7365	+1.1
2 to 5	839.7897	−3.4
2 to 6	NO OBSERVATION	
2 to 7	NO OBSERVATION	
3 to 4	395.7070	+3.0
3 to 5	741.7592	−.5
3 to 6	986.4126	−.9
3 to 7	NO OBSERVATION	
4 to 5	346.0781	+5.1
4 to 6	590.7376	−1.5
4 to 7	619.1496	+1.9
5 to 6	244.6886	−1.2
5 to 7	273.1010	+1.7
6 to 7	28.4534	−3.6

(16 OBSERVATIONS).

ADJUSTED DISTANCES (metres)

1 to 2	47.5240
1 to 3	145.5516
1 to 4	541.2271
1 to 5	887.2758
1 to 6	1131.9287
1 to 7	1160.3440

ADDITIVE CONSTANT	—34.5 mm
STANDARD ERROR OF OBSERVATIONS	3.4 mm
STANDARD ERROR OF CONSTANT	2.1 mm
STANDARD ERROR OF DISTANCE 1 TO 7	6.1 mm

Table 4

REFERENCES

1. SCHWENDENER, H.R., Electronic Distancers for Short Ranges: Accuracy and Checking Procedures, Survey Review, Vol. 21 No. 164, 1972.
2. PHELPS, H.O., DENNIS, R.A. and TAYLOR, L.O., Piarco International Airport Development Study 1972—1990, 1972.
3. BURNSIDE, C.D., Electromagnetic Distance Measurement, Second edition, 1972.
4. COOPER, M., New Instrumentation: an End to Survey Observations?, Land and Minerals Surveying, Vol. 4, No. 4, 1986.
5. DODSON, A. H. and ZAHER, M., Refraction Effects on Vertical Angle Measurements, Survey Review, Vol. 28, No. 217, 1985.

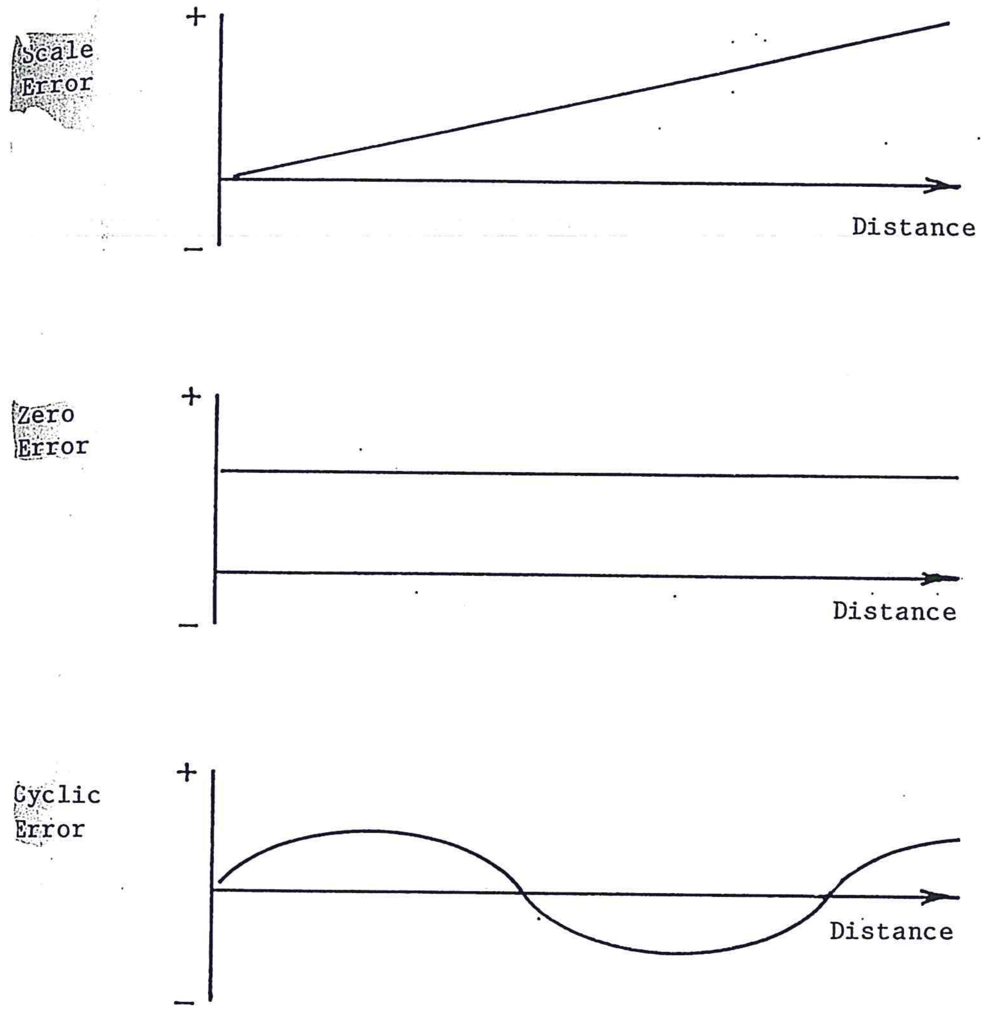

Fig. 1 Systematic errors in E.D.M.

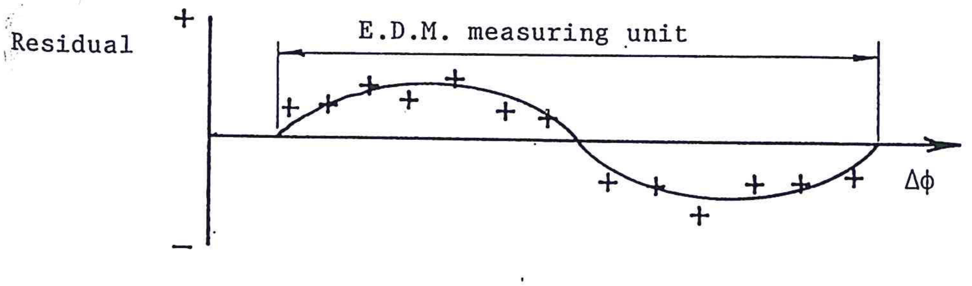

Fig. 2 Cyclic error revealed by plotting residuals

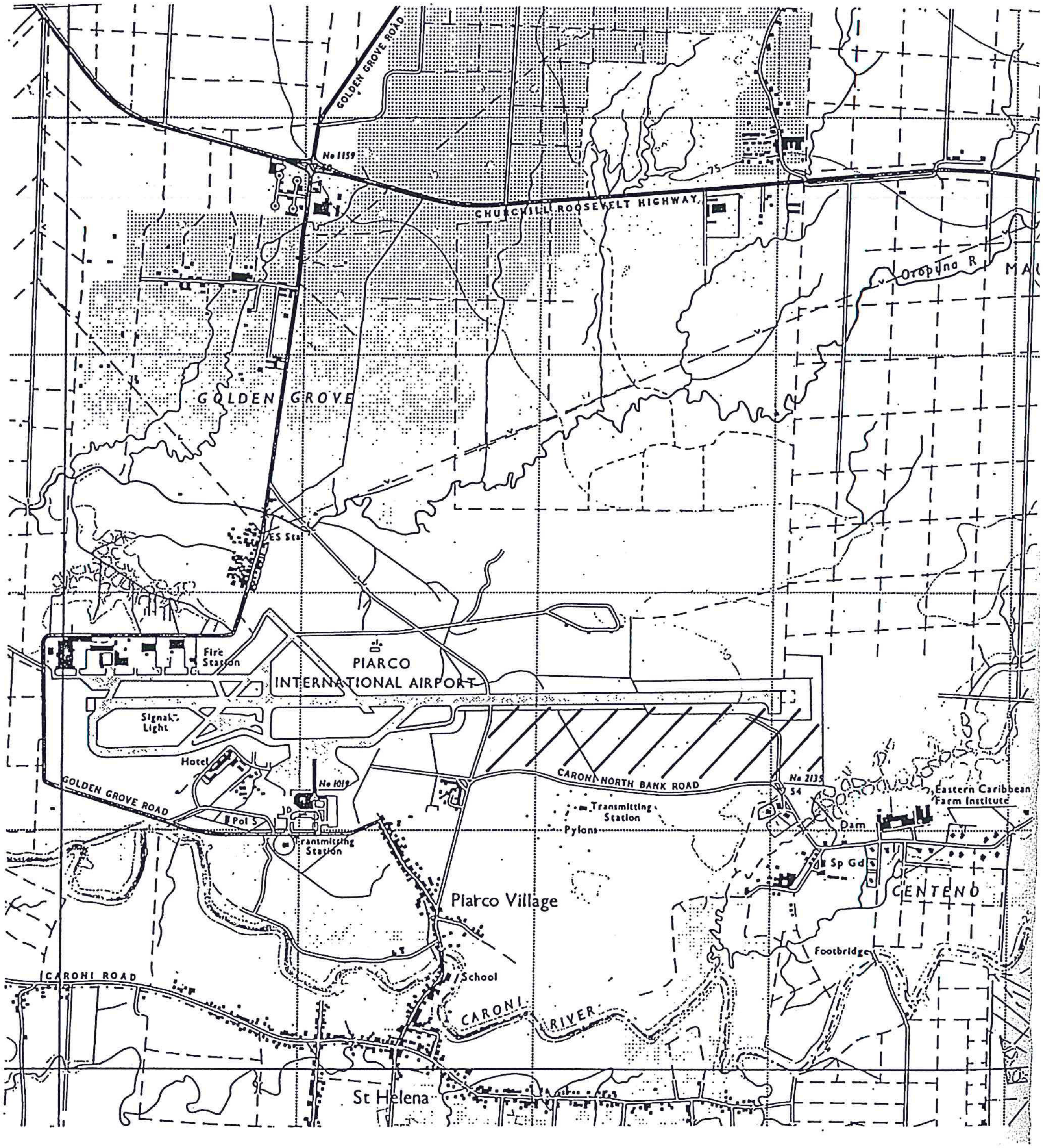

Fig. 3 Site for calibration base (shaded)

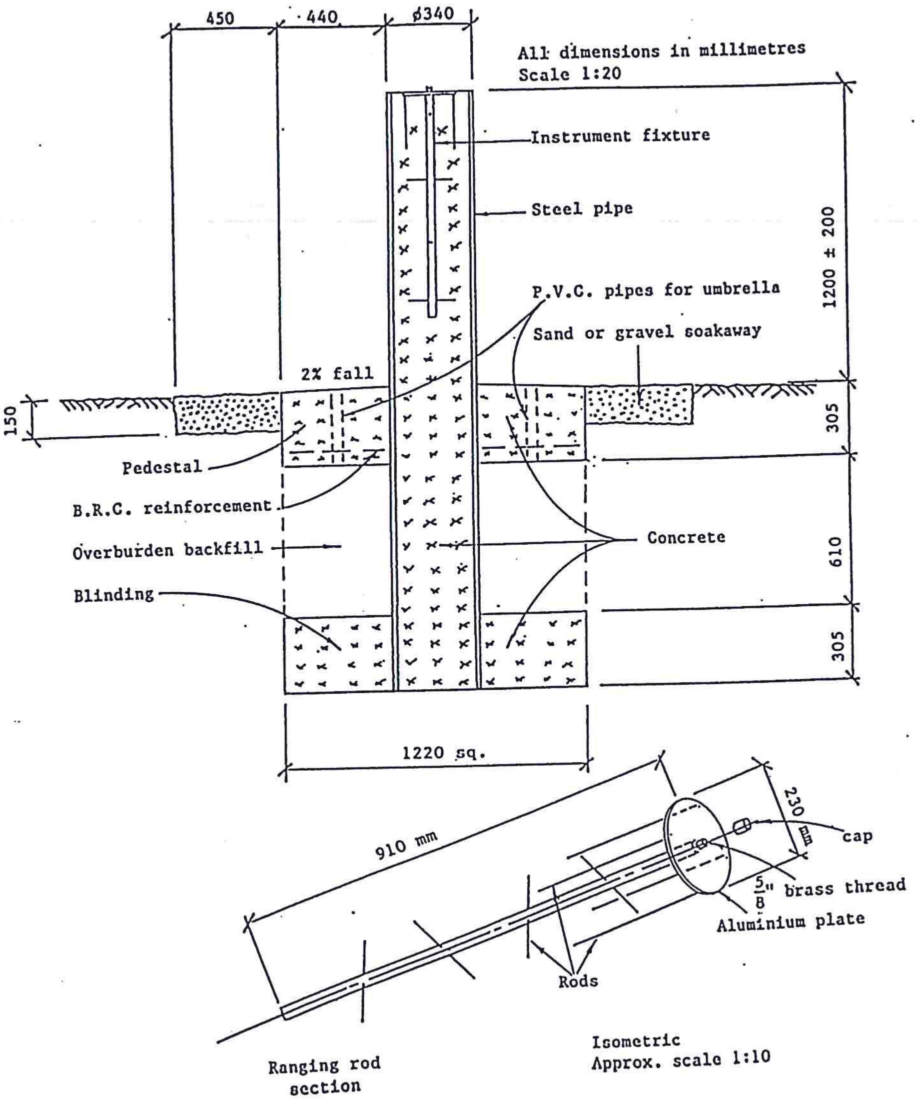

Fig. 4 Pillar cross-section and instrument fixture.

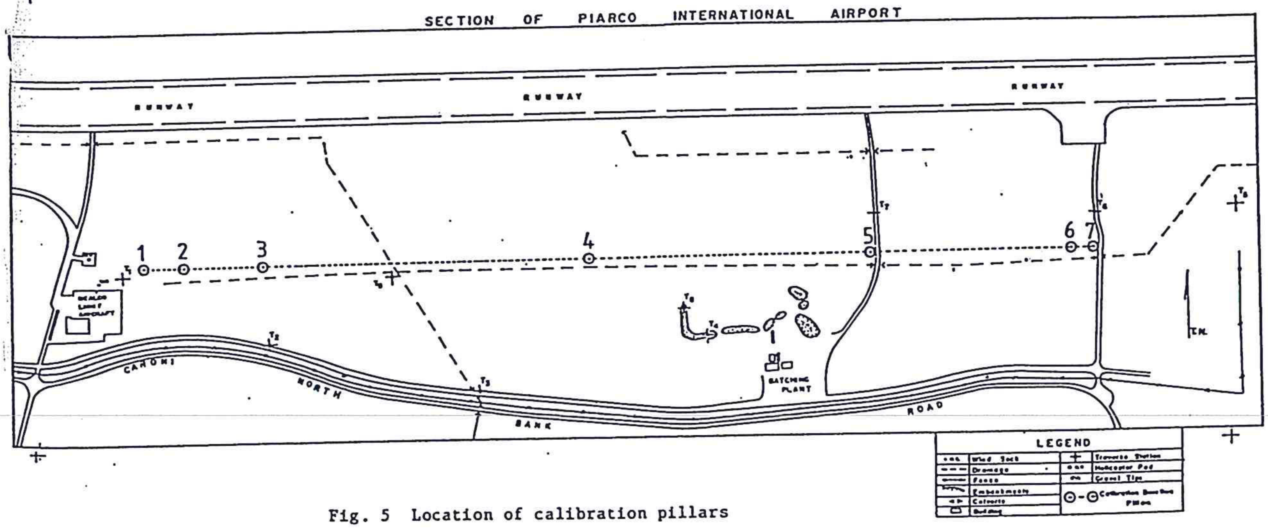

Fig. 5 Location of calibration pillars

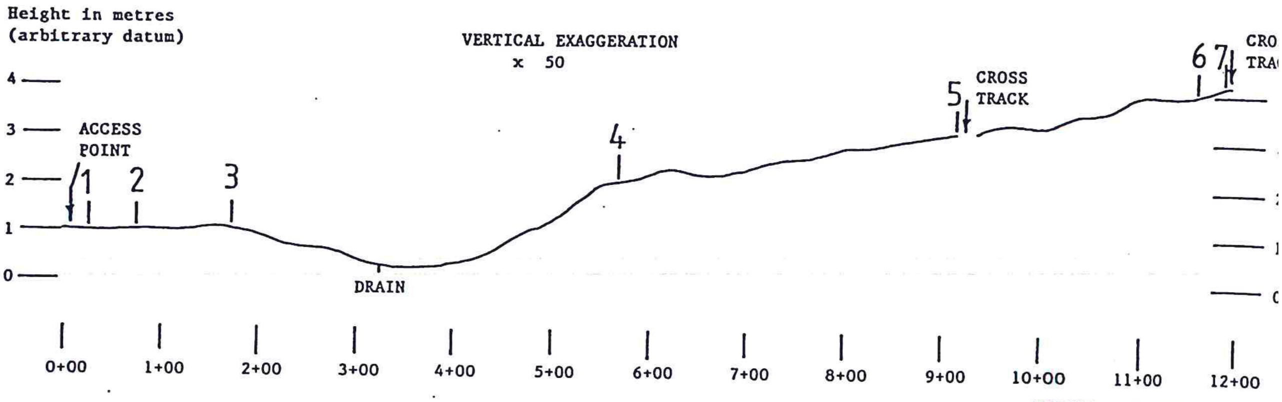

Fig. 6 Ground profile and pillar positions (numbered)

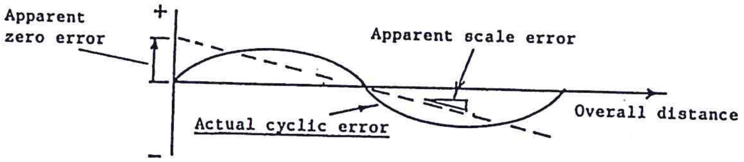

Fig. 7 Effect of correlation between fine and overall distance

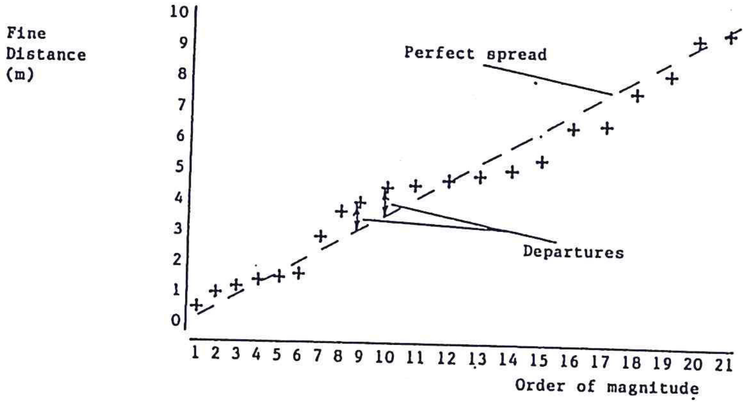

Fig. 8 Distribution of fine distances in a 10-metre range

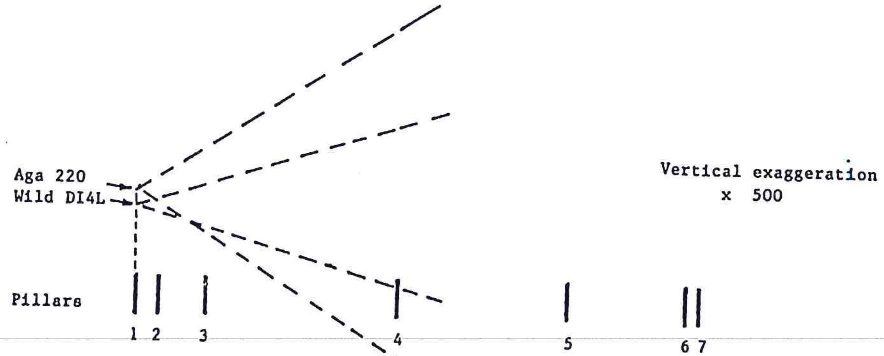

Fig. 9 Signal propagation cones for Wild DI4L and Aga 220