DEPARTMENT OF
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Record 1976/46

BAROMETRIC LEVELLING TEST SURVEY USING "MECHANISM LTD" PRECISION ANEROID BAROMETERS, TYPE M2236/A MK-II SERIAL NOS 260, 261, 262, 263, 264 & 265, A.C.T., 1973

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SUMMARY

A barometric levelling test survey was carried out in the Canberra environs, using six new "Mechanism Ltd" Precision Aneroid Microbarometers, in two banks of three. 160 sets of readings were made at optically levelled bench-marks in 17 loops run on 6 different days under a variety of weather conditions.

The six barometers were used to produce ten elevation measurements, one using the mean reading from each bank of three barometers, and nine using the barometers separately. This gave 1600 elevation measurements and errors for the whole survey. The spread between the nine separate measurements was usually about three times the R.M.S. error. The best pair of barometers gave an overall R.M.S. error of 2.2 m for the survey, whereas the worst gave 2.8 m. Using the averaged value from each bank of three barometers gave an overall R.M.S. error of 2.3 m. Use of a modified reduction formula containing a 3% correction factor to remove a systematic elevation error gave an overall R.M.S. error of 1.3 m.

The results show that the accuracy of barometric levelling is particularly dependent on weather conditions. Best results were obtained on heavily overcast, calm days. The use of field temperatures in the reduction formula gave better results than did base temperatures. The difference between field and base temperatures generally correlates with errors caused by atmospheric pressure fluctuations, and with wind speed, and is therefore a good indicator of barometric levelling accuracy.

INTRODUCTION

A barometric levelling test survey was made in the ACT in 1973 to determine the operating characteristics of microbarometers, and to investigate the nature of barometric levelling errors. Broad recommendations for conducting an experimental barometric survey over known elevation ranges were made by Darby (1970) following an analysis of barometric levelling errors in reconnaissance helicopter gravity surveys.

The purchase by the BMR of six new "Mechanism Ltd" Precision Aneroid Barometers, Type M2236/A MK-11, Serial Nos 260, 261, 262, 263, 264, and 265, provided an opportunity to conduct a test survey. The new design and particularly the excellent working order of these barometers promised to provide reliable data on the accuracy of barometric levelling, and the nature of errors inherent to it. Over six days, in January and February, 160 optically levelled bench-marks were occupied in 17 loops within a 30 km radius of Canberra (Plate 1). The errors in barometric levelling obtained were plotted against time, temperature, and height interval to detect any relations which may exist. The weather and ground environment were also taken into consideration, with coefficients being assigned for wind speed, cloud cover, and distance to water.

SURVEY PROCEDURE

The six barometers were used in two banks of three, one bank at the base, and one for the field readings. Wet and dry temperatures were recorded at the base and in the field. The base barometers and thermometers were read at 10-min. intervals by one observer, and the field barometers and thermometers were read at bench-marks by a second observer travelling by vehicle.

Measurements were made in 17 loops of up to 2 hours duration within a 30 km radius of the city centre. A total of 160 bench-marks were occupied over 6 days, and a wide range of weather and environmental conditions together with varied combinations of elevation, distance, and time effects were experienced.

Reduction of data and plotting of errors was done using the CSIRO CDC 3600 computer. The barometric-to-elevation reduction formula of Clark (1953), converted to the metric system, was used.

$$H = 18400 (\log P_1 - \log P_0) \times A \times B$$

where:

H is the height interval in metres

$$A = \left(1 + 0.00264 \cos 2\phi + \frac{h_1 + h_2}{R} + \frac{3P}{8pm}\right)$$

$$B = (1 + 0.003665\ tm)$$

P_0 and P_1 are the barometric pressure readings (units not important).

ϕ is the mid-latitude of the stations.

R is the radius of the earth in metres (6.37×10^6).

h_1 and h_2 are the approximate elevations of the stations above sea level

tm is the mean air temperature

pm is the mean atmospheric pressure

P is the water vapour pressure

P = Pw - 0.00081 pm (td - tw) where td and tw are readings on the dry and wet bulbs of the hygrometer in centigrade and Pw the saturation pressure of the water vapour (in the same units as pm) at td.

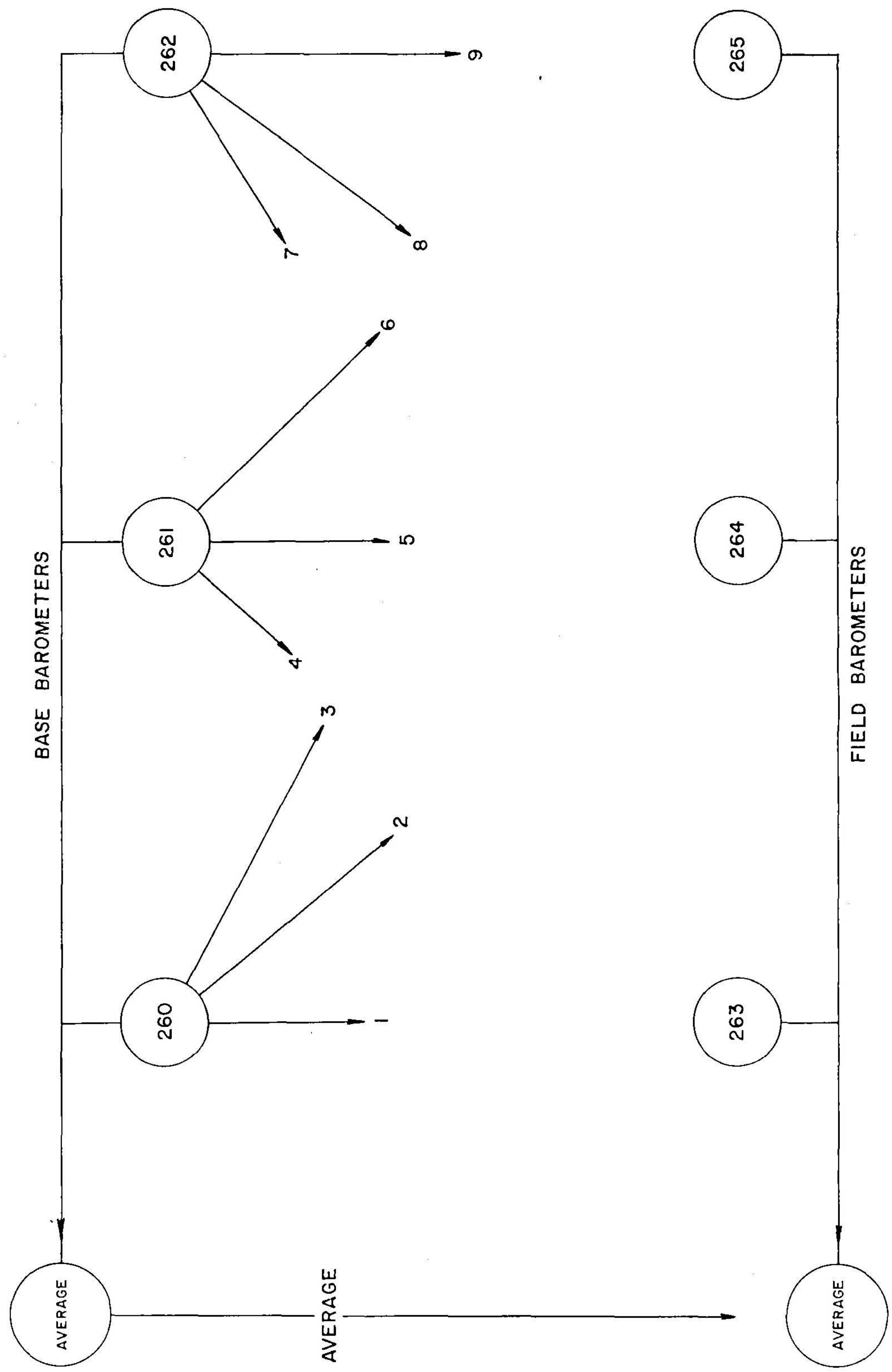
Ten elevation measurements were obtained for each bench-mark occupied, nine from the separate barometer readings, and one from the mean reading from each set (Fig. 1). Ten error values were therefore obtained for each bench-mark occupied. The errors for each loop separately, and for all the loops combined were studied in order to determine the effect on the accuracy of barometric levelling of the following parameters:

Duration of loop
Distance from base
Height interval measured
Wind intensity and cloud cover (estimated by observers)
Water proximity
Field and base temperatures.

SURVEY RESULTS AND STATISTICS

The overall survey results, showing the errors in metres for the mean and nine separate barometer readings and the effect of redistributing loop misclosure with respect to time are shown in Table 1. Survey statistics for Loops 1 to 17 are given in Table 2.

FIGURE 1



DERIVATION OF THE MEAN AND NINE COMBINATIONS OF SEPARATE PRESSURE DIFFERENCES FROM TWO SETS OF THREE BAROMETERS (BAROMETERS 260-265 USED)

TABLE 1. OVERALL SURVEY RESULTS
(MEAN OF FIELD AND BASE TEMPERATURES USED IN THE REDUCTION).

LOOP MISCLOSURES NOT REDISTRIBUTED WITH TIME

BAROMETER COMBINATION	1	2	3	4	5	6	7	8	9	10
MAXIMUM ERROR(m)	-12.8	-10.3	-11.3	-13.3	-10.8	-11.9	-13.3	-10.8	-11.9	-11.8
R.M.S. ERROR (m)	2.8	2.3	2.6	2.7	2.2	2.5	2.9	2.3	2.7	2.4
MEAN ERROR (m)	-1.4	-.6	-.8	-1.5	-.7	-.9	-1.6	-.9	-1.0	-1.0

LOOP MISCLOSURES REDISTRIBUTED WITH TIME

BAROMETER COMBINATION	1	2	3	4	5	6	7	8	9	10
MAXIMUM ERROR(m)	-11.3	-9.9	-11.0	-11.8	-10.4	-11.5	-11.5	-10.0	-11.2	-11.0
R.M.S. ERROR (m)	2.6	2.2	2.4	2.5	2.2	2.4	2.8	2.6	2.6	2.3
MEAN ERROR (m)	-1.2	-.9	-.8	-1.3	-1.0	-.8	-1.4	-1.2	-1.0	-1.1

TABLE 2. SURVEY STATISTICS

(ERRORS SHOWN ARE FROM MEAN BAROMETER READINGS).

RESULTS \ LOOP NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Number of Readings	9	10	5	10	9	5	8	11	15	16	7	16	5	7	8	9	10
Loop Duration (hr)	1.0	1.2	1.2	1.1	1.3	1.0	1.1	1.0	1.8	1.7	0.7	1.6	0.7	0.5	1.0	0.8	1.8
Maximum Distance from Base (km)	7	5	10	8	5	5	7	10	20	20	7	15	7	10	15	30	30
Maximum Height Interval Measured in Loop (m)	280	11	280	-16	-1	-1	-140	65	106	66	-16	65	280	-16	250	60	60
Mean Height Interval Measured in Loop (m)	54	5	170	7	1	1	85	27	38	21	7	32	140	7	65	32	26
Maximum Error (m)	-9.9	-3.0	-5.1	-2.6	-2.2	-2.2	4.7	-3.3	-4.4	-2.8	-1.4	-2.7	-11	-1.2	-5.9	-1.4	-3.9
Maximum Spread in Errors (m)	5	4	5	3	3	3	4	3	7	4	5	4	4	1.5	1.5	1.5	1.8
Mean Loop Error (m)	-1.9	-0.4	-3.0	0	-0.7	-0.4	2.2	-1.6	-3.0	-0.6	-0.2	-1.7	-5.3	0.3	-1.6	-0.1	-1.9
R.M.S. Loop Error (m)	3.8	1.5	3.6	1.2	1.1	1.2	2.6	1.9	3.7	1.5	1.0	1.7	7.7	0.6	2.9	0.5	2.2
Wind Strength (%) (Very Gusty = 100%)	50	50	25	25	50	75	25	80	80	30	40	50	50	25	25	25	50
Cloud Cover (%)	75	75	25	0	25	50	50	80	70	80	80	50	50	100	100	100	50
Nearest Water (km)	0.5	0.5	0.5	7	0	0	5	5	15	10	7	20	0.5	20	20	20	6

ANALYSIS OF RESULTS

The following analysis of the barometric levelling results is based on the data compiled in Tables 1-5 and plotted in Plates 2-11.

The errors in each loop

The errors in Loops 1-16 are shown plotted against time in Plates 2-9. One of the nine separate error plots is drawn as a continuous line. The graphs demonstrate the amount of spread amongst the separate barometer errors, the variation in the spreads, the overall pattern of errors within the loops, and the amount of misclosure. For loops run over level ground, the pattern of errors is exclusively the result of random fluctuations in pressure, registered separately by the base or field barometers. For loops run over hills, the errors include a systematic error in height measurement.

Magnitude of spread in the separate barometer errors

The magnitude of spread in the separate barometer errors shows the inherent inaccuracy when levelling with only a single pair of barometers. The maximum amount of spread ranges from 1.5 m in Loop 14 to 7.0 m in Loop 9. The spreads are the result of limited meter sensitivity, different readout by the different meters for the same pressure, fluctuations in pressure during the reading of the banks of 3 barometers, and to a lesser extent, operator error.

There are indications that the amount of spread and the size of errors vary with weather conditions. Table 2 shows that the two loops with the lowest Root Mean Squares (R.M.S.) errors, Loops 14 and 16, had the lowest maximum spread values, and that these loops were run in calm, heavily overcast weather. Conversely, Loop 9, which was run in very gusty conditions, has the largest maximum spread value and a large R.M.S. error.

Loop misclosures

The loop misclosures can be seen in Plates 2-9 as the errors for the last reading in each loop. They are generally less than 1.0 m, and when redistributed throughout a loop on a time basis usually decrease the overall loop error slightly. The results in Table 1 show that redistributing the misclosure decreased the whole survey R.M.S. and maximum errors for each combination of barometer pairs. However, it is also possible to slightly increase the errors in a loop by this procedure, as occurred in Loops, 7, 8 and 14. In general, the effect of redistributing misclosure error is small, testifying to the sensitivity of the barometers used, and the lack of hysteresis in their mechanisms. This suggests that the spread in the separate barometer errors is due more to pressure fluctuations than meter sensitivity.

Duration of loops

Loop duration varied from 0.6 to 1.8 hr, but no correlation is observable in Table 2 between R.M.S. error or loop misclosure with duration. The longest duration loops, Loop 9 (1.8 hr), Loop 10 (1.7 hr), Loop 12 (1.6 hr), and Loop 17 (1.8 hr) had R.M.S. errors of 3.7, 1.5, 1.7, and 2.2 m respectively, and the shortest duration loops, Loop 13 (0.7 hr) and Loop 14 (0.5 hr) had R.M.S. errors of 7.7 and 0.6 m respectively.

Distance effect

Stations were occupied at distances of up to 30 km from their bases, but no relationship of error with distance from base was observable. Loop 16 extended 30 km from its base, but produced very small errors.

Elevation effect

There is a marked relation between error size and the height interval measured, as previously observed by Darby (1970). The current results are shown in Plate 10. The errors plotted include random pressure fluctuation errors as well as elevation errors, but a line of best fit can be drawn with the equation Error = -0.03 x Height Interval which is in agreement with Darby's estimates. This 3% linear error associated with the height interval probably derives from the mathematics of the reduction formula, as it is the same for different types of barometers. It could be removed by introducing a 3% compensating factor into the reduction formula as follows:-

$$H = 18400 (\log P_1 - \log P_o) \times A \times B \times 0.97.$$

Re-processing the survey data using this formula gave a significantly better result, particularly for loops in which large height intervals were measured. For example, in Loop 1, the maximum error was decreased six-fold and the R.M.S. error four-fold. The overall survey result improved considerably as shown in Table 3.

TABLE 3. EFFECT OF INTRODUCING A 3% CORRECTION FACTOR INTO THE REDUCTION FORMULA.

	Standard formula	Modified formula
Maximum error (m)	-11.0	4.3
R.M.S. error (m)	2.3	1.3
Mean error (m)	-1.1	-0.3

The effect of applying the 3% correction is particularly evident in the values of mean error in Table 3. Use of the modified formula caused a reduction in the mean error from -1.1 m to -0.3 m, signifying the almost total elimination of the persistent systematic elevation error from the survey results.

Wind and cloud effect

The results in Table 2 show that heavily overcast, calm weather conditions prevailed on those days when the most accurate survey results were obtained. Loops 7, 14, 15, and 16 have noticeably lower R.M.S. and maximum errors than other loops with comparable average heights. Loops 14, 15, and 16 also have amongst the largest maximum distances from base, and are not connected to their bases. This demonstrates that under still, heavily overcast weather conditions, pressure conditions are exceptionally stable over distances of at least 30 km, and conditions for barometric levelling are at an optimum. Conversely, windy, sunny days appear to be worst for barometric levelling.

Water effect

The presence of water in the immediate vicinity of the base or field barometers would be expected to cause local thermal disturbances, and adversely affect barometric levelling accuracy. Loops 5 and 6 were both measured around Lake Burley Griffin, but gave very moderate R.M.S. errors of 1.1 and 1.2 m. This result suggests that local bodies of water do not necessarily cause large pressure fluctuations in the vicinity of their perimeters.

Loop and base connections

The survey results show that it is not absolutely necessary to start and end a loop at the location of the base barometers. Ten-km separations between base and nearest loop stations did not result in noticeably worse R.M.S. errors for Loops 8, 14, 15, 16, and 17.

TABLE 4. OVERALL SURVEY RESULTS SHOWING THE ERRORS OBTAINED USING BASE AND FIELD TEMPERATURES SEPARATELY.

REDUCTIONS MADE USING FIELD TEMPERATURES

BAROMETER COMBINATION	1	2	3	4	5	6	7	8	9	10
MAXIMUM ERROR (m)	-9.8	-8.8	-9.5	-10.3	-8.9	-10.0	-10.0	-9.0	-9.6	-9.5
MEAN ERROR (m)	-1.2	-0.9	-0.7	-1.2	0.9	-.08	-1.4	-1.1	-0.9	-1.0
R.M.S. ERROR (m)	2.4	2.1	2.3	2.4	2.1	2.2	2.6	2.2	2.4	2.2

REDUCTIONS MADE USING BASE TEMPERATURES

BAROMETER COMBINATION	1	2	3	4	5	6	7	8	9	10
MAXIMUM ERROR (m)	-12.6	-11.2	-12.3	-13.1	-11.6	-12.8	-12.7	-11.3	-12.4	-12.2
MEAN ERROR (m)	-1.3	-1.0	-0.8	-1.3	-1.4	-0.8	-1.5	-1.2	-1.0	-1.1
R.M.S. ERROR (m)	2.7	2.4	2.6	2.7	2.3	2.4	2.7	2.5	2.7	2.5

Field and base temperature differences

The temperature difference $\gamma = (td - tw)_{Field} - (td - tw)_{Base}$ i.e. the instantaneous difference between the wet and dry bulb temperature in the field and at the base, varied by up to $4^{o}C$. The following effects related to this difference were noted:

1. The use of field temperatures in the reduction formula invariably produced smaller errors than did base temperatures (Table 4). This indicates that in general, field thermometers more accurately register the temperature of the air column representing the height interval being measured than base thermometers, which are usually at a distance.

2. Levelling errors derived from field and base temperatures for comparable heights are smaller, and the difference between them is less, on calmer days (Table 5).

TABLE 5. CORRELATION BETWEEN WIND STRENGTH AND BAROMETRIC LEVELLING ERRORS DERIVED FROM BASE AND FIELD TEMPERATURES.

LOOP	1	3	13	15
Height measured (m)	280 m	280 m	280 m	250 m
Error using field temperatures (m)	-8.7	-4.2	-10.3	-5.6
Error using base temperatures (m)	-11.1	-6.1	-13.1	-6.1
Wind strength% (100%= very gusty)	50	25	50	25

3. A plot of the γ population for the whole survey (Plate 11) indicates that the values of γ are low, and the spread in γ is the least for loops 14, 15, and 16. These loops were run on days when the weather was very overcast and fairly still (Table 2).

These results show that field temperatures are likely to produce more accurate heights than base temperatures. Also, the difference between the field and base temperatures may be a good advance indicator of the suitability of weather conditions for barometric levelling, and could be used as a criterion for rejecting potentially inaccurate barometric levelling results.

Relative accuracy of single barometers and use of banks of barometers

It can be seen in Plates 2-9 that in some loops, the position of each separate barometer error within an error spread is fairly constant and that the spreads are fairly uniform. This occurs when all six barometers give a slightly different readout under the same pressure conditions. In other loops, the spreads and positions are more irregular, probably because of unsettled barometric conditions. The errors caused by unsettled barometric conditions could be reduced by simultaneously sampling at the field station and base stations over a period of several minutes, and obtaining the mean of the readings (this would require radio contact). The spreads demonstrate the inherent limit of resolution of a single barometer pair in barometric levelling work, and it is noteworthy that the maximum spread in a loop is often more than twice the R.M.S. error of the loop (Table 2).

The overall survey results (Table 1) show that the R.M.S. errors for the different barometer combinations vary from 2.2 to 2.8 m, as against 2.3 m for the average. Consequently, a good pair of barometers alone could have been used to give the best overall survey result. However, as shown by the error spreads, a single pair of barometers is susceptible to the inherent uncertainty of a single pressure measurement at a station and will therefore give a more erratic result locally than the averages of two banks of barometers. The use of banks of barometers rather than a single pair is also preferable in order to safeguard against the possibility of partial mechanism failure in some of the barometers.

Maximum errors between adjacent stations and the use of the R.M.S. error as a measure of survey accuracy

The R.M.S. error is probably that best indicator of overall survey accuracy as it accentuates the spread in errors. The R.M.S. errors obtained for Loops 1-17 varied from 0.5 to 7.7 m, depending on the average height intervals measured, and the type of weather conditions prevailing. However, the R.M.S. error is the product of the application of an essentially averaging-type arithmetic formula to a group of survey errors, and therefore does not directly indicate the true nature of local errors.

The size of local errors between adjacent stations is of considerable importance in barometric levelling. The present results show that the error between adjacent stations or series of adjacent stations in a loop can be considerably larger than the R.M.S. error for the loop, and can have both a systematic and random character. The following are several types of errors which are all separately larger than the R.M.S. error, and which in combination could theoretically produce much larger errors than the R.M.S. error suggests:

1. Systematic elevation errors, such as in Loop 8 (Plate 5) where the accumulated systematic error over 6 stations is twice the R.M.S. value for the loop.

2. Systematic pressure fluctuation errors. Loops 2 and 4 have small measured height intervals, and systematic local errors which do not correlate with the elevation profile (Plates 2 and 3). Loop 2 has a cumulative systematic error of 4 m over 6 consecutive stations, and Loop 4 has a systematic error of 3 m over 5 stations, which is nearly three times the R.M.S. value in both cases.

3. Random pressure fluctuation errors, as in Loop 4 where there is a jump of 4 m in the error curve between two stations. This jump is more than three times the R.M.S. value for the loop and almost equal to the size of the interval being measured.

4. Measuring resolution errors. The uncertainity in measurement by a single barometer pair, as shown by the spread in the separate barometer errors at a station is often over three times the R.M.S. value for a loop.

This suggests that whereas the R.M.S. error may be used as a basis for comparing the accuracies of separate surveys, it is a poor guide to the size and relative effectiveness of local errors.

CONCLUSIONS

The results of the barometric levelling test survey corroborate previous findings by Darby (1970) that a systematic error of about 3% error occurs, proportional to the height interval measured. This error probably originates in the reduction formula, and can be largely removed by inserting a multiplication factor of 0.97 into it.

The use of banks of three barometers for the base and field readings shows that the uncertainty of a measurement using a single pair of barometers can vary from 1.5 to 7.0 metres, and is usually about three times the R.M.S. error. The uncertainty can cause erratic errors between adjacent stations, and the use of average values from banks of barometers is therefore recommended. The cumulative error for a series of adjacent stations resulting from random and systematic local pressure variations can be many times greater than the R.M.S. error for a loop. It should therefore be assumed that the effective error between some adjacent stations in a group of stations will be at least 2 or 3 times the R.M.S. error of the group.

The optimum weather condition for barometric levelling is the still, heavily overcast, low-cloud, verging-on-drizzle type. On such days errors are minimal over distances of at least 30 km between base and field stations, even when loops do not connect with their bases. The use of field temperatures in the reduction formula gives smaller errors over base temperatures, particularly on windy days when the difference in temperatures is greatest. The difference between field and base temperatures may in fact be a useful criterion for assessing the accuracy of barometric levelling, particularly for pre-determining the suitability of weather conditions for levelling operations.

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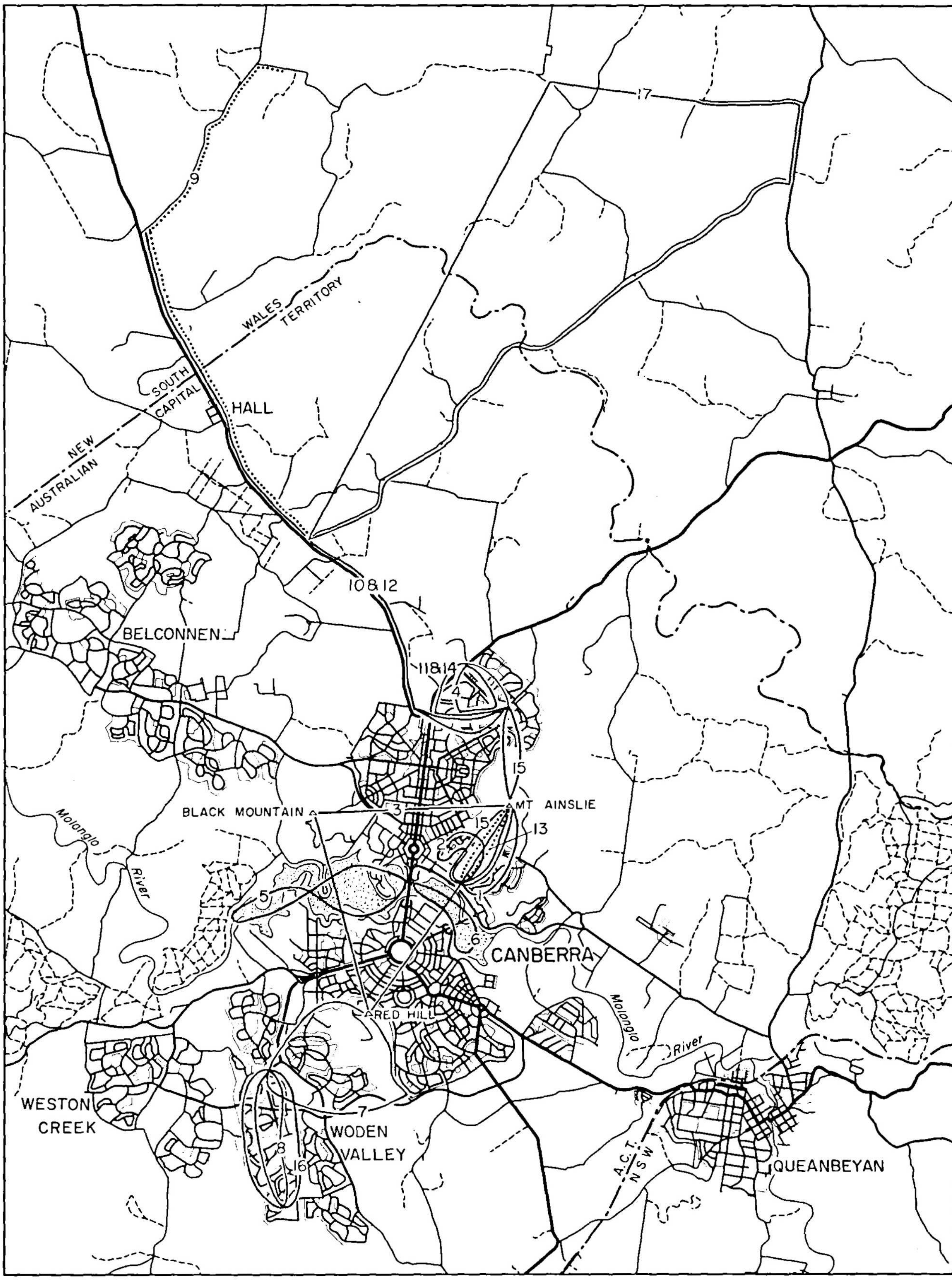
DARBY, F., 1970 - Barometric heighting - an assessment of the accuracy achieved during reconnaissance gravity surveys in Australia. Bur. Miner. Resour. Aust. Rec. 1970/89 (unpubl.).

PLATE 1



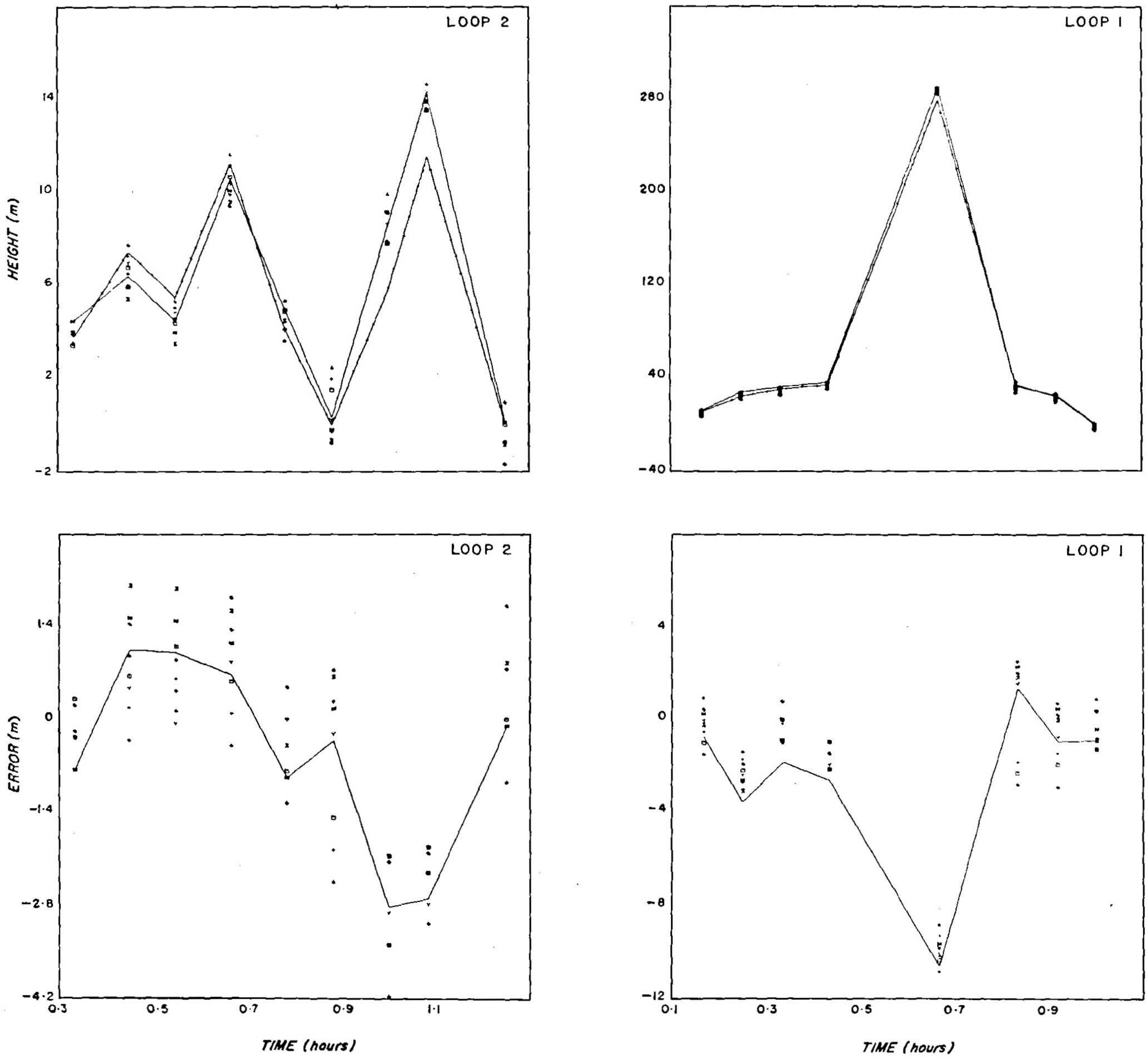
A.C.T. TEST BAROMETRIC LEVELLING SURVEY, 1973

LOOP LOCATIONS

0 2 4 6 km

Record 1976/46

I55/B2-63A



TOP: PLOT OF ACTUAL AND BAROMETRICALLY DETERMINED HEIGHTS

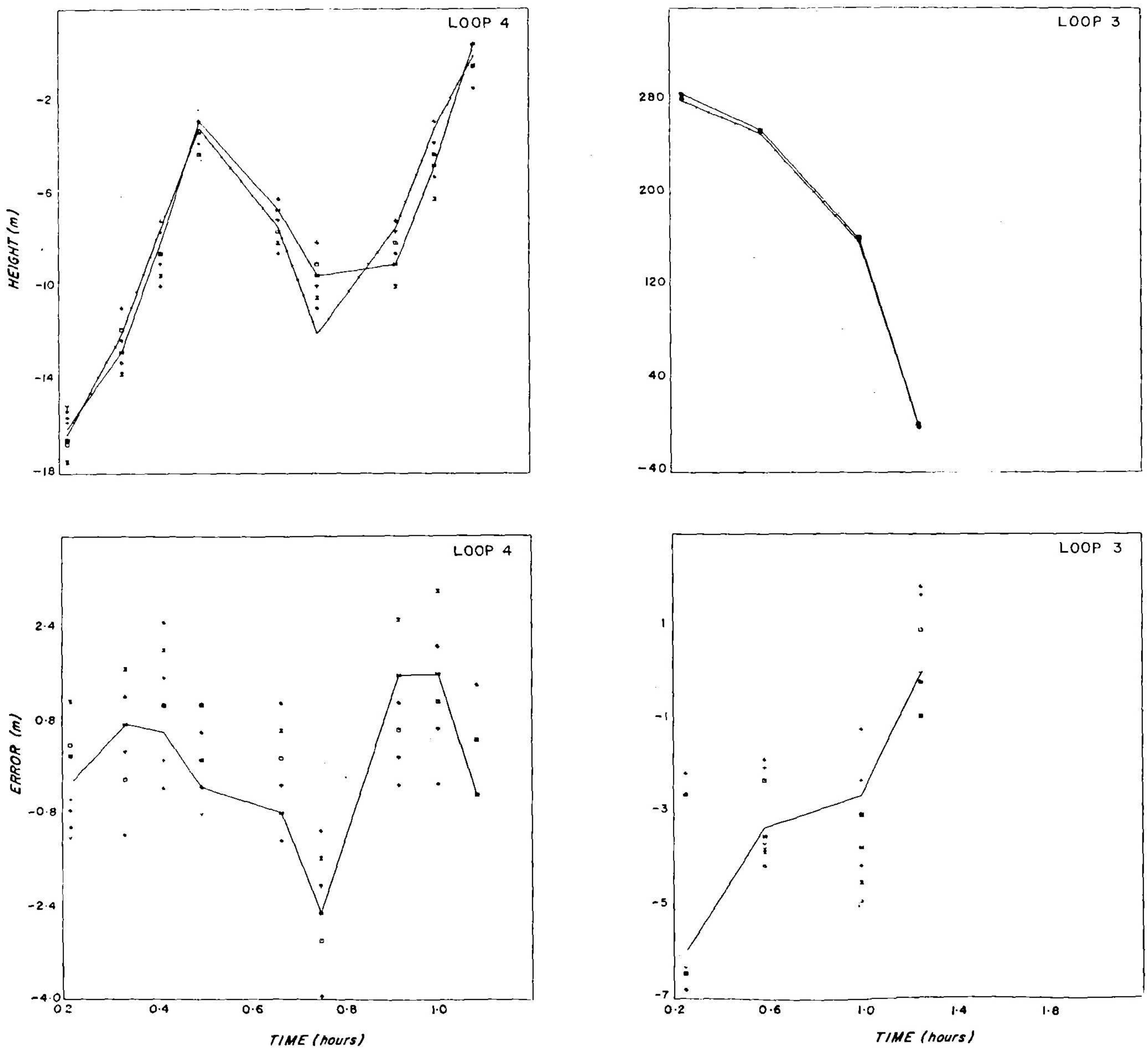
AGAINST TIME IN LOOP FOR COMBINATIONS 1-9

ACTUAL HEIGHT –+–+–+– 9TH COMBINATION ———

BOTTOM: PLOT OF ERRORS AGAINST TIME IN LOOP FOR COMBINATIONS 1-9

(MISCLOSURE NOT REMOVED)

9TH COMBINATION ———



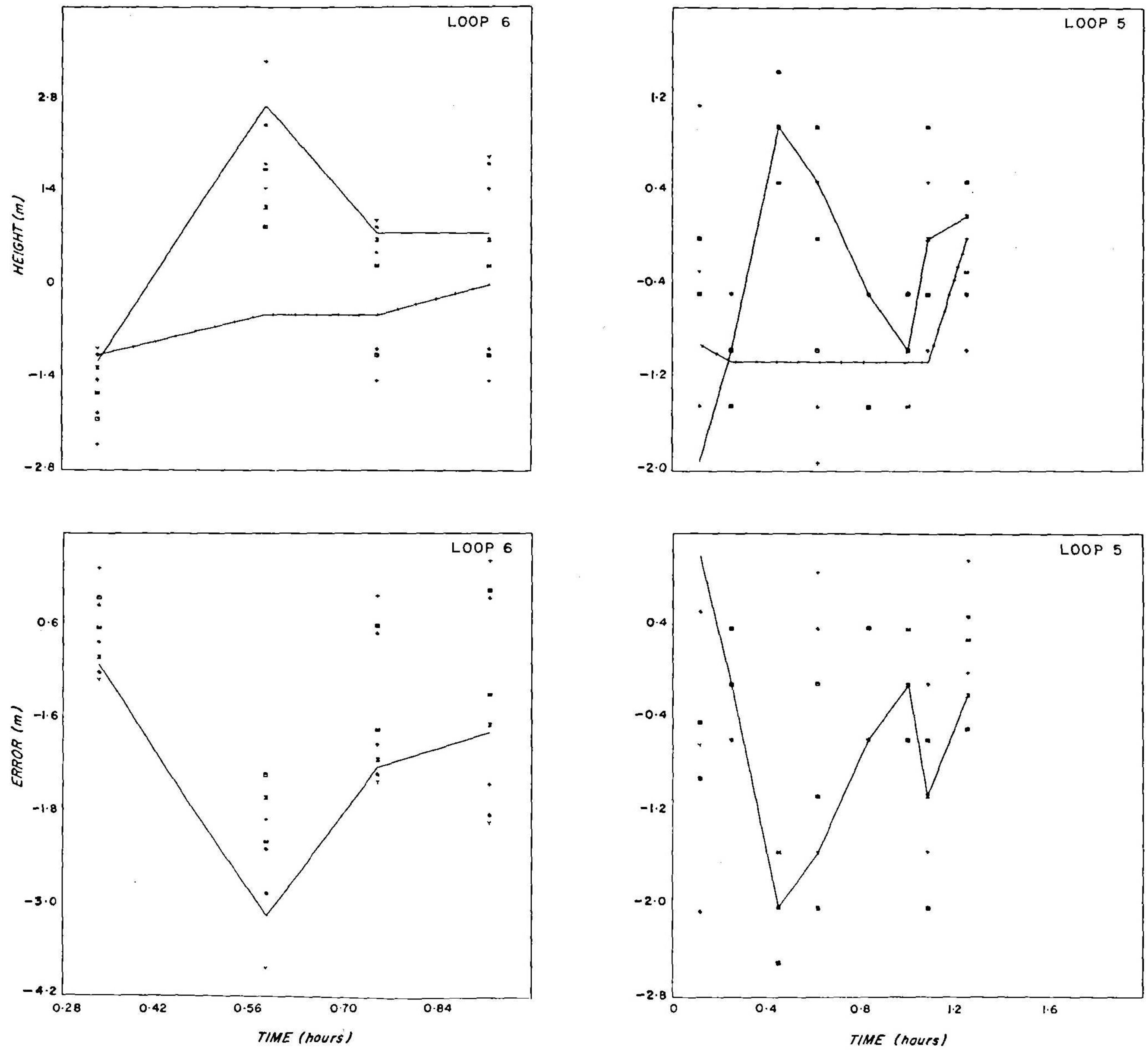
TOP: PLOT OF ACTUAL AND BAROMETRICALLY DETERMINED HEIGHTS AGAINST TIME IN LOOP FOR COMBINATIONS 1-9

ACTUAL HEIGHT +++++ 9TH COMBINATION ———

BOTTOM: PLOT OF ERRORS AGAINST TIME IN LOOP FOR COMBINATIONS 1-9

(MISCLOSURE NOT REMOVED)

9TH COMBINATION ———

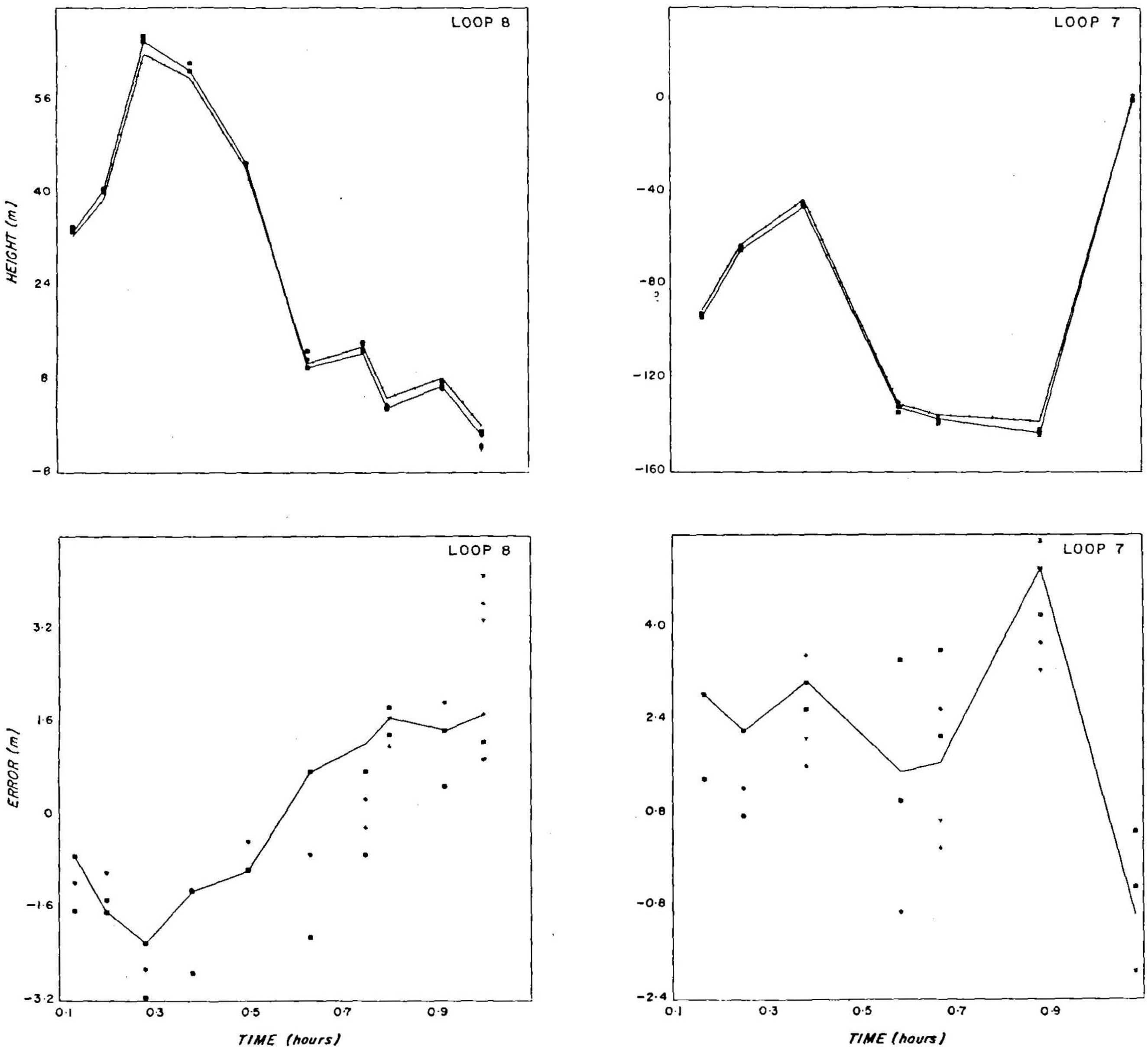


TOP: PLOT OF ACTUAL AND BAROMETRICALLY DETERMINED HEIGHTS AGAINST TIME IN LOOP FOR COMBINATIONS 1-9

ACTUAL HEIGHT —+—+—+— 9TH COMBINATION ———

BOTTOM: PLOT OF ERRORS AGAINST TIME IN LOOP FOR COMBINATIONS 1-9 (MISCLOSURE NOT REMOVED)

9TH COMBINATION ———



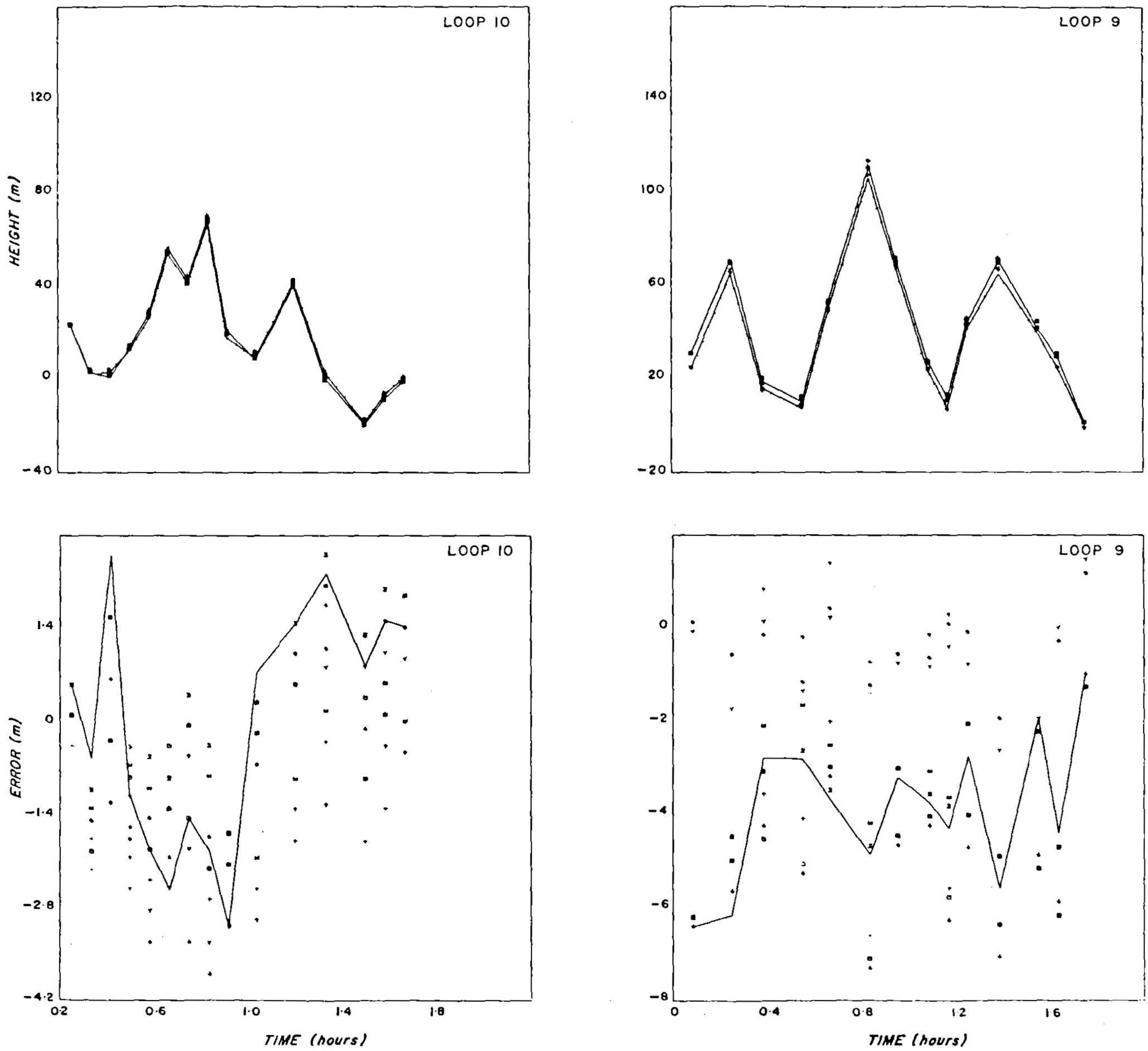
TOP: PLOT OF ACTUAL AND BAROMETRICALLY DETERMINED HEIGHTS AGAINST TIME IN LOOP FOR COMBINATIONS 1-9

ACTUAL HEIGHT ——+—+—+— 9TH COMBINATION ————

BOTTOM: PLOT OF ERRORS AGAINST TIME IN LOOP FOR COMBINATIONS 1-9 (MISCLOSURE NOT REMOVED)

9TH COMBINATION ————

PLATE 6



TOP: PLOT OF ACTUAL AND BAROMETRICALLY DETERMINED HEIGHTS

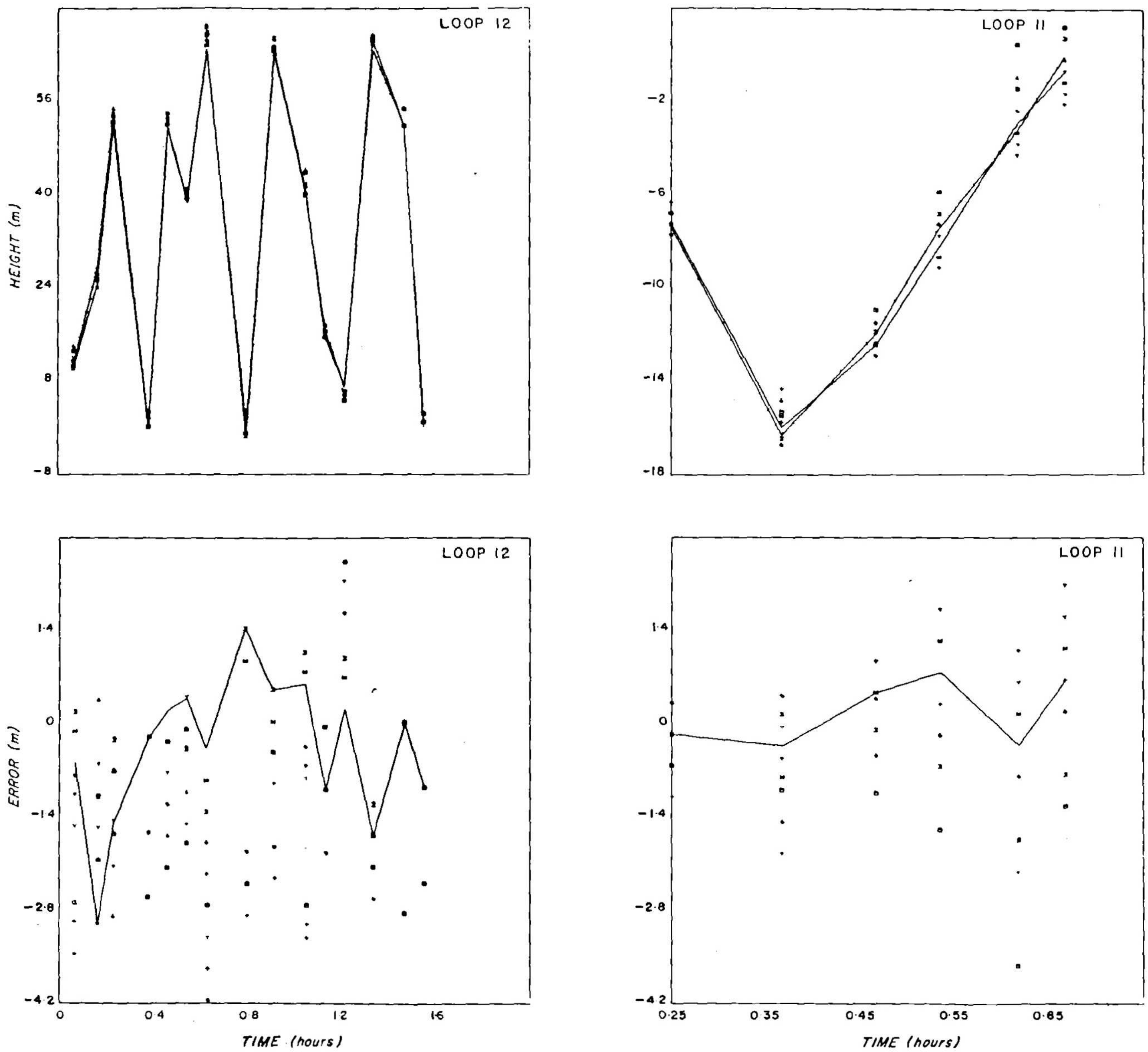
AGAINST TIME IN LOOP FOR COMBINATIONS 1-9

ACTUAL HEIGHT —+—+— 9TH COMBINATION ———

BOTTOM: PLOT OF ERRORS AGAINST TIME IN LOOP FOR COMBINATIONS 1-9

(MISCLOSURE NOT REMOVED)

9TH COMBINATION ———

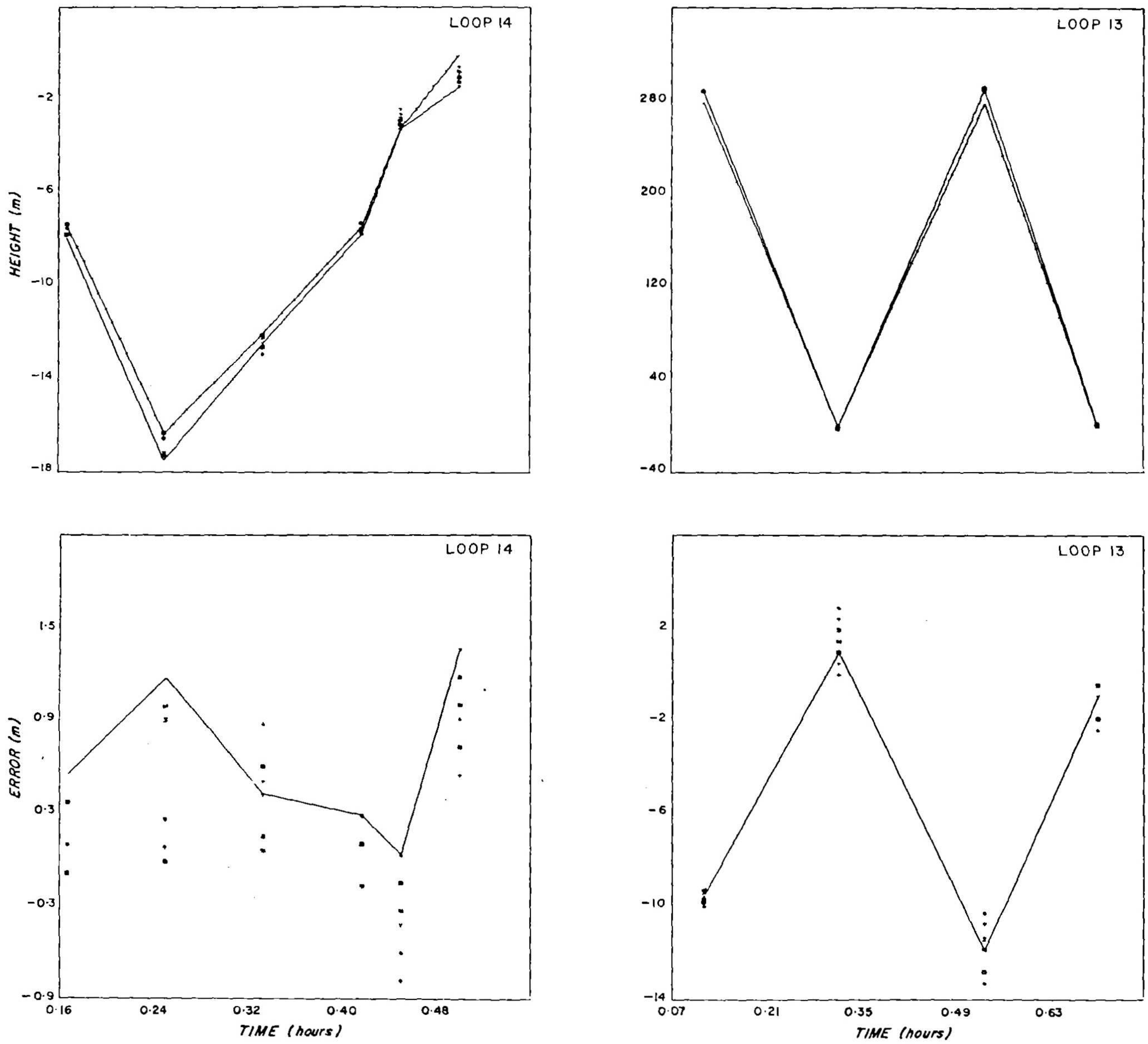


TOP: PLOT OF ACTUAL AND BAROMETRICALLY DETERMINED HEIGHTS AGAINST TIME IN LOOP FOR COMBINATIONS 1-9

ACTUAL HEIGHT ——+—+—+—— 9TH COMBINATION ————

BOTTOM: PLOT OF ERRORS AGAINST TIME IN LOOP FOR COMBINATIONS 1-9 (MISCLOSURE NOT REMOVED)

9TH COMBINATION ————

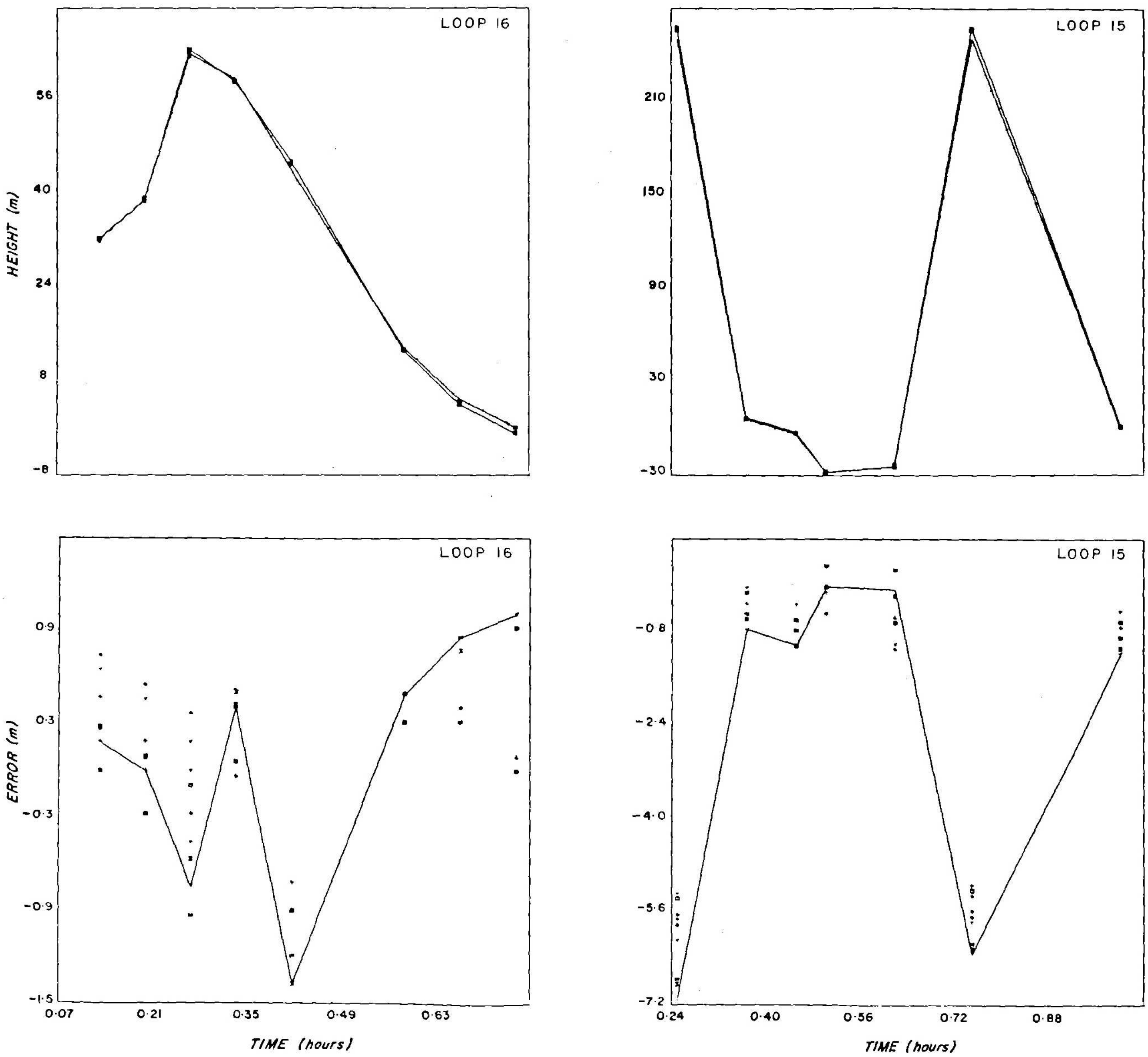


TOP: PLOT OF ACTUAL AND BAROMETRICALLY DETERMINED HEIGHTS AGAINST TIME IN LOOP FOR COMBINATIONS 1-9

ACTUAL HEIGHT ——— 9TH COMBINATION ———

BOTTOM: PLOT OF ERRORS AGAINST TIME IN LOOP FOR COMBINATIONS 1-9 (MISCLOSURE NOT REMOVED)

9TH COMBINATION ———



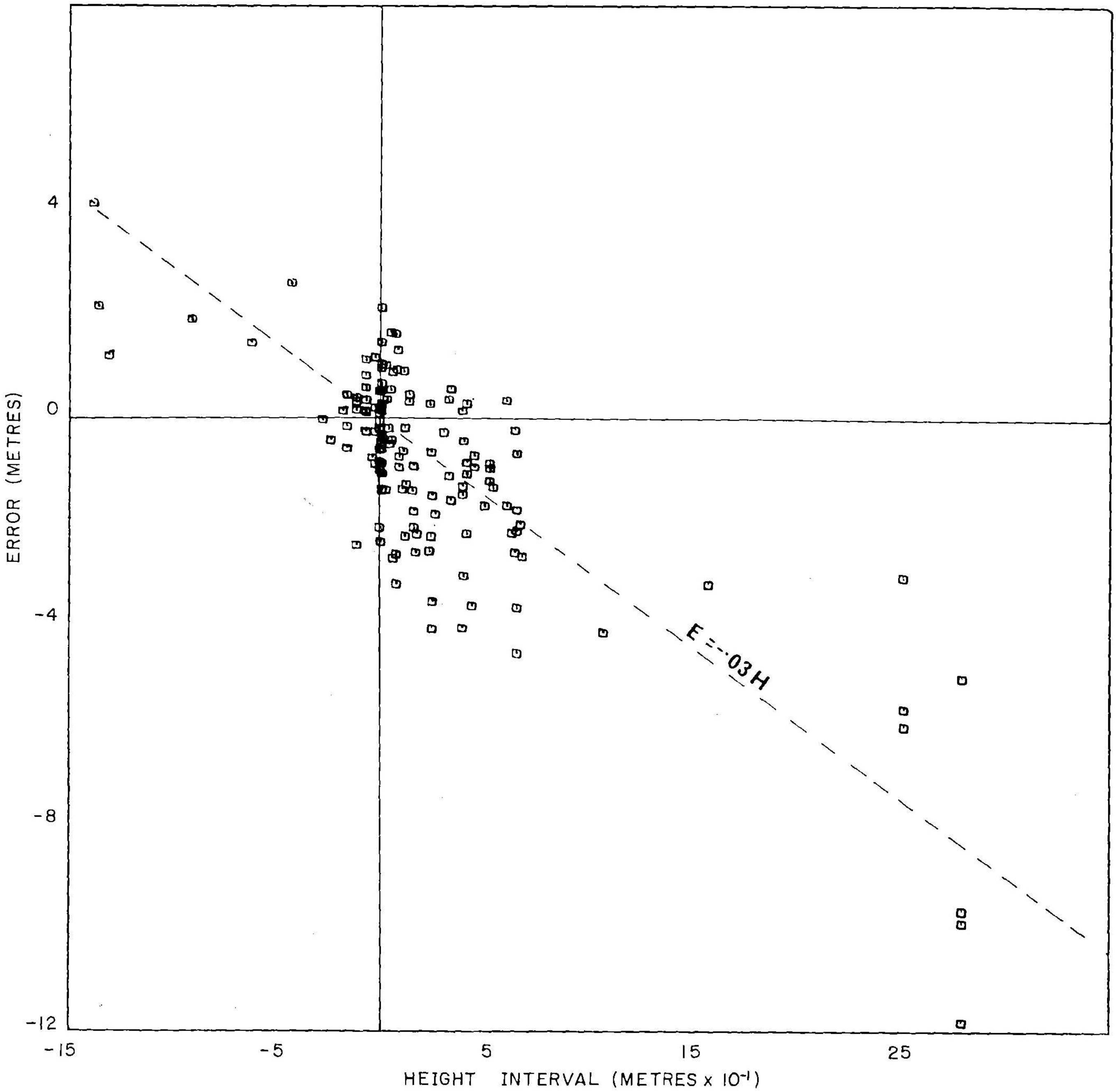
TOP: PLOT OF ACTUAL AND BAROMETRICALLY DETERMINED HEIGHTS AGAINST TIME IN LOOP FOR COMBINATIONS 1-9

ACTUAL HEIGHT ─┼─┼─┼─ 9TH COMBINATION ────

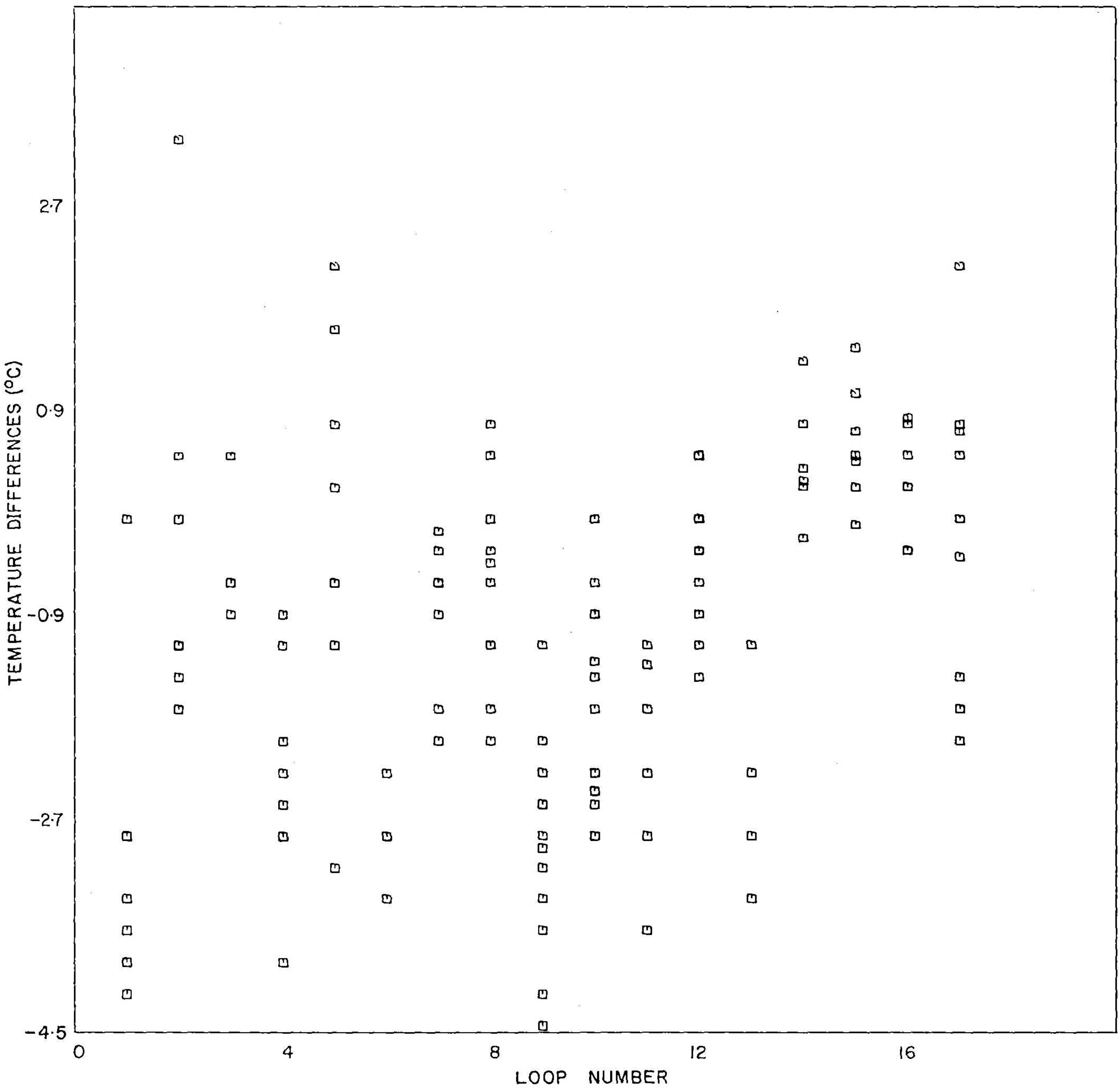
BOTTOM: PLOT OF ERRORS AGAINST TIME IN LOOP FOR COMBINATIONS 1-9

(MISCLOSURE NOT REMOVED)

9TH COMBINATION ────



PLOT OF ERROR AGAINST HEIGHT INTERVAL



FIELD BASE TEMPERATURE DIFFERENCES POPULATION PLOT, LOOPS 1-17