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RECORDS 1961 No. 24

INTERNATIONAL GRAVITY METER TIES, 1959

by

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ABSTRACT

Worden gravity meters were read for base drift control at Australian pendulum stations and sent by aircraft to overseas gravity stations within small-dial range, where they were read by overseas observers, with the aim of obtaining accurate values for the intervals between the Australian and overseas stations. Results are presented, and their analysis discussed. Values for the intervals derived are tabulated.

1. INTRODUCTION

Following the recommendation of a sub-committee of the I.U.G.G., the Geophysical Branch of the Bureau of Mineral Resources carried out a series of international gravity ties in April and May 1959. These were designed, in conjunction with similar measurements between other countries, to provide more accurate values for the gravity intervals between stations on different continents.

The principles involved in drawing up the programme were:-

(a) to use Worden-type gravity meters in order to avoid the use of heating batteries and so facilitate transport.

(b) to use as many of these gravity meters as were available, to increase the accuracy of the tie.

(c) to select pairs of stations, one in Australia and one overseas, at which the gravity values would be within about 80 milligals of each other, so that the interval between them could be measured using only the fine reading dial (small dial) of the gravity meter, thus ensuring the greatest accuracy possible.

(d) to ensure that convenient air services were available between the two stations in each pair, so that the time of transit could be minimised, thus reducing the effect of uncertainties in the drift rate.

From these considerations, three pairs of gravity stations were selected to link the Australian pendulum station network (Dooley et al, in press) with those of Japan, South Africa, and New Zealand. These were:-

(1) Sydney and Tokyo,

(2) Cairns and Johannesburg,

(3) Melbourne and Auckland.

2. PROGRAMME OF READINGS

It was decided that three Worden gravity meters would be used for these ties. Arrangements were made with the co-operation of overseas geophysical organisations (see Section 6, "Acknowledgements") for geophysicists in each of the overseas countries to receive the meters and carry out the readings there. QANTAS Empire Airlines and Tasman Empire Airways agreed to co-operate by conveying the meters in the personal care of the captains of the aircraft concerned, and a schedule was drawn up to allow three days of drift readings to be made at the appropriate Australian pendulum station before and after each overseas flight.

In the interval between the completion of these arrangements and the commencement of the programme, two of the Bureau's Worden gravity meters unfortunately became defective and had to be returned to the makers for repair. Fortunately, a replacement meter was made available at short notice by the Australian National University, and this made it possible to send three meters as planned to Tokyo and Auckland. However, only two of the meters available could be operated at Cairns and Johannesburg. Because of the many arrangements which would have had to be altered to delay this tie until another instrument was available, it was decided to proceed as planned with the Johannesburg tie, but using only two gravity meters.

The measurements carried out were as follows:-

(1) SYDNEY-TOKYO

The meters used were Worden Geodetic meters, Serial Numbers 140, 169, and 201. They were adjusted to the appropriate "small dial" settings at B.M.R. pendulum station No. 5 (National Standards Laboratory, Sydney) and the geodetic dials were then removed. Readings were then taken periodically until immediately before the meters had to be handed to the captain of the aircraft at Sydney Airport.

On arrival at Haneda Airport in Tokyo, Japan, the meters were taken to Hakone gravity station, a subsidiary station which had been tied to the Japanese National Fundamental Station at Kyoto, and they were read there at intervals until the time of departure of the aircraft.

When the meters returned to Sydney, early on Sunday morning 12th April, they were read for one day at a subsidiary station at the airport, to avoid inconvenience associated with occupying the pendulum station over the weekend. This subsidiary station was subsequently tied to the pendulum station, and a further two days of drift readings were carried out at the pendulum station.

(2) CAIRNS-JOHANNESBURG

Worden gravity meters Nos. 140 and 201 were used for this tie. Worden 169 would have been "off range" at Cairns.

Readings at Cairns were taken at B.M.R. pendulum station No. 52, and later, when vibrations from various causes made readings impossible at this station, at a subsidiary station which was tied to the pendulum station. After three days' readings in Cairns the meters were flown to Sydney to be put on the aircraft for Johannesburg. On their return from Johannesburg they were received at Sydney and flown to Cairns for a further three days' readings.

Most of the observations at Johannesburg were made at the South African Fundamental Base Station, which is at the Bernard Price Institute for Geophysical Research. Readings were also taken at Jan Smuts Airport immediately after arrival there and immediately before dispatch to Australia.

(3) MELBOURNE-AUCKLAND

The three gravity meters used for this tie were Worden Nos. 140, 169, and 201. They were read for drift at the Australian National Gravity Base Station (B.M.R. pendulum station No. 1, at Footscray, a suburb of Melbourne) and at a subsidiary station tied to it. Readings were made for three days prior to departure for Auckland and for three days after return of the meters.

At Auckland, the meters were read at Whenuapai Airport immediately on arrival and just prior to departure. Most of the readings were made at the New Zealand National Base Station, which is at Auckland Museum. In addition one of the meters, Worden 169, was read over the Auckland Calibration Range, to compare the accepted gravity intervals over the Australian and New Zealand standard calibration ranges. Results of these measurements are not yet available, but will be communicated later.

3. RESULTS

Earth tide gravity corrections (Goguel, 1954) were applied to all readings. The results are plotted on Plates 1 to 3.

Straight lines were fitted to the corrected readings at each of the Australian base stations, by the "least squares" method. Similarly, drift lines were fitted to the results from the overseas stations, but these were used only as a check on the mean drift rate and do not enter into the calculation of the gravity intervals (see Section 4, "Analysis of Results").

The results from each meter for each tie are now described separately. The principal statistics are tabulated in detail in Table 1.

(1) SYDNEY-TOKYO (Figs. 1, 2)

Worden Serial Number 140

The observations at Sydney lie quite well along a single straight line, although it will be noted that at some times, particularly on 13th April, the observations lie consistently along a curve deviating from the mean drift line. This is probably a temperature effect. Even with the scatter from this effect the standard deviation of a single observation from the line is quite small (0.033 mgal).

The observations at Hakone lie along a line representing a drift rate not very different from that observed at Sydney.

Worden Serial Number 169

The results from this meter are not quite so satisfactory. The readings do not fit well along a single drift line; it appears that between the time of departure from Sydney and subsequent return the drift rate changed. No reason for this change is apparent.

Separate straight lines have been fitted to the "pre-departure" observations and the "post return" observations.

The Hakone observations lie quite well (S.D. = 0.012 mgal) along a line with a slope very close to the "pre-departure" Sydney slope. This supports the assumption that the change in drift rate occurred after the Hakone readings were completed, and appears to justify using only the "pre-departure" Sydney values in calculating the gravity interval, as has been done.

Worden Serial Number 201

The observations from this meter show very considerable scatter and marked changes in drift rate at both Sydney and Hakone; any drift interpolation would be too speculative to give reliable results.

After completion of the series of international ties it was found that the pressure inside the inner evacuated can of this meter had reached an unsatisfactorily high value. Owing to the fact that this meter was received only on the day the measurements were to start, there was no time to check its performance before the series of measurements began.

(2) CAIRNS-JOHANNESBURG (Figs. 3, 4)

Worden Serial Number 140

The observations at Cairns lie quite well along a single straight line (S.D. = 0.093 mgal). The fit would be improved slightly by using different lines before and after the overseas flights. The reasons for not doing so are given in Section 4, "Analysis of Results".

The Johannesburg readings lie well along a single straight line.

Worden Serial Number 201

The results from this meter, while not as consistent as those from Worden 140, are much better than those obtained with it for the Sydney-Tokyo and Melbourne-Auckland ties. As the results from this meter are the only ones available to corroborate those from Worden 140, it has been thought worth while to present them.

The mean drift rates at Cairns and Johannesburg will be seen to be reasonably consistent (Table 1).

(3) MELBOURNE-AUCKLAND (Figs. 5, 6)

Worden Serial Number 140

The scatter about the mean drift line for Melbourne will be seen to be greater than that observed at the other base stations. This is probably due in some measure to vibration interference at this station, resulting from road traffic.

The Auckland readings lie very well along a single straight line not very different in slope from the mean rate observed at Melbourne.

Worden Serial Number 169

The scatter of the Melbourne readings again appears to have been increased by vibration interference.

Worden Serial Number 201

The results from this meter were again too erratic to allow any reasonable drift interpolation to be made.

4. ANALYSIS OF RESULTS

(1) Measurement of gravity intervals

In order to compute the gravity interval from each Australian base station to the corresponding overseas station it is necessary to interpolate a drift curve over the interval that the gravity meter is away from the base station. The "most likely" interpolation, in the statistical sense, is the one which makes the product of two factors a maximum. These factors are:-

(a) the intrinsic probability of the assumed drift curve, bearing in mind the physical causes of the drift and how they may be affected by temperature changes, vibration encountered in transportation, etc.

(b) the probability of the observed readings, assuming a particular drift curve and regarding deviations from this curve as due to such causes as random errors in reading and random interference by vibration at the time of reading.

The first of these factors is difficult to assess. It is generally assumed that the basic drift of a gravity meter, measured under ideal conditions (e.g. constant temperature, no vibration) and allowing for tidal effects, is produced by fatigue of the components, and is a linear function of time. More certainly, any deviation from linearity is more likely to be measurable over periods of months than over a few days.

Under the more usual conditions where the instrument is subject to movement, vibration, and temperature changes between readings, this linear drift is disturbed. The effect of external temperature changes has been studied (e.g. Caputo, 1957) and it appears that, for each meter, characteristics can be measured from which the effect of such changes on drift readings can be predicted. The effect of changes in atmospheric pressure, such as are encountered in transportation by aircraft, has also been studied and appears to be of short duration, disappearing a few hours after return to normal pressure. Pressurised aircraft were used in all cases during the ties described here.

The effects of mechanical vibration and shock are less well known. Experience suggests that, up to a minimum acceleration level which is not often exceeded in normal transport, the effects are very small but that, beyond that level, changes in drift rate lasting for intervals of a few days, and almost instantaneous "jumps" of a few tenths of a milligal, can be produced by shock or excessive vibration.

In the case of the measurements described here consistent deviations from the mean drift curve, over an interval of about one day, can be seen on some of the plots, e.g. Worden 140 at Sydney on 13th April. This is probably due to the temperature effect, but as no temperature records were kept this cannot be confirmed.

In principle, drift curves of considerable complexity could be fitted to the observed data in order to increase factor (b) above by reducing the scatter of the observations about the drift curves. Such curves would follow the variations which have been attributed to temperature changes. However, there is no information on which to base the interpolated part of such curves and therefore the intrinsic probability of any one such curve must be considered lower than that of a straight line interpolation, because of the large number of such curves which could be fitted to the observed data. In view of the precautions taken in loading the instruments for transport, drift rate changes resulting from mechanical shock would also appear to be of low probability and could only be accepted if there were strong evidence to suggest them. It appears that although there is strong evidence that in fact the drift curves deviate from straight lines, there is insufficient evidence about the deviations from linearity occurring during absence from the base station. Therefore straight line drift must be assumed, and the probable error arising from this assumption assessed from the data available.

Having selected the form of the drift curve in this way, the curve (in this case a straight line or lines) is fitted to the observations by the method of "least squares", which makes the probability of the observations (factor (b)) a maximum.

As the observations at the overseas stations in each case occupy a much shorter interval of time than those at the Australian base station, they have very much less weight in determining the drift interpolation, and in fact they have been ignored in determining the slope of the drift lines. However, if observations at the overseas stations had continued over an interval of time more nearly equal to that at the base stations, account would have to be taken of them in computing the drift line. In the case of the present measurements, only the mean point of the overseas observations has been used in computing the intervals. That is, the mean value of the observed readings at each overseas station has been referred to the line through the base station observations at the mean time of the overseas observations.

It is considered that in only one case is there sufficiently strong evidence to justify using more than one line for the drift interpolation. This is the set of results from Worden 169 for the Sydney-Tokyo tie. There is a marked change in slope between the readings at Sydney before departure for Tokyo and after return from Tokyo. The readings at Hakone (Tokyo) closely agree in slope with those obtained at Sydney before departure. This suggests strongly that the change in drift rate is real and that it occurred after the Hakone readings were completed. The Hakone readings have therefore been referred to the "pre-departure" drift line at Sydney, in measuring the gravity interval from this set of observations.

(2) Accuracy of the measured gravity intervals

In this report we are concerned only with the probable accuracy of the measured intervals considered as part of the Australian gravity network. If the value of the Australian calibration range is adjusted at some future date, these intervals will have to be adjusted proportionally, but this type of possible error is not considered here.

The remaining sources of error fall into three groups:-

(a) errors in calibration of the instruments, including the assumption that the meter has a linear response to varying gravity.

(b) errors in the form of drift curves used.

(c) random errors of measurement.

Considering the first source of error, the calibration of the scale factor for the "small dial" can generally be repeated to one part in a thousand, or better. Thus the possible error introduced is smaller than that from other causes in this case, but is not negligible. The calibrations were carried out close in time to the measurements; non-linearity of spring response should be negligible because of the small gravity intervals measured.

The second source of error, selection of the form of the drift curve for interpolation, has been discussed in sub-section (1) "Measurement of gravity intervals". This error cannot be assessed accurately, but an indication of its probable magnitude is given by the range of variation seen on those plots, particularly for Worden 140 at Sydney, where more or less periodic variations ascribed to temperature changes are noticeable. In the instance cited these variations are the principal source of scatter about the drift line, so that this scatter is an indication of the magnitude of possible errors due to temperature effect. Pressure effects are probably smaller. The results of vibration and shock would probably be detectable if they were at all important (as they are believed to have been in the case of Worden 169 on the Sydney-Tokyo tie. Thus this type of error must be regarded as equivalent to a random error of measurement, and its magnitude is probably of the same order as the observed scatter about the drift lines adopted.

Owing to the fact that most of the observations at the base stations were made during daylight hours, it is possible that a small systematic error has been introduced in computing the drift lines, because of the periodic daily variations which are probably produced by temperature changes. However, because of the form of the daily variations observed, such errors are most likely to be within the standard errors quoted in Table 1.

The other random errors of measurement are:-

(a) personal errors in balancing the beam - about 0.03 mgal. at most

(b) random variations, sometimes of considerable magnitude, introduced by vibrations at the time of reading.

Thus a "standard error" derived from the observed scatter about the assumed drift line will include:-

(a) the effect of all random errors of measurement

(b) part of, and probably the greater part of, the effect of errors involved in the selection of drift curves fitted to the instrument readings.

This "standard error" will indicate the relative weight to be attached to the measurements from the different instruments for each tie. The true accuracy of the measurements would probably be indicated by a standard error of about twice this amount, which would include the variance from calibration errors, but there is insufficient evidence to justify a definite statement of true accuracy.

"Standard errors" derived from the observed scatter about the drift lines and the standard error of the mean observation at each overseas station are entered in Table 1.

5. CALIBRATION RANGE

The Calibration Range used in determining the scale factors of the gravity meters was the B.M.R. standard range between "Brenock Park" and "Kallista outer station". At the time of the measurements the adopted value for this interval was -55.60 mgal. This value had been measured with a Worden gravity meter whose scale value was determined by re-occupying five pendulum stations established with the Cambridge Pendulums (Dooley et al., in press). The pendulum stations were at Mildura, Melbourne, Kallista, Yarram, and Bombala.

It is intended to extend considerably the loop of gravity meter interconnections between pendulum stations, and this may make necessary a revision of the adopted value for the standard range.

6. ACKNOWLEDGEMENTS

It is desired to acknowledge the co-operation of the following persons who arranged for the gravity meters to be received, taken through customs, and read at their overseas destinations:-

Dr. Toyozo Okuda, Meguro, JAPAN

Professor A.L. Hales, Johannesburg, SOUTH AFRICA

Dr. E.I. Robertson, Wellington, NEW ZEALAND.

The co-operation of Professor J.C. Jaeger, of the Australian National University, Canberra, who made a Worden gravity meter available at short notice, is also gratefully acknowledged.

Acknowledgement is gratefully made of the assistance given by QANTAS Empire Airlines Limited, Sydney, who conveyed the instruments overseas under the care of the captains of their aircraft; and of the assistance given by Trans-Australia Airlines Limited, Melbourne, who made special arrangements for the transport of the gravity meters within Australia.

7. REFERENCES

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TABLE 1

Gravity intervals and principal statistics of the observations

Base Gravity Station	Gravity Meter	Mean Drift Rate (mgal/hr)	Standard Deviation from Drift Line (mgal)	Overseas Gravity Station	Mean Drift Rate (mgal/hr)	Standard Deviation of Mean of Observations (mgal)	Gravity Interval between Overseas Station and Base Station
BMR Pendulum Station No.5, Sydney	W-140	+0.0179	0.033	Hakone, Japan	+0.0232	0.013	W-140 + 335.08 small dial divisions = <u>+ 37.28 mgal</u> (standard error = 0.036 mgal from drift line assumed)
"	*W-169	a)-0.00078 b)+0.0092	a)0.038 b)0.10	"	-0.00068	0.001	*W-169 + 352.35 smalldial divisions = <u>+ 37.31 mgal</u> (standard error = 0.039 mgal from drift line assumed)
"	W-201	too erratic		"	too erratic		W-201 no result
BMR Pendulum Station No.52, Cairns	W-140	+0.0164	0.093	Bernard Price Institute, Johannesburg	+0.058	0.015	W-140 + 441.53 small dial divisions = <u>+ 49.12 mgal</u> (standard error = 0.095 mgal from drift line assumed)
"	W-201	+0.0230	0.346	"	0.0207	0.061	W-201 +557.00 small dial divisions = <u>+ 49.03 mgal</u> (standard error = 0.35 mgal from drift line assumed)
BMR Pendulum Station No.1, Melbourne	W-140	+0.0168	0.171	Auckland Museum (Auckland "A")	+0.01[illegible]	[illegible].028	W-140 - 279.00 small dial divisions = <u>- 31.04 mgal</u> (standard error = 0.173 mgal from drift line assumed)
"	W-169	+0.0100	0.205	"	-0.00095	0.013	W-169 - 292.16 small dial divisions = <u>- 30.94 mgal</u> (standard error = 0.205 mgal from drift line assumed)
"	W-201	too erratic		too erratic			W-201 no result

* Drift rate changed - see Section 4 of text

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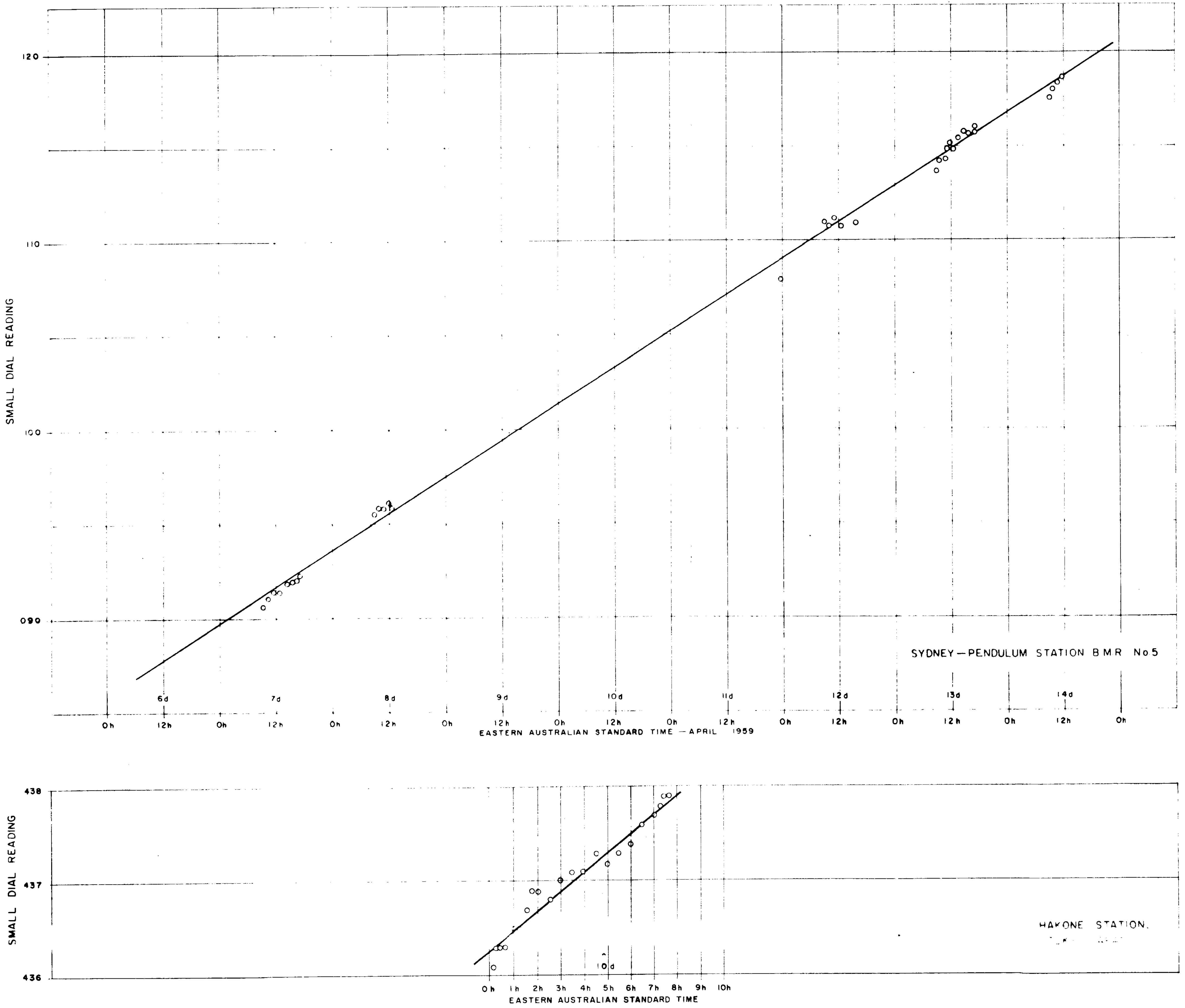

FIG.1 CORRECTED READINGS FROM WORDEN GRAVIMETER SER. No. 140

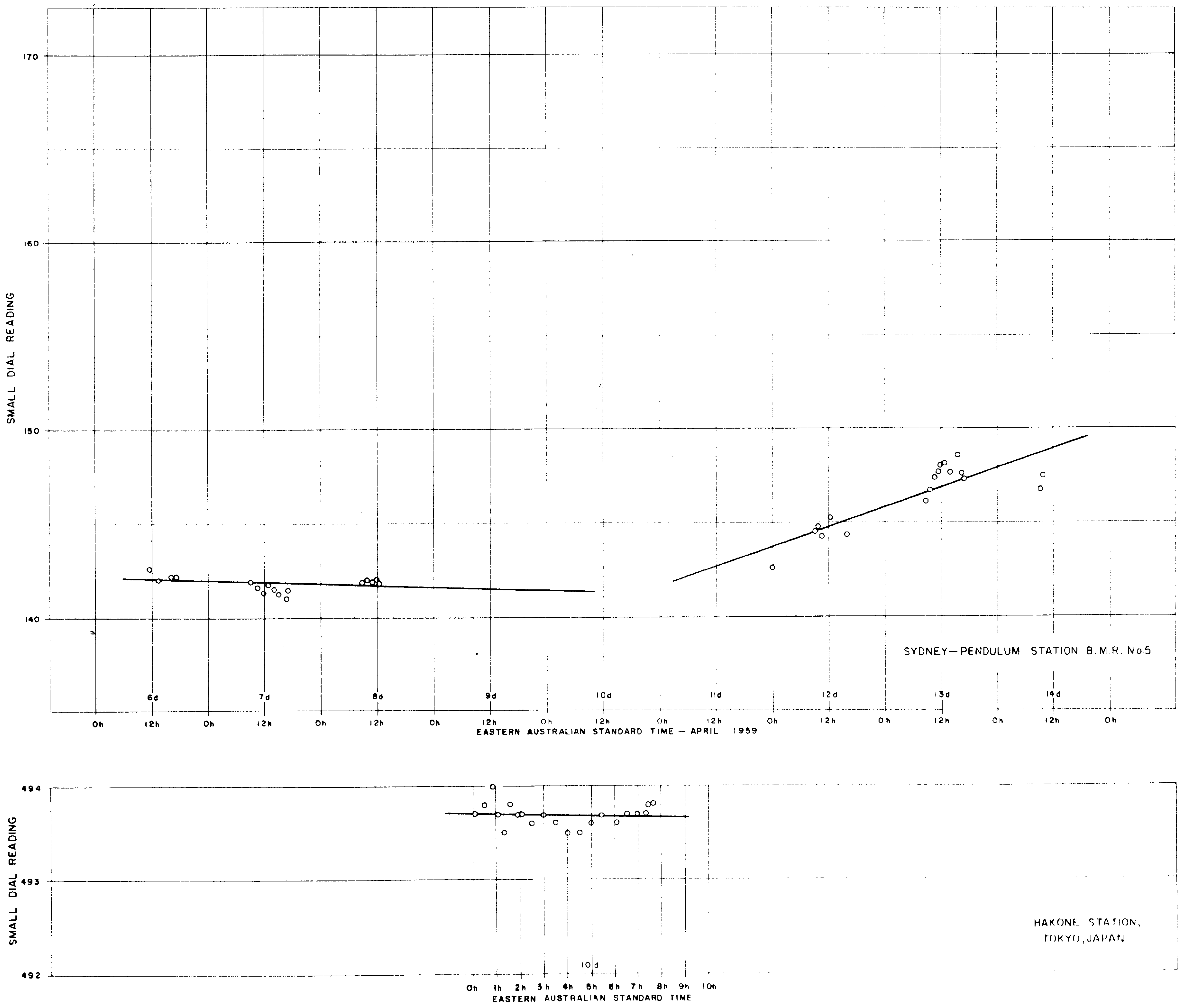

FIG.2 CORRECTED READINGS FROM WORDEN GRAVIMETER SER. No. 169

READINGS AT OVERSEAS STATION PLOTTED WITH "TIME" AND "READING" SCALES EXPANDED EQUALLY — SLOPE OF DRIFT LINE IS DIRECTLY COMPARABLE WITH THAT OF AUSTRALIAN BASE STATION READINGS

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FIGURES 3,4

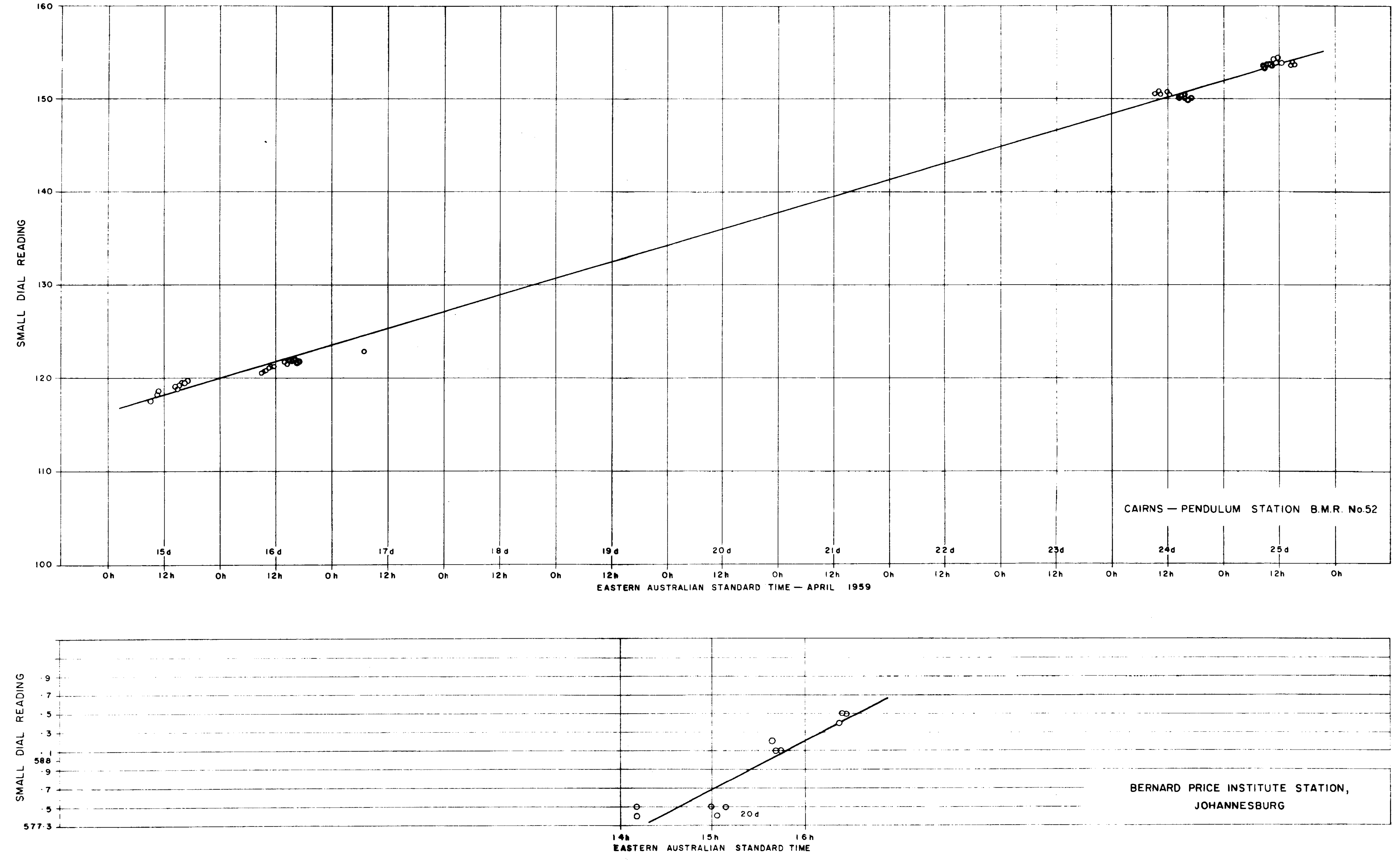

FIG. 3 CORRECTED READINGS FROM WORDEN GRAVIMETER SER. No. 140

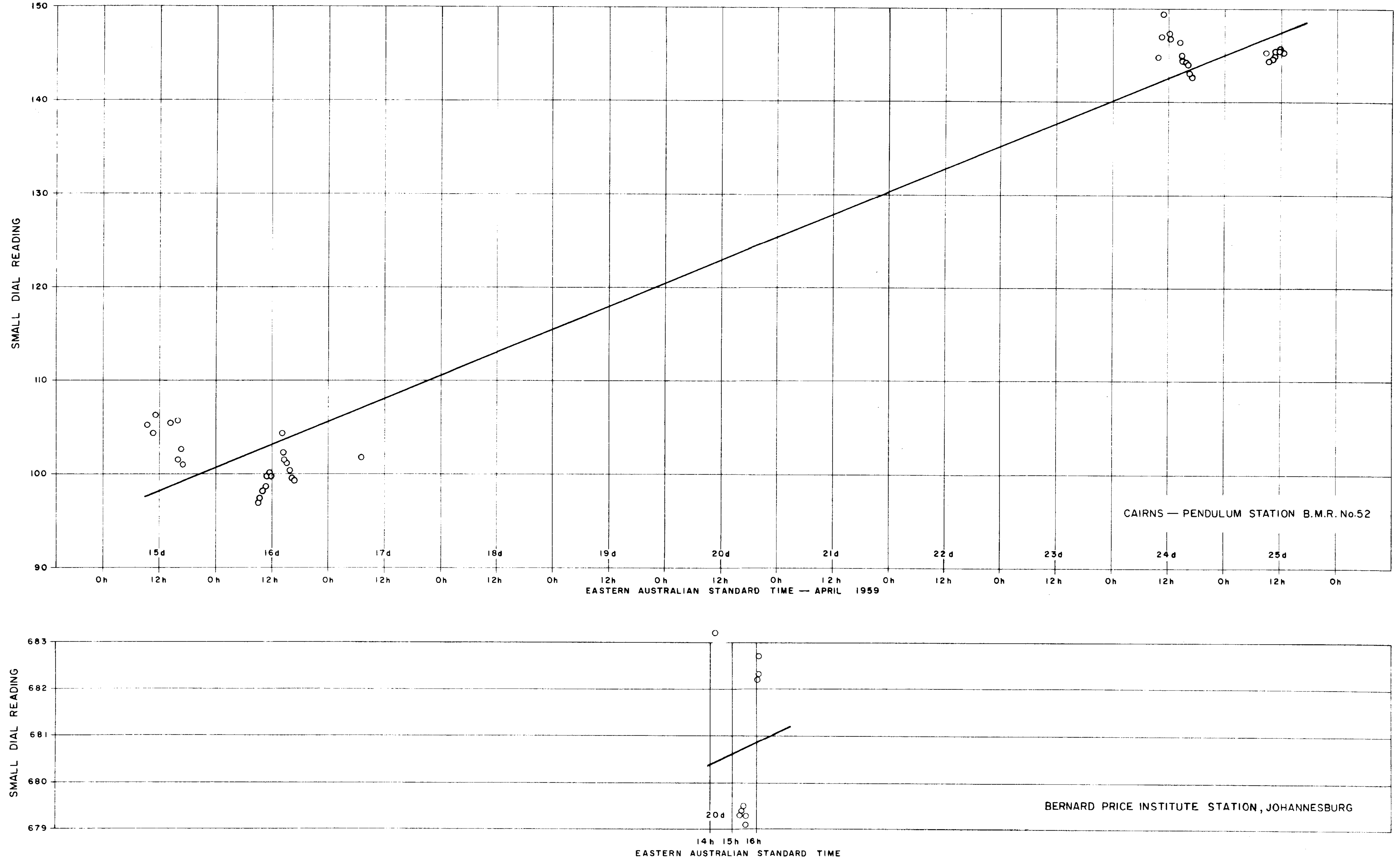

FIG. 4 CORRECTED READINGS FROM WORDEN GRAVIMETER SER. No. 201

READINGS AT OVERSEAS STATION PLOTTED WITH "TIME" AND "READING" SCALES EXPANDED EQUALLY — SLOPE OF DRIFT LINE IS DIRECTLY COMPARABLE WITH THAT OF AUSTRALIAN BASE STATION READINGS

International Gravity Meter Ties, 1959

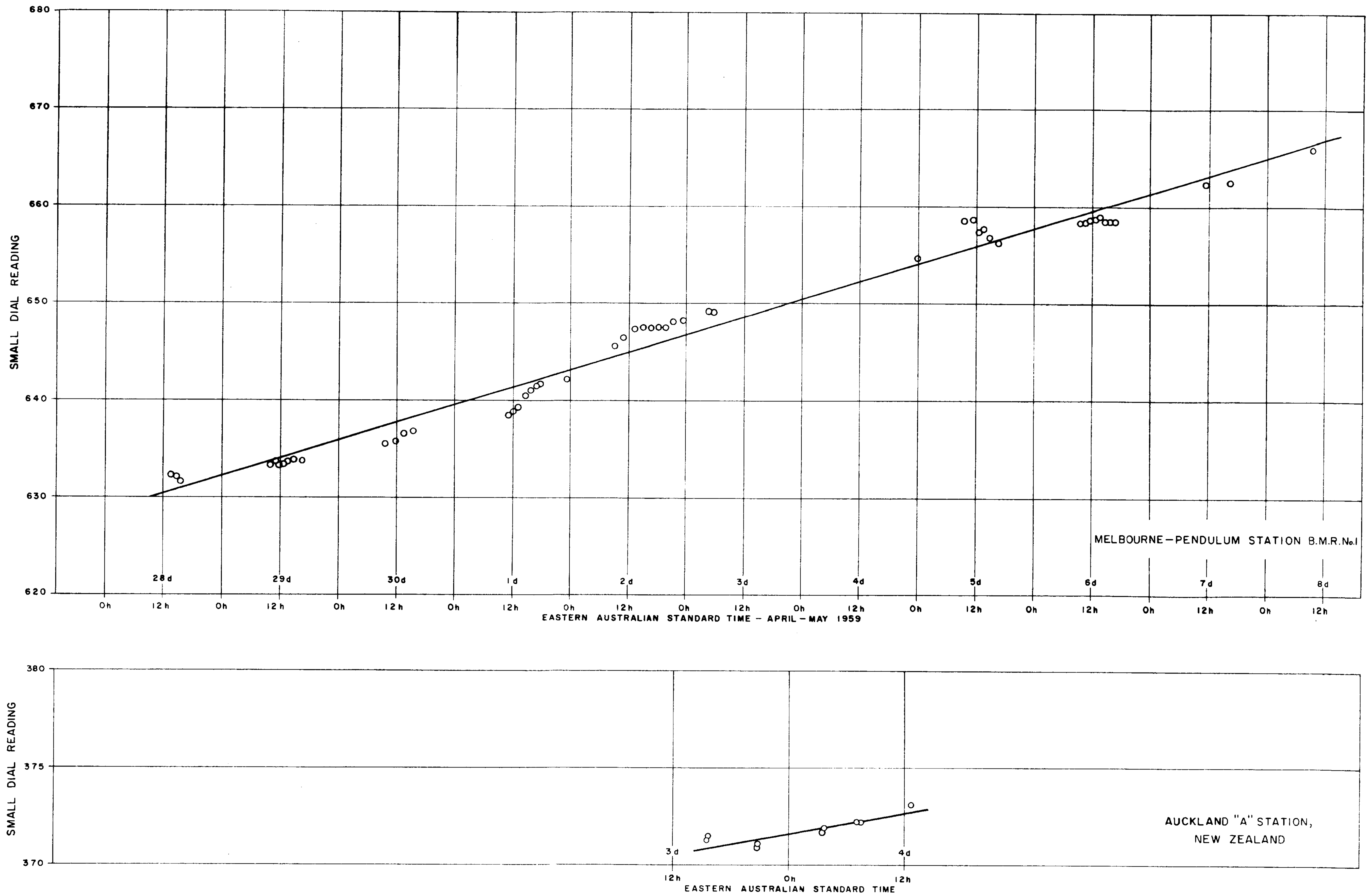

FIG. 5 CORRECTED READINGS FROM WORDEN GRAVIMETER SER. No. 140

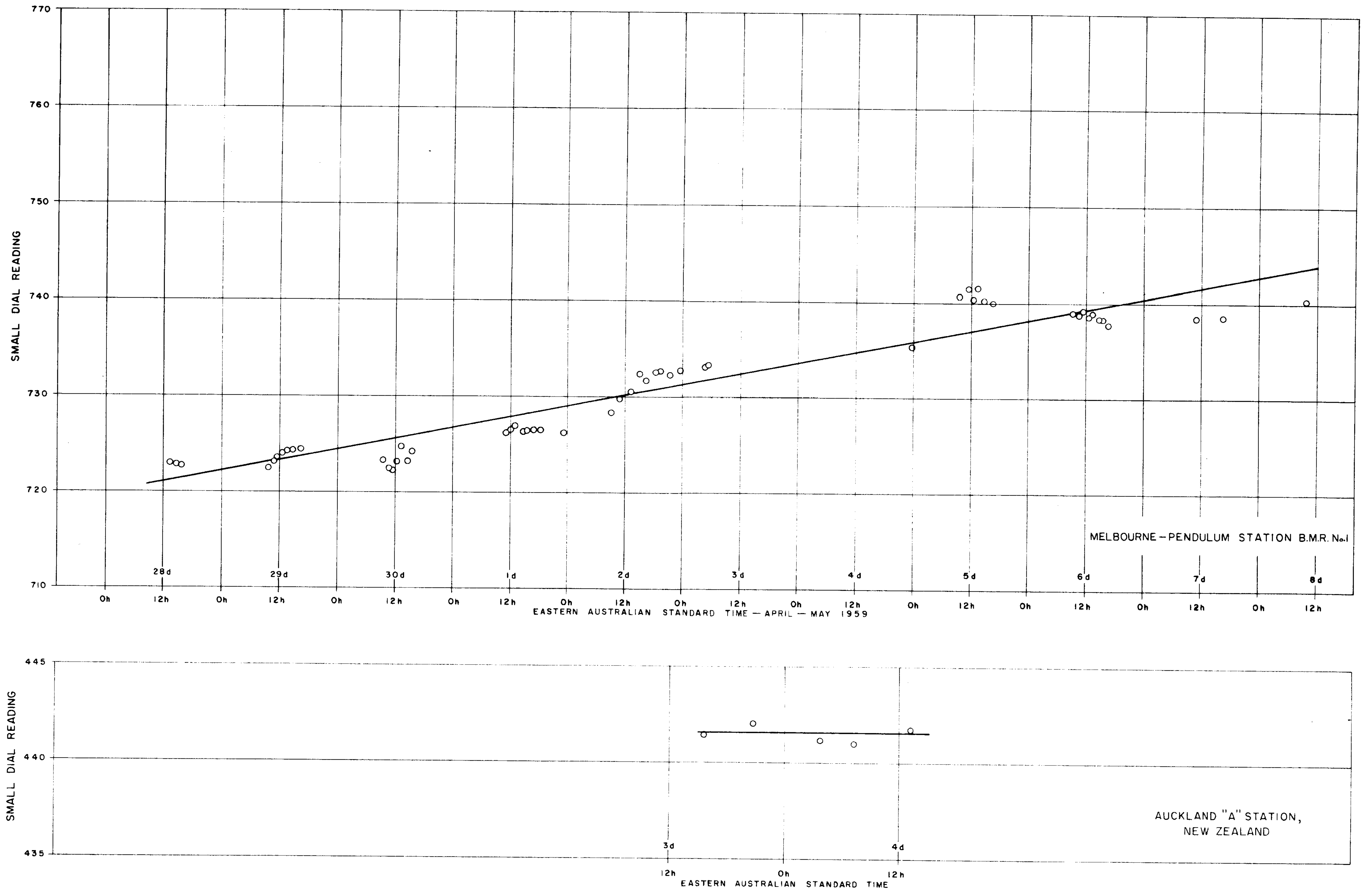

FIG. 6 CORRECTED READINGS FROM WORDEN GRAVIMETER SER. No. 169

READINGS AT OVERSEAS STATION PLOTTED WITH "TIME" AND "READING" SCALES EXPANDED EQUALLY — SLOPE OF DRIFT LINE IS DIRECTLY COMPARABLE WITH THAT OF AUSTRALIAN BASE STATION READINGS

International Gravity Meter Ties, 1959