NATURAL ENVIRONMENT RESEARCH COUNCIL

INSTITUTE of HYDROLOGY

REPORT No 21 August 1973

FIELD PERFORMANCE OF INSTITUTE OF HYDROLOGY AUTOMATIC WEATHER STATION

by

M N Leese, I C Strangeways and R F Templeman

INSTITUTE OF HYDROLOGY
CROWMARSH GIFFORD
WALLINGFORD
BERKS

CONTENTS

FIGURES

TABLES

INSTITUTE OF HYDROLOGY

Report No. 21 July 1973

FIELD PERFORMANCE OF INSTITUTE OF HYDROLOGY AUTOMATIC WEATHER STATION

by

M. N. Leese

I. C. Strangeways

R. F. Templeman

ABSTRACT

Details of the design of the Institute of Hydrology's automatic weather station are discussed, together with possible sources of inaccuracy in the measurements recorded. A model which has been used to estimate the precision of the data and to quantify the errors due to different sources is outlined. The programs used for data reduction are described and statistics are given of station and sensor reliability based on approximately 10 station-years of data.

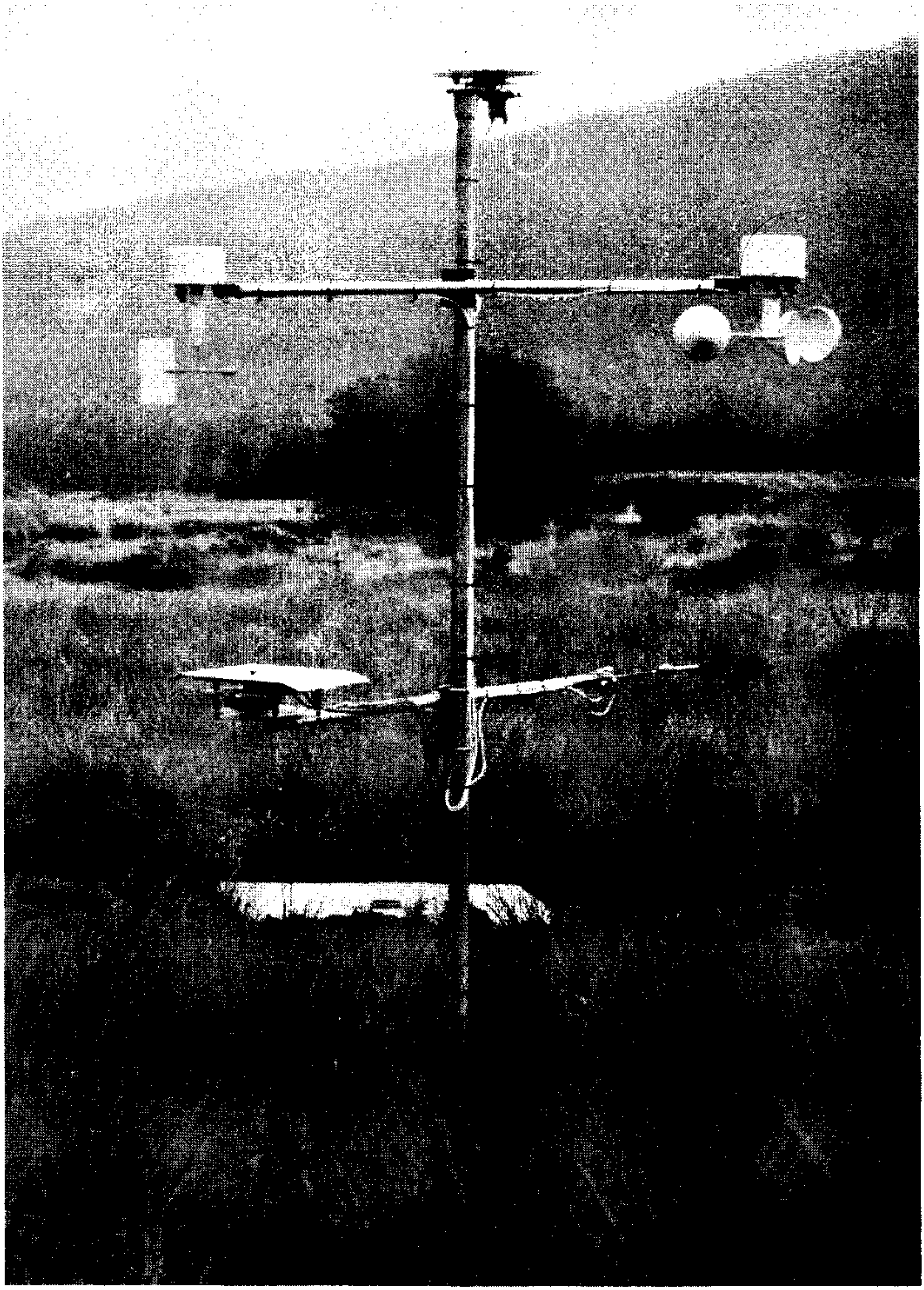

Fig 1 Institute of Hydrology automatic weather station

1. INTRODUCTION

The development of automatic weather stations was stimulated by the Water Resources Act of 1963 which imposed a statutory obligation on River Authorities to take all necessary hydrological measurements for the assessment of the water resources in their areas. From a research point of view, the necessity for the automatic recording of rainfall and the climatological data from which evaporation could be computed using Penman's equation (Penman 1948) was foreseen early on in the Institute's research programme (McCulloch and Strangeways 1966), especially for work in remote catchments. Because of the spatial variability of the measurements required, it was more important to be able to distribute cheap, simple stations, each logging data of reasonable accuracy rather than employing a sophisticated device providing great accuracy at a single point. The remoteness of some of the catchments also imposed the further constraints of ruggedness and operation from battery power.

The Institute now has about a dozen automatic weather stations (AWS) providing data on a regular basis in the United Kingdom and several others in overseas catchments. Knowledge of the system's reliability and precision is essential for instrument network design and in attaching significance to apparent areal variations. It is also important to ascribe the errors to specific sources so that the appropriate improvements in the instrumentation can be made.

2. THE AUTOMATIC WEATHER STATIONS

The automatic weather station is based on a compact magnetic tape data logging system which is capable of recording up to 12 analogue voltage inputs in digital form on Philips cassettes, written as 8-bit words serially along the 0.15" wide tape. The sensors measuring solar and net radiation, air temperature, wet bulb depression, wind run and wind direction are mounted on a simple mast with two cross arms while the raingauge is sited on the ground some 20 feet from the mast (see Fig. 1). Each sensor converts a measured value into an electrical signal which is then converted to a logger-compatible voltage by a compact interface unit (Fig. 2).

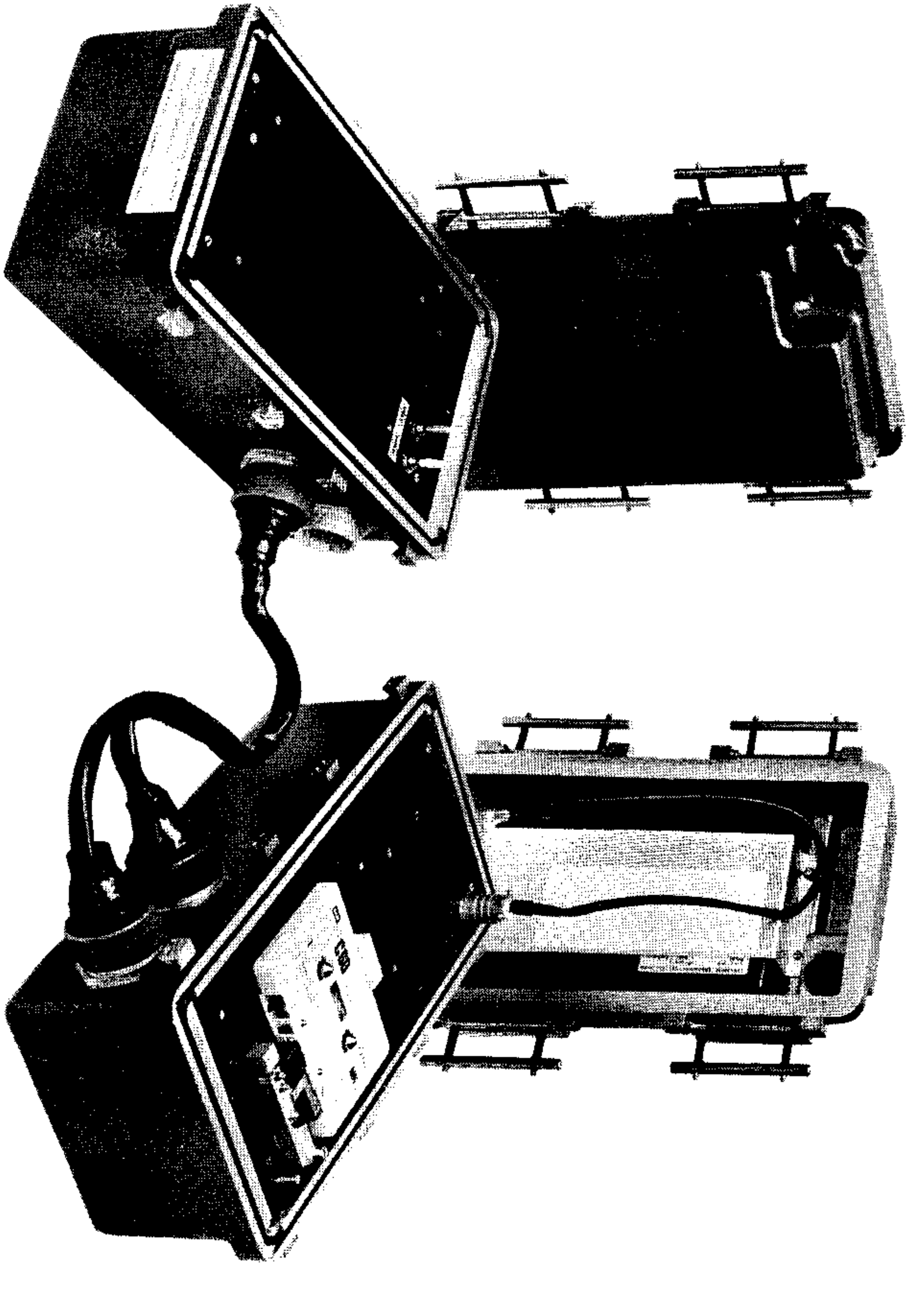

Fig 2 Interface unit and logger

These analogue signals are sequentially sampled, digitised and recorded by the battery-powered data logger; each sampling and recording sequence is termed a 'scan'. Scans take place at five minute intervals, giving a three to four week period of unattended operation when using C60 cassettes. The logger and interface units are powered by one rechargeable, nickel-cadmium battery housed in the logger's lid; they draw current only during the actual recording of data, i.e. with a half per cent duty cycle. Both units are pressurised to prevent the entry of dust or damp air and are manufactured by Microdata Ltd.

When stations are visited to retrieve the data tapes, complete loggers are interchanged. This means that the cassettes and batteries can be exchanged in the safer environment of the catchment office. While at the station, the operator records the time of change-over together with various information to help diagnose any faults discovered when the analysis is made. Routine inspection and maintenance are also performed; for example, checking that the radiometers and raingauge are level and clean, that the wet bulb is moist and the wind run sensor bearings are free. Cassettes containing data are subsequently returned to the Institute where they are read through a reader interfaced into the Institute's PDP8 computer. Hence, the expense of this central facility is shared by all the out-stations, which still provides fairly rapid identification of any station malfunction so that this information can be fed back to the field.

3. SOURCES OF EQUIPMENT ERROR

3.1 THE LOGGER

The accuracy of the logger is determined by the 8-bit analogue to digital converter (ADC). A drift of $\pm$ 2 logger steps in the full scale of 200 steps is typical over the temperature range of $-10^{\circ}C$ to $+40^{\circ}C$ specified for the stations. Nevertheless some correction can be made for this, since a stable reference voltage is recorded at the start of each scan (this word is called the scan mark) and is subject to the same fractional drift as the data channels.

3.2 THE SENSORS AND INTERFACES

Solar Radiation

The solarimeter used is manufactured by Kipp & Zonen, in the Netherlands, and is capable of measuring intensities up to 2 langleys/min. It measures the voltage generated by a thermopile,the hot junctions of which are in contact with a blackened disc exposed to the sun's radiation while the instrument case is screened by a large white disc which keeps it at ambient air temperature. The black disc is protected by two glass domes, the outer one being removable to allow cleaning to prevent accumulation of dust. There is a removable cartridge of silica gel crystals to keep the interior of the unit dry and so prevent condensation on the inside of the glass domes. The solarimeter is mounted at the top of the mast to avoid shading effects. The most important error arises if the instrument is tilted, especially on days when most of the radiation is direct. Other errors can arise from the azimuthal variation of the instrument's sensitivity, from the variation in its sensitivity with temperatures (about 0.2 per cent ^{o}C), and from cooling of the outer dome due to wind and/or evaporation of water after rain (Robinson 1966).

The instantaneous intensity is recorded every five minutes thus giving an hourly total based on twelve spot readings. This can introduce large random errors over short periods but over a day the effect is negligible. A quantitative analysis of this effect for hourly totals is given in a later section.

The drift in the interface amplifier can be up to two logger steps over the temperature range on the stations under discussion, although this has been reduced to less than one step on more recent models. Care has to be exercised when setting up the amplifier zero and again before the station is used in the field since an error of one logger step represents an error of about 17 langleys/day. Alternatively the zero may be set so that a positive reading is recorded for zero radiation; the true radiation may then be calculated by subtraction of the midnight reading from all other readings. This also allows correction for any long-term drifts which might occur in the threshold setting.

Net Radiation

The net radiometer is manufactured by Philipp Schenk Ltd., Austria, and operates over a range - 0.3 to + 1.5 langley/min. This instrument comprises a thermopile sited between two blackened discs, one pointing upwards, the other downwards. These are protected by polythene domes which provide the required wider spectral transmission (0.35 to 60μ). The sources of error are those mentioned for the solarimeter, principally condensation on the domes and tilt. A compromise has to be reached between possible shading effects of the mast and the length of boom on which it is mounted. Special care is necessary when setting up the amplifier zero, since net radiation can be negative at night when the earth's black body radiation exceeds the energy input; hence no simple quality control program check as can be made for solar radiation is possible.

Temperature

The sensor, manufactured by Sangamo Weston Ltd., is of the platinum resistance type. It forms one arm of a bridge circuit in the interface which allows temperatures in the range -10^{o}C to +40^{o}C to be recorded with a tolerance of 0.6^{o}C. The accuracy of the temperature determination depends largely on the stability of the bridge amplifier and power supply circuits and on the care taken in setting them up. It is essential that the thermometer is in good thermal contact with the air (good ventilation) and screened from sources of radiant energy. The thermometer is therefore enclosed in a compact, simple screen the efficiency of which has been proven in field conditions of high solar intensity and low wind speed by comparing the temperatures as measured in the screen with those obtained with a large board shading the screen. The accuracy is obviously limited at low wind speeds and possibly also when reflection from snow occurs, since it is not practicable to achieve forced ventilation from batteries. However, the screen employed is expected to be at least as efficient as the standard meteorological (Stevenson) screen.

Wet bulb temperature depression

Wet bulb temperature depression is measured by using two extra Sangamo Weston thermometers inside the same screen but with one enclosed in a tight-fitting muslin sleeve dipping into a container of distilled water.

These sensors form two arms of a bridge circuit, the output of which is proportional to the temperature depression. The thermometers are best selected in pairs because of the greater precision required (the range covered is 0 to 12^{O}C which is adequate for U.K. conditions but may need extension for use overseas). The muslin and water must be kept clean since solutes affect the evaporation from the wet bulb although the largest errors are due to lack of ventilation.

Wind run

Wind run is measured with a 3-cup anemometer, manufactured by Rock & Taylor, which drives the wiper arm of a continuous rotation servo potentiometer through a 3000 : 1 reduction gear train; wind speeds of up to 110 km/hour can be recorded. Since no amplifier or bridge circuit is involved, the errors in measurement are due entirely to the sensor. The main problems are friction and wear in the bearings and dirt on the potentiometer, the latter causing intermittent open circuits, which will often be interpreted as complete revolutions of the wiper by the analysis program, hence adding a spurious 9.7 km to the calculated wind run. With proper maintenance these problems can be kept to a minimum.

Wind direction

Wind direction is sensed by means of an array of 20 radially mounted reed switches activated by a magnet connected to the vane's shaft. The reeds connect into a network of resistors which divides the voltage across them according to the position of the vane. Small errors may be introduced by the change in wind pattern due to the mast but as the direction is not required accurately (and in any case the measurement is in 18^{O} steps) these can be ignored.

Rainfall

Rainfall is measured by a "Rimco" tipping bucket gauge manufactured by Rauchfuss Ltd., Australia, which has a collecting area of 327 cm^2. Each 0.5 mm of rain causes the bucket to tip, taking a magnet past a fixed reed switch which in turn activates an electro-mechanical counter in the interface. Errors in the interface can only arise from missed counts. Rainfall measurement is prone to well-known errors, the catch depending on exposure and aerodynamic effects. The gauge is mounted at ground level within an anti-splash grid and employs a syphon device in the funnel to limit flow at times of intense rainfall, so minimising errors due to the tipping action. Intensities up to 5.5 mm in 5 minutes can be measured, which may impose a limitation on the use of the current stations in some overseas catchments.

3.3 MAGNETIC TAPE DECK, CLOCK MECHANISM AND CASSETTE READING EQUIPMENT

The accuracy of data is influenced by the accuracy of the clock mechanism and the reliability of the magnetic tape deck. If the clock runs incorrectly or scans are missed completely, time synchronisation is lost which leads to daily totals and means being calculated for incorrect periods. Errors can also occur during the transfer of data words from the analogue to digital converter to the cassette, and in reading the cassette through the reader and interface into the computer. However, the use of serial recording provides better data integrity than does parallel recording where problems due to tolerances on skew and tape path alignment can produce bit dropout rates of 1 in 10^4.

4. DATA TRANSLATION AND ANALYSIS PROGRAMS

The sophistication of the computer programs used to translate the cassettes, to quality-control the data and to convert the various measurements into units in common usage imposes a final constraint on the quality of the data produced by the weather stations.

Cassettes are translated using a PDP8 computer. This has an 8K (12-bit word) core and a number of peripherals including a lineprinter and DECtape units. The translation process is carried out in two distinct stages:

4.1 CASSETTE TRANSLATION TO DECTAPE

The assembly language program, which controls the transfer of data from cassette through the Microdata reader interface into the PDP8 and then out to permanent storage on DECtape, uses the time between servicing interrupts to check the format of the scans and compile a frequency histogram of the number in the scan mark channel. If all scans are written correctly, the tape consists of scan marks (any number over 220) separated by 7 data channels. However, when the sequence is broken the program tries to classify the error into one of four classes and takes appropriate action to maintain the time sequence through the cassette. These are:-

Short Scan: when there are less than seven channels between two scan marks, the program makes up deficient channels with error mark words (2047).

Single extra channel: when there are eight channels between successive scan marks, the eighth data word is dropped and 512 added to the seventh to mark the error.

Missing scan mark: when there are fourteen channels between scan marks, an artificial scan mark (240) is inserted after the seventh data channel; both scans have 512 added to their last channels.

Other long scan scans or compound errors: artificial scan marks are inserted after each seventh data channel until a real scan mark is encountered; any deficiency is then made up with error marks. All scans so generated have 512 added to their last channels.

Data are stored in hourly blocks on DECtape (96 data words per block). Each DECtape has a capacity of about 60 days. The first blocks on the tape contain a directory of the data files on the tape plus the data from the last part-hour of the last cassette. This can then be retrieved when the next cassette is translated and inserted before its data to maintain continuity between cassettes.

4.2 CONVERSION OF RAW DATA TO DAILY AND HOURLY TOTALS AND AVERAGES

The second stage program, written in FORTRAN, takes the data from DECtape and generates either raw data listings on the lineprinter (see Fig. 3) or lineprinter or DECtape dumps of the daily and hourly totals of solar, net, wind run and rainfall measurements and averages of temperature, depression and wind direction as shown in Fig. 4. The start time of the data is stored as part of the DECtape directory and five minutes is added to this time for each scan, whether good or bad, throughout the data

EISTEDDFA GURIG *1

RAW DATA LISTING

SCAN	SOLAR	NET	DEP	TEMP	RUN	DIRN	RAIN	
239	35	75	14	89	65	84	107	9.00HRS ON 28/ 6/1972
239	42	82	16	88	97	78	107	9.05HRS ON 28/ 6/1972
239	66	109	14	87	126	80	107	9.10HRS ON 28/ 6/1972
239	53	90	16	88	156	78	107	9.15HRS ON 28/ 6/1972
239	55	100	16	94	185	80	107	9.20HRS ON 28/ 6/1972
239	29	69	15	90	10	80	107	9.25HRS ON 28/ 6/1972
239	36	78	15	88	37	78	107	9.30HRS ON 28/ 6/1972
239	43	84	20	91	68	81	107	9.35HRS ON 28/ 6/1972
239	48	94	21	94	98	78	107	9.40HRS ON 28/ 6/1972
239	69	92	18	93	124	81	107	9.45HRS ON 28/ 6/1972
239	106	158	24	97	156	72	107	9.50HRS ON 28/ 6/1972
239	123	180	26	98	191	80	107	9.55HRS ON 28/ 6/1972

SCAN	SOLAR	NET	DEP	TEMP	RUN	DIRN	RAIN	
239	116	170	27	99	19	87	107	10.00HRS ON 28/ 6/1972
239	31	73	19	99	49	87	107	10.05HRS ON 28/ 6/1972
239	27	64	18	91	76	87	107	10.10HRS ON 28/ 6/1972
239	112	163	23	97	103	72	107	10.15HRS ON 28/ 6/1972
239	55	123	23	96	135	81	107	10.20HRS ON 28/ 6/1972
239	67	101	14	92	168	93	107	10.25HRS ON 28/ 6/1972
239	46	90	21	95	197	84	107	10.30HRS ON 28/ 6/1972
239	37	77	21	93	25	74	107	10.35HRS ON 28/ 6/1972
239	45	86	19	92	56	87	107	10.40HRS ON 28/ 6/1972
239	60	105	24	96	87	85	107	10.45HRS ON 28/ 6/1972
239	36	74	19	91	117	74	107	10.50HRS ON 28/ 6/1972
239	47	87	20	93	147	72	107	10.55HRS ON 28/ 6/1972

SCAN	SOLAR	NET	DEP	TEMP	RUN	DIRN	RAIN	
239	41	81	20	92	180	79	107	11.00HRS ON 28/ 6/1972
239	28	67	8	87	9	68	107	11.05HRS ON 28/ 6/1972
239	32	71	7	89	32	62	107	11.10HRS ON 28/ 6/1972
239	17	56	6	87	58	66	107	11.15HRS ON 28/ 6/1972
239	25	61	9	84	87	74	119	11.20HRS ON 28/ 6/1972
239	33	71	9	85	115	72	131	11.25HRS ON 28/ 6/1972
239	25	64	7	85	142	81	131	11.30HRS ON 28/ 6/1972
239	21	61	4	85	166	72	131	11.35HRS ON 28/ 6/1972
239	24	63	1	84	191	66	131	11.40HRS ON 28/ 6/1972
239	54	93	3	85	19	68	131	11.45HRS ON 28/ 6/1972
239	72	113	4	92	42	66	131	11.50HRS ON 28/ 6/1972
239	37	80	4	90	66	68	131	11.55HRS ON 28/ 6/1972

Fig 3 Raw data from Eisteddfa Gurig

EISTEDDFA GURIG #1

HOURLY & DAILY DATA

SOLAR FACTOR= 122 NET FACTOR= 86

HOUR FROM	SOLAR CALS/CM**2	NET CALS/CM**2	DEP DEGREES C	TEMP DEGREES C	RUN KMS	DIRN DEGS	RAIN MMS	GOOD SCANS	
9	43.2	31.7	0.99	8.4	15.8	238.	0.0	12	28. 6.1972
10	41.6	31.7	1.14	9.0	17.3	247.	0.0	12	28. 6.1972
11	25.1	17.4	0.38	7.5	15.5	211.	1.0	12	28. 6.1972
12	69.0	48.8	0.99	9.4	15.3	244.	0.0	12	28. 6.1972
13	40.9	27.9	0.77	8.4	18.0	235.	0.5	12	28. 6.1972
14	69.0	45.8	0.65	9.1	14.1	226.	0.0	12	28. 6.1972
15	32.3	21.4	0.55	8.5	10.3	206.	0.0	12	28. 6.1972
16	19.7	12.7	0.50	8.2	0.0	249.	0.0	12	28. 6.1972
17	7.7	4.3	0.51	7.7	0.5	237.	0.0	12	28. 6.1972
18	7.5	4.0	0.50	7.3	0.8	243.	0.5	12	28. 6.1972
19	4.1	1.7	0.40	7.0	0.0	253.	0.0	12	28. 6.1972
20	1.2	-2.0	0.23	6.1	0.4	264.	0.0	12	28. 6.1972
21	0.7	-1.4	0.18	5.2	0.0	230.	0.0	12	28. 6.1972
22	0.7	-0.5	0.11	5.4	0.0	239.	0.0	12	28. 6.1972
23	0.7	-0.2	0.05	5.8	0.0	219.	0.0	12	28. 6.1972

HOUR FROM	SOLAR CALS/CM**2	NET CALS/CM**2	DEP DEGREES C	TEMP DEGREES C	RUN KMS	DIRN DEGS	RAIN MMS	GOOD SCANS	
0	0.7	0.1	0.00	5.5	0.9	217.	0.0	12	29. 6.1972
1	0.7	0.0	0.01	5.3	0.0	220.	0.0	12	29. 6.1972
2	0.7	0.1	0.00	5.4	0.0	217.	0.0	12	29. 6.1972
3	0.7	0.1	0.00	5.4	0.0	209.	0.0	12	29. 6.1972
4	1.1	0.3	0.00	5.3	0.0	214.	0.0	12	29. 6.1972
5	4.9	2.5	0.00	5.7	0.0	184.	0.0	12	29. 6.1972
6	9.0	5.6	0.09	6.4	10.7	152.	0.0	12	29. 6.1972
7	11.9	7.5	0.33	6.8	0.0	178.	0.0	12	29. 6.1972
8	18.5	12.1	0.48	7.1	1.5	173.	0.0	12	29. 6.1972

==

411.7	271.6	0.37	6.9	121.2	221.	2.0	DAILY CALCULATIONS BASED ON 24 HOURS OF DATA FOR 28/ 6/1972

==

Fig 4 Daily listing from Eisteddfa Gurig file. The solar and net radiation channels are converted to energy fluxes using the manufacturers' calibration figures which vary from instrument to instrument. The other channels have calibration factors which are the same for every station, although the cyclic nature of the wind run and rainfall channels requires special attention. Using only good scans, (that is excluding short scans which are terminated by error mark words and long scans marked by the addition of 512 to the normal maximum of 132 in the rainfall channel) each channel is first corrected for ADC drift using the scan mark channel value, and then hourly totals of each variable are accumulated. During the quality control stage some of the errors marked during translation can be corrected and the resulting scans used in the totals. For example inspection of a short scan often enables the missing channel to be identified and inserted, and subtraction of 512 from the last channel of certain long scans will yield correct original data. The solar and net totals are then corrected for missing scans, and the temperature, depression and wind direction measurements averaged over the good scans. In order that the totals are still good estimates even when errors have occurred, it is important that errors are identified and that in the cases of net and solar radiation where large fluctuations can occur during an hour, the number of errors is kept to a minimum. This is also true for wind run and rain where it is assumed that a complete cycle has not taken place between good scans.

The hourly totals and averages are then totalled over 24 hours to produce daily totals and averages, normally working on a 09.00 to 08.55 day. Where a cassette ends with the day incomplete, totals are compiled to the end of the cassette, and then added in at the beginning of the next, providing the data are continuous.

5. QUALITY OF DATA

Using data gathered during 1972 from sites at Plynlimon (at Eisteddfa Gurig = EG, Tanllwyth = T and Carreg Wen = CW) and at Coalburn in Northumberland (= CB), it has been possible to quantify the effects of the four main factors affecting the quality of weather station data. At most of these locations there were two station sites, designated as, for example, T1 and T2 for those at Tanllwyth.

TABLE I STATISTICS ON LOGGER RELIABILITY

	EG1	EG2	T1	T2	CW1+	CW2	CB1	CB2
Length of period of station operation (days)	365	365	365	365	345	323	353	353
Number of Cassettes	26	26	26	26	21	24	19	19
Number of suspected operator errors (and number of days data lost as consequence)	0(0)	2(33)	2(29)	3(34)	1(21)	1(14)	3(55)	1(19)
Number of confirmed operator errors	0(0)	0(0)	1(14)	1(15)	0(0)	0(0)	0(0)	1(16)
Number of logger malfunctions	0(0)	0(0)	1(0.5)	1(1.5)	0(0)	2(11.5)	1(4)	4(24.5)
Total data loss due to all causes (days)	0	33	43.5	50.5	21	25.5	59	59.5
Data return %	100	91	88	86	94	92	82	82
Number of cassettes affected by slow running clock	4	3	0	2	0	0	1	3
Data return pair	100		100		- (station removed for use elsewhere)		100	

+ this station operated at Grendon Underwood (Bucks) from April 1972

5.1 LOGGER RELIABILITY

The logger reliability is summarised in Table I. Failures are classified in three categories:-

System malfunction: No logger under investigation developed any component failure. Where data loss occurred it could be traced to problems such as an unusual accumulation of oxide dust on the recording head (apparently, in a short time) or a battery becoming flat (which can also sometimes be an operator error).

Operator error: This was suspected when a cassette contained no data and when the same logger performed satisfactorily for a subsequent period. Three errors actually noticed and reported by operators were a battery not connected, failure to engage the head with the tape and putting on a cassette the wrong way round. Small amounts of data have also been lost due to operators not winding cassettes past the tape leader before starting.

Slow running clocks or failure of the clock mechanism: This fault shows up as an intermittent drift, typically of about two hours per day in the time of apparent sunrise. It is hoped this infrequent problem will be cured by replacing the present battery wound, mechanical clocks with electronic clocks; useful information can often be retrieved from the affected cassettes but its abstraction is somewhat tedious.

In addition 40 days of data were lost at CW2 due to a rabbit chewing through the cable between the sensors and the interface. This period has been excluded from Table I.

A data return of 100 per cent was achieved at each site when pairs of stations were considered. The average individual return was 89 per cent with a range of 82 to 100 per cent. The greatest losses occurred at Coalburn where the cassettes are changed at three week intervals, as compared with two weeks elsewhere. Since one operator error can invalidate a complete cassette and because sensor, interface and logger errors cannot be detected, diagnosed and rectified until the cassette is processed, extended periods of unattended operation of single stations should be avoided if very high data returns are essential.

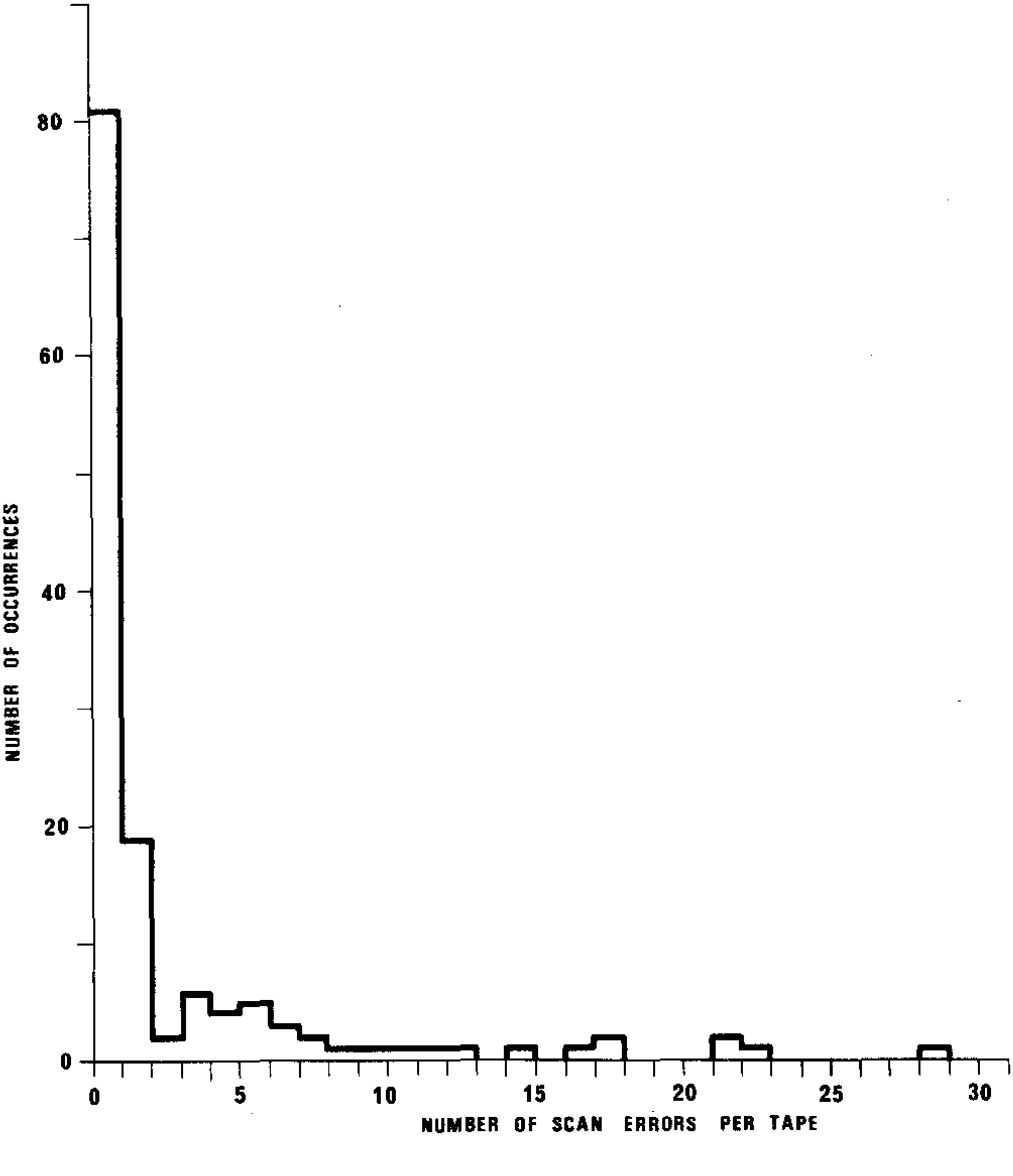

Fig 5 Scan error frequency distribution

5.2 SENSOR RELIABILITY

Sensor failure is difficult to quantify since it is seldom catastrophic. It normally leads to a reduction in measurement accuracy, and often has to be accepted as such. These effects are included in the statistical model described later. The only way in which small errors can be identified is by comparison with a neighbouring station, which is an additional reason for operating stations in pairs if high quality data are required.

This comment applied equally well to manually read data, where errors of even 20 per cent in solar and net radiation might otherwise go undetected.

Sensor errors can be divided into two classes:

Natural cuases: The most common errors were those connected with wind run measurement due to bearings wearing and potentiometer wipers becoming dirty. The bearings have since been redesigned and better potentiometers are now being used. Snowfall affected the data recorded by all the sensors, so periods during which snow fell will have larger errors. Condensation on the domes of the solarimeters and net radiometers was often observed, and the net radiometer domes were damaged by rain and birds (the former only in the tropics).

Operator slackness: particularly in checking that the radiometers were kept level and that the wet bulb water supply was maintained.

5.3 ACCURACY OF ANALYSIS PROCEDURES

Errors introduced into the data by loss of time synchronisation have been eliminated on virtually all cassettes. Fig. 5 shows a frequency distribution of the number of errors found on each cassette. 70 per cent of the cassettes had 0 or 1 error and 90 per cent less than 10 errors. A few cassettes had many errors, but this was due to logger malfunctions which have already been discussed in section 5.1. In all cases checked, the assumptions described in section 4.1 to maintain time synchronism appeared to be justified. Similarly, errors introduced because of the assumptions made when taking account of missing scans during the averaging procedures will also be negligible due to the few scans involved.

EISTEDDFA GURIG (PLYNLIMON, WALES)

DATE	SOLAR C/SQC 1	SOLAR C/SQC 2	SOLAR C/SQC DIFF	NET C/SQC 1	NET C/SQC 2	NET C/SQC DIFF	DEP DEG C 1	DEP DEG C 2	DEP DEG C DIFF	TEMP DEG C 1	TEMP DEG C 2	TEMP DEG C DIFF	WIND RUN KM 1	WIND RUN KM 2	WIND RUN KM DIFF	WIND DIRN DEG 1	WIND DIRN DEG 2	WIND DIRN DEG DIFF	RAIN MM 1	RAIN MM 2	RAIN MM DIFF	STATI 12
14 -6-72	422.	414.	-8.	222.	213.	-9.	1.4	1.8	0.5	9.1	9.3	0.2	181.0	196.0	15.0	176.0	168.0	-8.0	2.5	2.5	0.0	00
15 -6-72	280.	295.	15.	139.	132.	-7.	0.2	0.4	0.2	7.1	7.5	0.4	154.0	190.0	36.0	228.0	231.0	3.0	0.0	0.5	0.5	00
16 -6-72	509.	520.	11.	268.	302.	34.	1.0	1.2	0.3	8.8	9.1	0.3	278.0	284.0	6.0	245.0	258.0	13.0	1.5	1.0	-0.5	00
17 -6-72	106.	120.	14.	67.	75.	8.	0.0	0.1	0.1	8.1	8.5	0.4	879.0	867.0	-12.0	217.0	225.0	8.0	27.5	26.5	-1.0	00
18 -6-72	172.	186.	14.	101.	102.	1.	0.2	0.4	0.2	5.7	6.1	0.4	464.0	461.0	-3.0	256.0	265.0	9.0	13.0	13.0	0.0	00
19 -6-72	354.	370.	16.	209.	209.	0.	0.5	0.8	0.3	5.6	6.0	0.4	389.0	420.0	31.0	237.0	247.0	10.0	1.5	1.0	-0.5	00
20 -6-72	98.	113.	15.	59.	66.	7.	0.1	0.2	0.2	6.3	6.7	0.4	741.0	734.0	-7.0	217.0	227.0	10.0	6.5	7.0	0.5	00
21 -6-72	170.	189.	19.	103.	109.	6.	0.2	0.4	0.2	6.6	7.0	0.4	787.0	760.0	-27.0	244.0	253.0	9.0	3.5	2.5	-1.0	00
22 -6-72	257.	285.	28.	162.	169.	7.	0.6	0.8	0.3	6.2	6.6	0.4	589.0	576.0	-13.0	267.0	276.0	9.0	3.0	3.5	0.5	00
23 -6-72	212.	224.	12.	140.	141.	1.	0.2	0.4	0.2	7.2	7.6	0.4	573.0	564.0	-9.0	245.0	255.0	10.0	2.0	1.5	-0.5	00
24 -6-72	185.	192.	7.	127.	121.	-6.	0.0	0.1	0.1	8.5	8.8	0.3	590.0	584.0	-6.0	222.0	230.0	8.0	5.0	5.0	0.0	00
25 -6-72	86.	104.	18.	55.	60.	5.	0.0	0.1	0.1	8.6	9.0	0.4	400.0	444.0	44.0	221.0	231.0	10.0	39.5	39.0	-0.5	00
STATION MEANS	238.	251.	13.	138.	142.	4.	0.4	0.6	0.2	7.3	7.7	0.4	502.1	506.7	4.6	231.2	238.8	7.6	8.8	8.6	-0.2	
STATION ERRORS			9.33			1.58			0.15			0.26			0.00			5.25			0.10	
RANDOM ERRORS			5.97			7.87			0.08			0.05			15.69			3.83			0.38	
TOTAL ERRORS			11.08			8.03			0.17			0.26			15.69			6.50			0.40	

NUMBER OF DAYS IN PERIOD UNDER INVESTIGATION= 12

Fig 6 Comparison of daily means at Eisteddfa Gurig

One source of error has arisen due to operators swapping or replacing broken net and solar sensors without passing the information back to base. This has led to confusion as to which calibration factors should have been used for certain periods.

Rounding errors due to computation have been minimised and the number of significant figures printed for hourly and daily totals has been chosen so that the figures are at least as accurate as the basic measurement.

5.4 THE PRECISION OF SENSORS AND INTERFACES

To estimate the errors in measurements produced by the automatic weather stations over long periods of field running, two types of analysis of variance were performed on the 1972 data from Plynlimon (three locations) and Coalburn; the aim of the first was to give estimates of the errors in daily values, and the aim of the second was to estimate the significance of the average differences between sensors and between interfaces over periods of about a fortnight.

Errors in daily values

At each of the four locations in the study there were two weather stations thus giving 2n values per period of each variable at each location, where n is the number of days in the period. An example of the data available at each location is illustrated in Figure 6, produced by the PDP8 from the DECtapes containing daily data. A separate analysis was performed for each period in 1972 and was repeated for the first five parameters in the table. Wind direction was excluded because its unit of measurement is circular and rainfall because of the preponderance of zeros in its data.

In our model two sources of variation are considered to affect the value of a variable (given a particular period and location), namely, the day and the site (weather station) at which it was observed. The variation of any daily mean or total x_{ij} (on the ith day at the jth site) from the overall mean μ of the period is assumed to arise from three independent sources:

(a) a day effect d_i differing from day to day but common to both sites

(b) a site effect s_j differing from site to site, but common to all days

TABLE II STANDARD ERRORS OF DAILY VALUES

		Solar Rad. ($cal.cm^{-2}$)	Net Rad. ($cal.cm^{-2}$)	Depression (^oC)	Temperature (^oC)	Wind Run (km.)
Coalburn	I	4.1	6.7	0.03	0.07	5.8
	II	10	20	0.1	0.30	50
	III	19.5	45.4	0.31	1.26	131.8
Tanllwyth	I	4.7	3.5	0.02	0.05	8.3
	II	10	10	0.1	0.15	50
	III	25.3	15.6	0.14	0.43	109.7
Eisteddfa Gurig	I	9.0	5.2	0.01	0.05	9.6
	II	15	15	0.1	0.25	25
	III	21.8	26.9	0.58	0.39	66.6
Carreg Wen	I	7.0	6.5	0.01	0.03	48.0
	II	15	10	0.05	0.10	70
	III	45.2	15.8	0.13	0.17	130.8

I represents - lowest value.

II represents - typical value.

III represents - highest value.

(c) a random component ε_{ij} corresponding to the residual variation after removal of d_i and s_j.

An additive model is assumed as follows:

$$x_{ij} = \mu + d_i + s_j + \varepsilon_{ij} \; (i = 1, n \; ; \; j = 1,2)$$

The means of d_i, s_j and ε_{ij} are assumed to be zero and their variances, assumed constant, are denoted by σ_D^2, σ_S^2 and σ_R^2 respectively.
Since a daily value from either site is supposed to be representative of the location as a whole, site to site differences within the location are regarded as contributing to the error, so the total variance of the daily mean or total, σ_T^2 is given by

$$\sigma_T^2 = \sigma_S^2 + \sigma_R^2$$

Sums of squares of deviations from means and mean squares of the daily values were calculated using the PDP8 computer. The site to site mean square gives an estimate of $\sigma_R^2 + n\sigma_S^2$ and the residual mean square an estimate of σ_R^2. From these σ_S^2 and thus σ_T^2 were determined. The results for one period also appear in Figure 6 where σ_S and σ_R are referred to as station and random errors respectively.

For periods where clock and operator errors were not suspected, the estimates for σ_T were tabulated for each variable, followed by abstraction of the lowest, highest and representative values as shown in Table II.

The results show that the radiation measurements have reasonably small errors although, inevitably, the percentage errors on net radiation are high in the winter when the net radiation itself is near zero. The least satisfactory measurement was wind run which showed typical errors of around 50 km day^{-1}. The influence of site to site differences was suggested by these figures but this was not borne out by the results presented in the next section, probably because the dirty potentiometer fault responsible for the errors had to a large degree been cured for the period of the second variance analysis. Temperature and depression were measured adequately for their use in the Penman equation.

Sensor and Interface Study

The study of daily values revealed site to site variations which could be due either to real site to site differences in the variables measured or to sensor or interface differences. Two experiments lasting 16 weeks (June - September 1972) were carried out at Eisteddfa Gurig and Tanllwyth aimed at separating the components of variance. Both experiments involved the regular interchange of sensors S_1 and S_2 and interfaces I_1 and I_2 from position P_1 to position P_2 at intervals of about a fortnight on the completion of each cassette. Two replications of the complete interchange cycle were made according to the scheme shown in Table III.

TABLE III

ROTATION SCHEME FOR SENSOR AND INTERFACE INTERCHANGE

Period	Mean of variable at P_1	Sensor at P_1	Interface at P_1	Mean of variable at P_2	Sensor at P_2	Interface at P_2	Replication
1	y_{1111}	S_1	I_1	y_{2221}	S_2	I_2	
2	y_{1211}	S_2	I_1	y_{2121}	S_1	I_2	R_1
3	y_{1221}	S_2	I_2	y_{2111}	S_1	I_1	
4	y_{1121}	S_1	I_2	y_{2211}	S_2	I_1	
1	y_{1212}	S_2	I_1	y_{2122}	S_1	I_2	
2	y_{1122}	S_1	I_2	y_{2212}	S_2	I_1	R_2
3	y_{1222}	S_2	I_2	y_{2112}	S_1	I_1	
4	y_{1112}	S_1	I_1	y_{2222}	S_2	I_2	

Y_{ijkl} represents the period mean (ie the mean of the daily values over the period) of a variable (solar, net, depression, temperature or wind run) recorded at position P_i by sensor S_j and interface I_k in replication R_l.

The mathematical model assumed for y_{ijkl} was

$$y_{ijkl} = \upsilon + (P)_i + (S)_j + (I)_k + (R)_l + (PS)_{ij} + (SI)_{jk} + (PI)_{ik}$$

$$+ (PSI)_{ijk} + \eta_{jkl} + \varepsilon_{ijkl} \quad (i,j,k,l = 1,2)$$

where υ is the overall mean for both stations over the experimental period, $(P)_i$, $(S)_j$, $(I)_k$ and $(R)_l$ are the effects due to the appropriate position, sensor, interface and replication respectively; $(PS)_{ij}$ and similar terms are interaction effects and η_{jkl} and ε_{ijkl} are random components assumed to be distributed independently with zero means and variances σ_η^2 and σ_ε^2 respectively.

The experimental design and model described represent a 'split-plot' type of analysis of variance (Kempthorne 1952) which allows the effects of principal interest (those due to sensors and interfaces) to be estimated with greatest precision.

Period *I* measurements (y_{1212}) at Tanllwyth were missing and had to be estimated before the analysis could be completed. Each variable was approximated by

$$y_{1212} = y_{2122} + \delta$$

where $\delta = \frac{1}{3} \quad y_{1211} + y_{2211} + y_{2212} - y_{2121} - y_{1121} - y_{1122}$,

that is, the values for the $S_1\ I_2$ combination in the same period as the missing $S_2\ I_1$ combination were adjusted by the average differences between all other $S_2\ I_1$ and $S_1 I_2$ combinations. This meant that one degree of freedom was lost in the analysis.

The results of the experiment are shown in Table IV for Eisteddfa Gurig and in Table V for Tanllwyth. Effects due to position are not given as they were negligible in all cases, as were interaction effects. The means are of the appropriate subsets of the y_{ijkl} values of Table III. The differences in the means indicate the degree of agreement, over the experimental period, of the sensors or interfaces; those at Tanllwyth agree more closely than those at Eisteddfa Gurig. It is possible that the differences arose merely by chance and a repetition of the experiment

TABLE IV SENSOR AND INTERFACE ERRORS AT EISTEDFFA GURIG

a <u>Sensors at Eisteddfa Gurig</u>

Variable:	Solar ($cals.cm^{-2}$)	Net ($cals.cm^{-2}$)	Dep(^{o}C)	Temp(^{o}C)	Wind Run (km)	Rainfall (mm)
Mean for sensor 1	308	157	0.8	9.1	339	5.44
Mean for sensor 2	321	172	0.7	9.3	353	5.45
Mean 2 - Mean 1	13	15	- 0.1	0.2	16	0.01
Standard error of difference	± 4	± 8	± 0.01	± 0.05	± 15	± 0.03
Significance level of difference	5%	None	5%	5%	None	None

b <u>Interfaces at Eisteddfa Gurig</u>

Variable:	Solar ($cals.cm^{-2}$)	Net ($cals.cm^{-2}$)	Dep(^{o}C)	Temp(^{o}C)	Wind Run (km)	Rainfall (mm)
Mean for interface 1	307	161	0.7	9.0	350	5.48
Mean for interface 2	321	169	0.8	9.4	344	5.41
Mean 2 - Mean 1	14	8	0.1	0.4	6	0.07
Standard error of difference	± 4	± 8	± 0.01	± 0.05	± 15	± 0.03
Significance level of difference	5%	None	5%	1%	None	None

TABLE V SENSOR AND INTERFACE ERRORS AT TANLLWYTH

a Sensors at Tanllwyth

Variable:	Solar (cal.cm^{-2})	Net (cal.cm^{-2})	Dep (^{o}C)	Temp (^{o}C)	Wind run (km)	Rainfall (mm)
Mean for sensor 1	346	152	1.1	10.7	159	3.80
Mean for sensor 2	339	166	1.1	10.7	182	3.63
Difference: Mean 2 - Mean 1	- 7	14	0.0	0.0	23	0.17
Standard error of difference	± 4	± 2	± 0.04	± 0.06	± 29	± 0.20
Significance level of difference	None	1%	None	None	None	None

b Interfaces at Tanllwyth

Variable:	Solar (cal.cm^{-2})	Net (cal.cm^{-2})	Dep (^{o}C)	Temp (^{o}C)	Wind run (km)	Rainfall (mm)
Mean for interface 1	341	159	1.1	10.7	167	3.79
Mean for interface 2	342	160	1.2	10.7	173	3.64
Difference: Mean 2 - Mean 1	- 2	1	0.1	0.0	6	0.25
Standard error of difference	± 4	± 2	± 0.04	± 0.06	± 29	± 0.20
Significance level of difference	None	None	None	None	None	None

on another occasion would give rise to contrary results. Only when the difference in means greatly exceeds the random variation in the data can that experimental difference be considered indicative of a long term effect. This can be expressed in terms of a statistical significance level, where a level of one per cent means that the probability of the difference arising by chance when no real difference exists is 0.01. Where no significance level is quoted for the difference, it is likely that it has arisen by chance.

The residual variation in the net radiation at Eisteddfa Gurig was high, possibly due to the use of incorrect calibration constants for part of the experimental period, thus casting some doubt on the validity of this result. With the exception of wind run, the other measurements at this location showed significant differences between sensors and between interfaces. At Tanllwyth the only significant difference was between the net sensors.

Since the experiments were not designed to estimate location to location differences (ie between Eisteddfa Gurig and Tanllwyth), the experiments should be considered independently but the means over the experimental period at each location are shown in Table VI for interest.

TABLE VI

OVERALL MEANS AT EISTEDDFA GURIG AND TANLLWYTH DURING THE EXPERIMENTAL PERIOD.

Location	Solar ($cals.cm^{-2}$)	Net ($cals.cm^{-2}$)	Dep (^oC)	Temp (^oC)	Wind Run (km)	Rainfall (mm)
Eisteddfa Gurig	314	165	0.8	9.2	347	4.8
Tanllwyth	343	159	1.1	10.7	169	3.7

6. COMPARISON OF SOLAR MEASUREMENT FROM AWS WITH THAT FROM INTEGRATING RECORDER

It has been suggested that the method used for determining hourly and daily totals of solar radiation by combining spot readings taken at five minute intervals might lead to errors. In order to investigate this, data recorded by the Microdata weather station at the Institute's meteorological site at Grendon Underwood was compared with the data produced by a Kent recorder mounted alongside the weather station. This device integrates solar radiation continuously for an hour and then prints out the total. Hence both devices produce digital output: a step on the weather station being 0.6 $cal.cm^{-2}. hr^{-1}$ and a step on the Kent 0.2 $cal.cm^{-2}.hr^{-1}$. Data from two six day periods, one in November 1972 and one in July 1972 were selected at random to be representative of winter and summer data and compared (see Figs. 7 and 8).

We assume that the Kent recorder produces an hourly reading K_i when the solar radiation is S during the ith hour according to

$$K_i = m_K S_i + Z_K + \varepsilon_i$$

where m_K is a sensitivity factor, Z_K is a zero offset (the radiation level above which the recorder produces an output), ε_i the random error for the ith hour, such that the ε_i have a mean of zero and a constant variance σ_ε^2. Similarly for the weather station we can write

$$W_i = m_W S_i + Z_W + \eta_i$$

for sums of solar readings from 12 scans. Assuming the $\varepsilon_i = 0$ since they are small,

$$S_i = \frac{K_i - Z_K}{m_K} = \frac{W_i - Z_W - \eta_i}{m_W}$$

Solving for W_i (the hourly solar reading from the weather station) we get

$$W_i = \frac{m_W}{m_K} K_i + (Z_W - \frac{m_W}{m_K} Z_K) + \eta_i .$$

A linear regression of the form

$$W = a + bK$$

was fitted to the Grendon data for each day using the daylight hours only. Figure 9 shows the scatter of the summer period data about the best fit line. Hence, assuming the ε_i are zero, estimates for a, b and σ_η were obtained for each day and for the six day periods, (Tables VII A and B). The constant b which is a measure of the relative calibration of the two

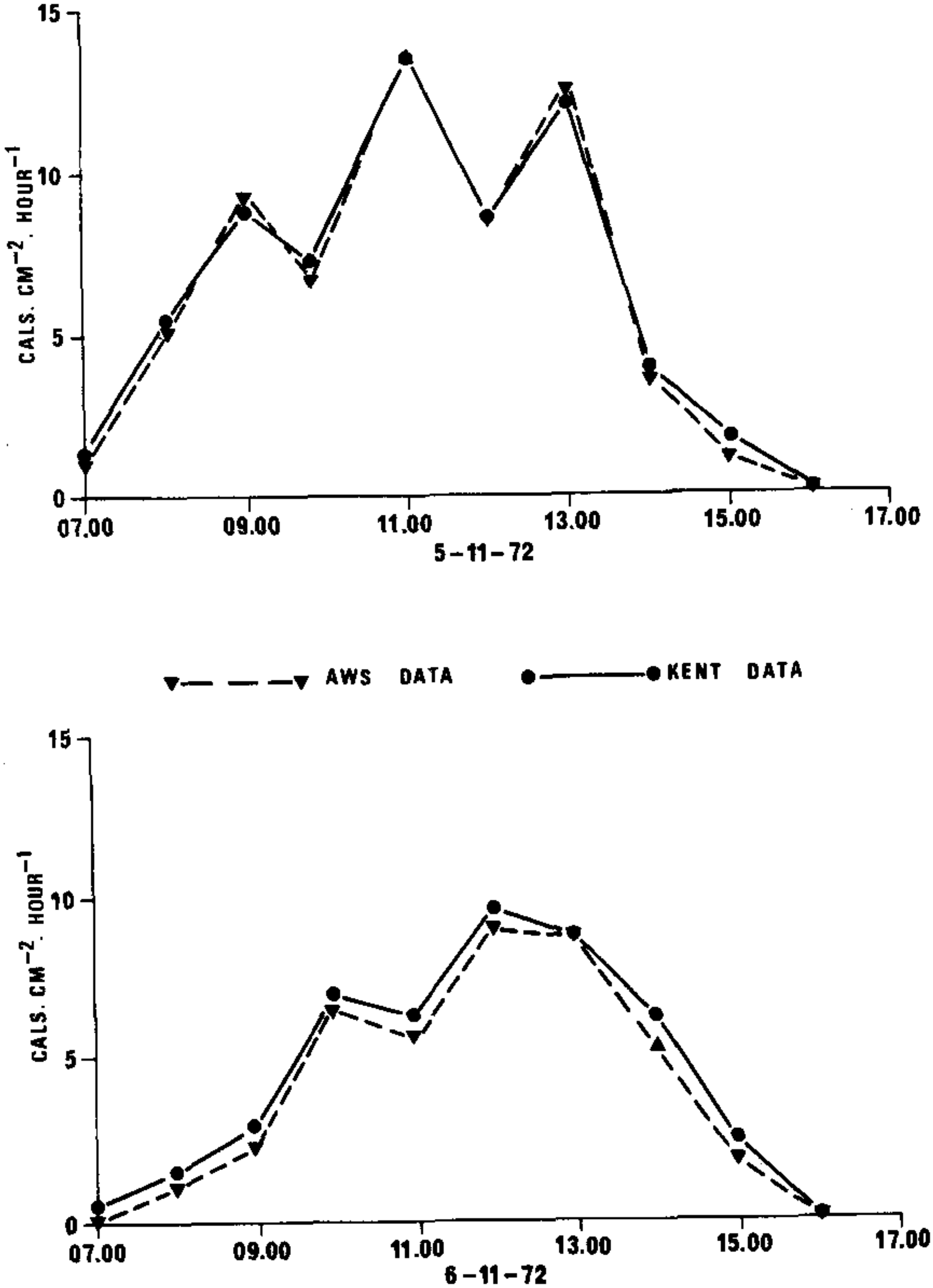

Fig 7 Comparison of winter solar radiation measured by automatic weather station and Kent recorder

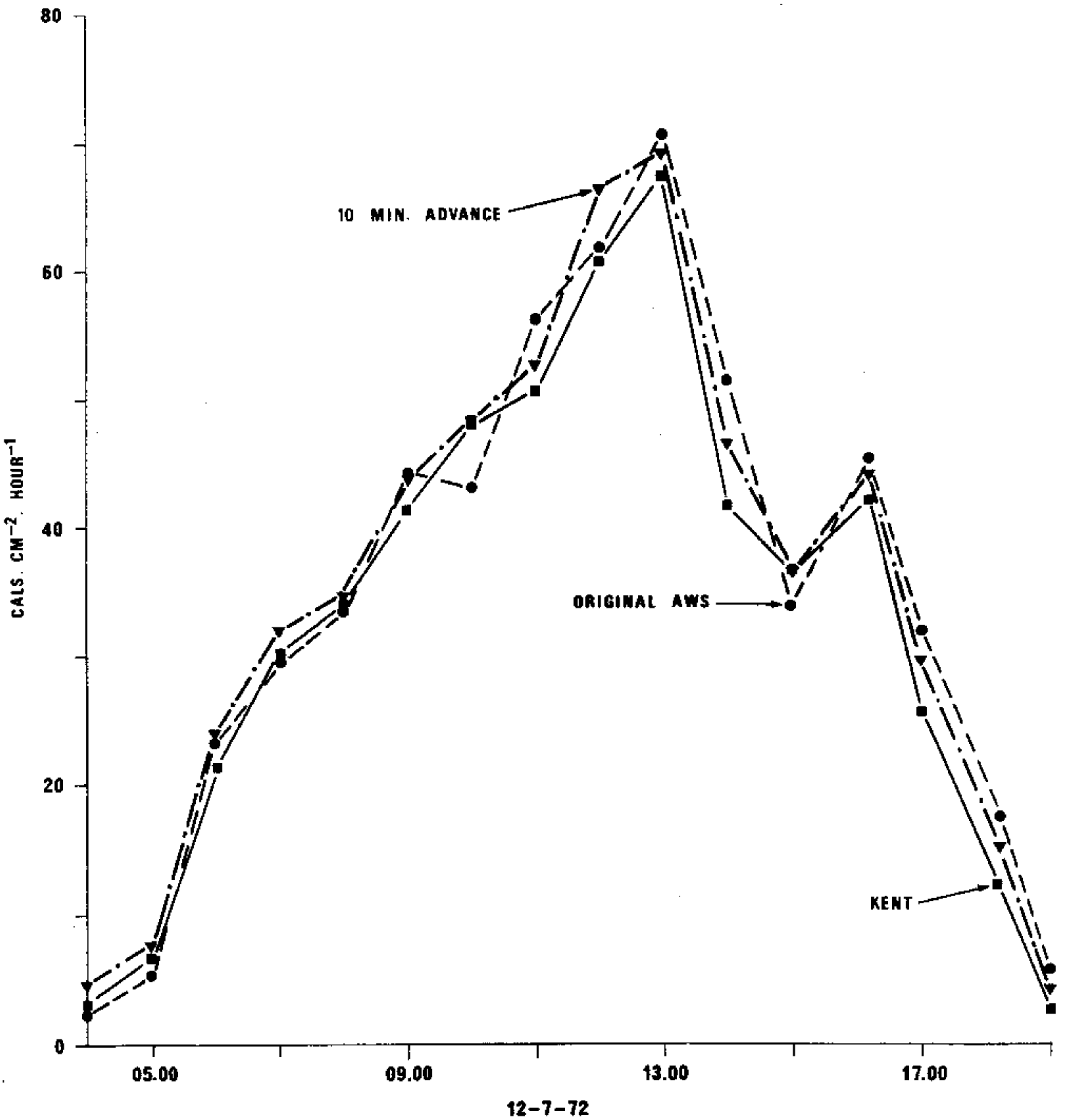

Fig 8 Comparison of summer solar radiation measurements

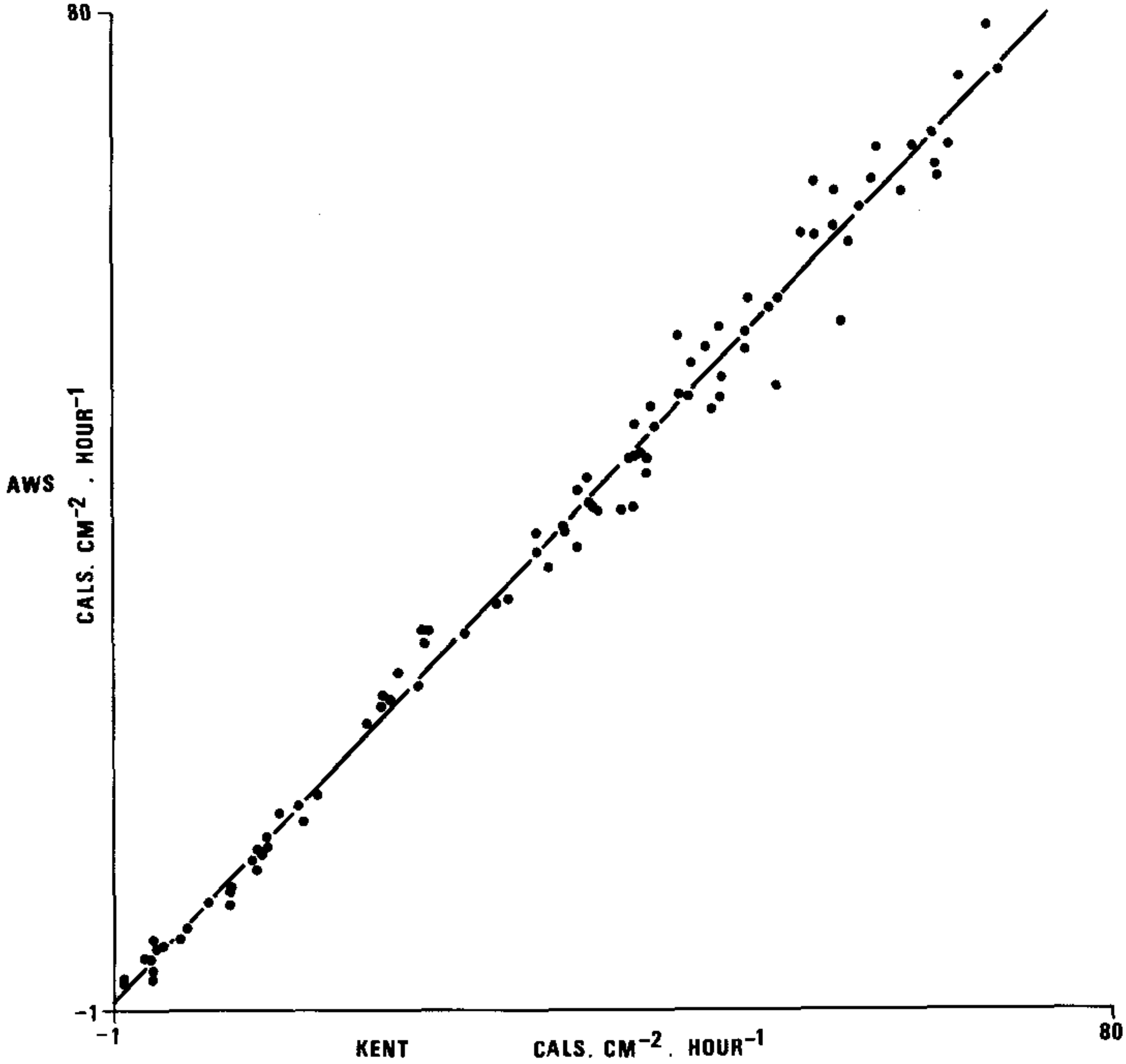

Fig 9 Automatic weather station versus Kent recorder solar radiation measurements regression

TABLE VII AUTOMATIC WEATHER STATION - KENT RECORDER REGRESSION CONSTANTS

A. Winter Period

Date	Regression Constants b	Regression Constants a. (cals.cm^{-2}hr^{-1})	Correlation Coefficient (%)	Solar Radiation (cals.cm^{-2}) Peak hourly	Solar Radiation (cals.cm^{-2}) Total	σ_n (cals.cm^{-2}hr^{-1})
1.11.72	1.02 ± .03	- 0.04 ± 0.29	99.6	20	77	0.6
2.11.72	1.05 ± .02	- 0.18 ± 0.18	99.7	17	66	0.3
3.11.72	1.05 ± .02	- 0.23 ± 0.14	99.8	13	59	0.2
4.11.72	1.02 ± .02	- 0.35 ± 0.11	99.9	12	58	0.2
5.11.72	1.04 ± .02	- 0.52 ± 0.13	99.9	13	55	0.2
6.11.72	1.01 ± .02	- 0.52 ± 0.13	99.8	9	40	0.2
Period	1.04 ± .01	- 0.34 ± 0.08	99.7			0.4

B. Summer Period

Date	Regression Constants b	Regression Constants a.(cals.cm^{-2}hr^{-1})	Correlation Coefficient (%)	Solar Radiation (cals.cm^{-2}) Peak hourly	Solar Radiation (cals.cm^{-2}) Total	σ_n (cals.cm^{-2}hr^{-1})
11.7.72	1.03 ± .07	0.82 ± 2.93	96.7	76	580	6.0
12.7.72	1.01 ± .05	1.71 ± 1.99	98.2	71	582	4.0
13.7.72	1.04 ± .04	0.95 ± 1.46	99.1	61	513	2.8
15.7.72	1.06 ± .04	0.72 ± 1.73	99.2	78	649	3.8
16.7.72	1.05 ± .04	1.08 ± 1.57	98.8	62	532	3.5
17.7.72	1.07 ± .04	0.61 ± 1.41	99.2	70	535	3.1
Period	1.04 ± 0.02	0.90 ± 0.74	98.6			3.8

TABLE VII continued ...

C. Summer Period. AWS data advanced

Date	Regression Constants b	Regression Constants a.(cals.cm^{-2}hr^{-1})	Correlation Coefficient %	σ_n (cals.cm^{-2}hr^{-1})
11.7.72	1.03 ± .04	1.13 ± 1.50	99.1	3.1
12.7.72	1.02 ± .02	1.60 ± 0.83	99.7	1.7
13.7.72	1.04 ± .02	1.02 ± 0.84	99.7	1.6
15.7.72	1.05 ± .03	1.32 ± 1.17	99.6	2.6
16.7.72	1.06 ± .04	0.83 ± 1.32	99.1	2.9
17.7.72	1.09 ± .02	- 0.15 ± 0.58	99.9	1.3
Period	1.05 ± 0.1	0.89 ± 0.43		2.3

instruments was found to be 1.04 for both periods, suggesting a relative calibration error of 4 per cent. The constant a, which represents the difference in the instruments' zero settings (taking $m_W/m_K = 1$) was - 0.3 $cals.cm^{-2}. hr^{-1}$ in winter and 0.9 $cal.cm^{-2}. hr^{-1}$ in summer, the change probably being attributable to temperature effects in one or both instruments.

In winter the standard error of the weather station hourly solar measurement was typically 0.3 $cals.cm.^{-2}hr^{-1}$ which can be explained purely by logger step size and computer rounding errors. In summer the standard error was typically 6 per cent of the peak hourly reading. However, attributing this to the sampling technique would be pessimistic as there is no guarantee that the two measuring instruments are in time synchronisation; indeed, when the weather station data was advanced by ten minutes, the totals recomputed and regressions coefficients redetermined, better fits were obtained and the standard error reduced to 3 per cent. (Table VII C). Assuming the data taken in this study to be representative, we can conclude that the random errors introduced by the sampling technique employed by the weather stations are not likely to be greater than systematic calibration errors, even for periods as short as one hour. This may not be too surprising if we bear in mind that the so-called spot readings are in fact measurements integrated over a period of about 20 seconds by the thermal capacity of the solarimeter. Similar comments can also be made about the net radiation measurements.

Acknowledgements

Acknowledgement is gratefully made to Institute staff responsible for operating the weather stations under all climatic conditions at remote sites, to Mrs Lynda Raynor for her efficient translation of the cassettes and to Mr Robin Clarke for many useful discussions during the design and analysis of the experiments.

References

1. McCulloch J S G & Strangeways I C, 'Automatic Weather Stations for Hydrology'. 1966 World Met Org Tech Conf

2. Penman, H L 'Natural Evaporation from Open Water, Bare Soil and Grass'. Proc Roy Soc (London) (A) 193, 120 (1948)

3. Robinson, N 'Solar Radiation' Elsevier Publishing Co 1966 347p.

4. Kempthorne, O 'The Design and Analysis of Experiments', 1952. John Wiley and Sons, London Chapter 19.