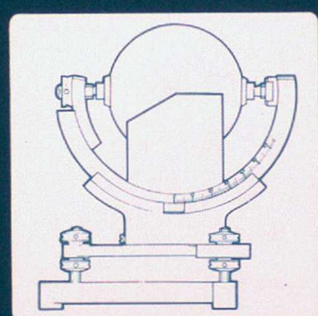
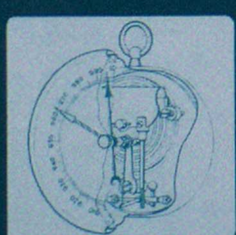
Meteorological Office

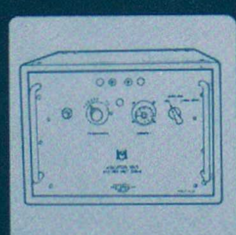
Handbook of Meteorological Instruments

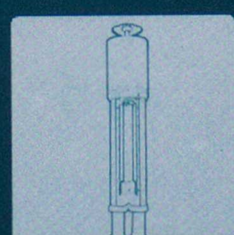
Second Edition

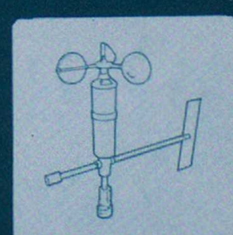
6 Measurement of Solar and Terrestrial Radiation

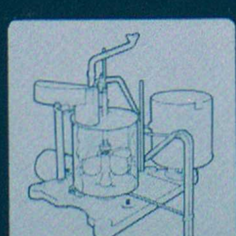


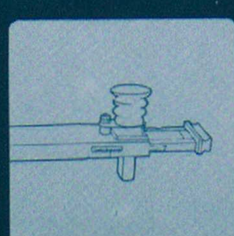


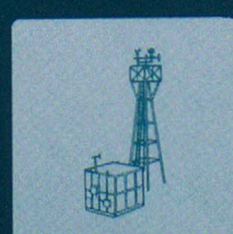












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METEOROLOGICAL OFFICE

HANDBOOK OF METEOROLOGICAL INSTRUMENTS

SECOND EDITION

VOLUME 6

MEASUREMENT OF SUNSHINE AND SOLAR AND TERRESTRIAL RADIATION

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INTRODUCTION

The first edition of the *Handbook of meteorological instruments* was prepared by the Instruments Division of the Meteorological Office in 1953, to provide a comprehensive source of information on the design, installation, operation and maintenance of all instruments then in use at Meteorological Office stations. Since then numerous improvements have been made to existing instruments, and new instruments and instrument systems introduced into service. This revised edition, whilst retaining some of the original material, gives information on the more recently developed instruments, and records the modifications made to some of the instruments previously described. In general, only instruments currently in use are included and if information is required on older, obsolete, types reference should be made to the previous edition.

Initially, eight separate volumes, each dealing with a specific aspect of meteorological instrumentation for surface observations, are being presented as follows:

Volume 1 Measurement of Atmospheric Pressure
Volume 2 Measurement of Temperature
Volume 3 Measurement of Humidity
Volume 4 Measurement of Surface Wind
Volume 5 Measurement of Precipitation and Evaporation
Volume 6 Measurement of Sunshine and Solar and Terrestrial Radiation
Volume 7 Measurement of Visibility and Cloud Height
Volume 8 General Observational Systems

When complete, the set can be bound to form one book.

Although this handbook is intended primarily to provide information for Meteorological Office personnel about the instruments used at official stations, particulars of some other types are included to illustrate different principles. Where these other types are not described in detail, sources of fuller information are given. It is hoped that the book will also be helpful to users of meteorological instruments outside the Meteorological Office. These readers should, however, understand that certain instructions on procedures are for the guidance of Meteorological Office personnel.

In addition to giving, where applicable, instructions for the installation, operation, and maintenance of Meteorological Office pattern instruments, this handbook deals with accuracy and sources of error.

The general requirements of meteorological instruments, both indicating and recording, are:

(a) Accuracy
(b) Reliability
(c) Ease of reading and manipulation
(d) Robustness and durability
(e) Low cost of ownership.

Most meteorological instruments have to be maintained in continuous operation and many are partially or wholly exposed to the weather. These restrictions call for especially high standards of design and manufacture. The need for uniformity is one of the most important requirements for meteorological measurements. The decisions and recommendations of the World Meteorological Organization, which affect instrument practice, have therefore been followed as closely as possible.

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VOLUME 6

MEASUREMENT OF SUNSHINE AND SOLAR AND TERRESTRIAL RADIATION

1 MEASUREMENT OF SUNSHINE — GENERAL

1.1 Methods of measurement

Measurement of the hourly or daily totals of the duration of sunshine are made with the use of sunshine recorders of which there are four main types:

(a) The Campbell–Stokes pattern in which the focused heat radiation from the sun is used to burn a trace on a card.

(b) The Marvin pattern in which the heat radiation actuates a thermometric switch controlling a recorder pen.

(c) The Jordan pattern in which the actinic radiation from the sun is made to record a trace on photographic paper.

(d) The Foster photoelectric sunshine switch.

The use of different types of instruments, recording materials and methods for measuring the records can introduce differences of up to 20 per cent in monthly sunshine totals. In an attempt to reduce such differences to an acceptable level, the World Meteorological Organization (WMO) decided in 1962 to adopt the Campbell–Stokes recorder as a reference standard, known as the Interim Reference Sunshine Recorder (IRSR).* By reduction of sunshine totals to the IRSR standard the WMO considers that 'it should be possible to achieve international uniformity to within ± 5 per cent for systematic differences'.

It is not practicable to define a precise lower threshold limit of the intensity of solar radiation for measurement of bright sunshine. The IRSR corresponds roughly to an average lower limit of 21 mW cm^{-2}. The actual limits depend on a number of factors, such as the transparency of the atmosphere, and have been found to vary between 7 and 28 mW cm^{-2}. This problem has been investigated by Bider (1959).

The WMO Commission for Instruments and Methods of Observation (CIMO) considered this problem for a number of years and made a recommendation (CIMO-VII, Recommendation 8) for 'adoption of a threshold value for sunshine of 20 mW cm^{-2} of direct solar irradiance'. This proposal was still under discussion at the date of publication.

1.2 Timing the sunshine records

Some of the main types of sunshine recorder use the movement of the sun to form the time base for their records. It is therefore necessary to know the relation between the position of the sun and the standard of time actually in use. The interval between two successive transits of the sun across the same meridian is called a true solar day, and time based on the length of this day is called the apparent solar time. Local Apparent Time (LAT) is the apparent solar time for any particular place such that the sun passes across the geographical meridian at noon. It is this time which is indicated by a sundial or sunshine recorder when it is correctly adjusted.

The true solar day, however, varies in length throughout the year. For convenience a mean sun is assumed, such that the length of a mean solar day is constant and equal to the

* For a Campbell–Stokes recorder to be considered as an IRSR it must comply with the specifications issued by the Meteorological Office and be used with sunshine cards complying with the specifications issued by the French Meteorological Service.

average value of the true solar day taken over the whole year. Local time based on the transit of the 'mean' sun is called Local Mean Time (LMT). Four times a year, about 16 April, 14 June, 1 September and 25 December, the LAT is the same as the LMT. At other times a certain quantity, known as the equation of time, has to be subtracted algebraically from the LAT to obtain the LMT. Table I gives the value of the equation of time for every day throughout the year; it varies a little from year to year but these values are sufficiently accurate for most meteorological purposes. More accurate values can be obtained from the *Nautical Almanac* if necessary.

Table I. *Value (to the nearest minute) of the 'equation of time' for each day of the year to give time of local noon (GMT)*

The value of the equation of time is used in the relationship:

Time of local noon = 1200 GMT − equation of time + longitude time correction.

Longitude time correction is plus four minutes for every degree west of Greenwich and minus four minutes for every degree east of Greenwich; e.g. for 18 March at a location 3°W: Time (GMT) of local noon = 1200 + 8 + 12 = 1220 hours.

Date	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	−3	−14	−13	−4	+3	+2	−4	−6	0	+10	+16	+11
2	−4	−14	−12	−4	+3	+2	−4	−6	0	+10	+16	+11
3	−4	−14	−12	−4	+3	+2	−4	−6	0	+11	+16	+11
4	−5	−14	−12	−3	+3	+2	−4	−6	+1	+11	+16	+10
5	−5	−14	−12	−3	+3	+2	−4	−6	+1	+11	+16	+10
6	−6	−14	−12	−3	+3	+2	−4	−6	+1	+12	+16	+9
7	−6	−14	−11	−2	+3	+1	−5	−6	+2	+12	+16	+9
8	−6	−14	−11	−2	+3	+1	−5	−6	+2	+12	+16	+8
9	−7	−14	−11	−2	+4	+1	−5	−6	+2	+12	+16	+8
10	−7	−14	−11	−2	+4	+1	−5	−5	+3	+13	+16	+8
11	−8	−14	−10	−1	+4	+1	−5	−5	+3	+13	+16	+7
12	−8	−14	−10	−1	+4	0	−5	−5	+3	+13	+16	+7
13	−8	−14	−10	−1	+4	0	−6	−5	+4	+14	+16	+6
14	−9	−14	−10	−1	+4	0	−6	−5	+4	+14	+16	+6
15	−9	−14	−9	0	+4	0	−6	−5	+4	+14	+15	+5
16	−9	−14	−9	0	+4	0	−6	−4	+5	+14	+15	+5
17	−10	−14	−9	0	+4	−1	−6	−4	+5	+14	+15	+4
18	−10	−14	−8	0	+4	−1	−6	−4	+6	+15	+15	+4
19	−11	−14	−8	+1	+4	−1	−6	−4	+6	+15	+15	+3
20	−11	−14	−8	+1	+4	−1	−6	−4	+6	+15	+14	+3
21	−11	−14	−8	+1	+4	−1	−6	−3	+7	+15	+14	+2
22	−11	−14	−7	+1	+3	−2	−6	−3	+7	+15	+14	+2
23	−12	−14	−7	+2	+3	−2	−6	−3	+7	+15	+14	+1
24	−12	−13	−7	+2	+3	−2	−6	−3	+8	+16	+14	+1
25	−12	−13	−6	+2	+3	−2	−6	−2	+8	+16	+13	0
26	−12	−13	−6	+2	+3	−3	−6	−2	+8	+16	+13	0
27	−13	−13	−6	+2	+3	−3	−6	−2	+9	+16	+13	−1
28	−13	−13	−5	+2	+3	−3	−6	−2	+9	+16	+12	−1
29	−13		−5	+3	+3	−3	−6	−1	+9	+16	+12	−2
30	−13		−5	+3	+3	−3	−6	−1	+10	+16	+12	−2
31	−13		−4		+3		−6	−1		+16		−3

The civil or standard time used for everyday purposes (e.g. Greenwich Mean Time or British Summer Time in the British Isles) is the Local Mean Time for some standard meridian (0° or 15°E respectively for the times mentioned for the British Isles). To calculate LMT from standard time it is necessary to know the longitude of the station and the longitude of the meridian used as the basis of standard time. Relative to a stationary observer on the surface of the earth, the sun circles the earth at a mean rate of 1° in 4 minutes, so that if the station is θ° west of the standard meridian the mean sun will cross the station meridian 4θ minutes after it crosses the standard meridian. The following equations then hold:

In the western hemisphere

LAT = LMT + equation of time

= standard time + $4(\theta_s - \theta)$ minutes + equation of time,

where θ_s is the west longitude of the standard meridian and θ that of the station meridian, in degrees. Note that in the British Isles θ_s is 0° or −15°.

In the eastern hemisphere

LAT = LMT + equation of time

= standard time − $4(\theta_s - \theta)$ minutes + equation of time,

where θ_s and θ are now east longitudes.

The main use of these equations is to calculate the standard time of local apparent noon (i.e. the time when the sun is due south). The equations may then be rearranged to read as follows:

In the western hemisphere

Standard time of local apparent noon = 1200 − equation of time − $4(\theta_s - \theta)$ minutes.

In the eastern hemisphere

Standard time of local apparent noon = 1200 − equation of time + $4(\theta_s - \theta)$ minutes.

To simplify the calculation of the time of local apparent noon in longitudes near the British Isles, Table II gives this directly in Greenwich Mean Time for each whole degree of longitude from 4°E to 10°W for every five days throughout the year. The required time for any other day or longitude can then be obtained by interpolation. It should be noted that the standard time equivalent to any other Local Apparent Time can be obtained by applying a correction to the LAT equal to the difference between the time given in Table II and 1200 and in the same sense. For example, local apparent noon at a station with a longitude of 5°W on 5 May is at 1217 GMT, therefore 0900 LAT is at 0917 GMT and so on.

Table II. *Time of local noon in GMT (to the nearest minute)*

The table is computed from the relationship:

Time of local noon = 1200 GMT − equation of time + longitude time correction. (Longitude time correction is plus four minutes for every degree west of Greenwich and minus four minutes for every degree east of Greenwich.)

Date	4°E	3°E	2°E	1°E	0°	1°W	2°W	3°W	4°W	5°W	6°W	7°W	8°W	9°W	10°W
1 January	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239	1243
5	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237	1241	1245
10	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239	1243	1247
15	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237	1241	1245	1249
20	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239	1243	1247	1251
25	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236	1240	1244	1248	1252
30	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237	1241	1245	1249	1253
1 February	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242	1246	1250	1254
5	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242	1246	1250	1254
10	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242	1246	1250	1254
15	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242	1246	1250	1254
20	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242	1246	1250	1254
25	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237	1241	1245	1249	1253
1 March	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237	1241	1245	1249	1253
5	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236	1240	1244	1248	1252
10	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239	1243	1247	1251
15	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237	1241	1245	1249
20	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236	1240	1244	1248
25	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242	1246
30	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237	1241	1245
1 April	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236	1240	1244
5	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239	1243
10	1146	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242
15	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236	1240
20	1143	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239
25	1142	1146	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238
30	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237

Table II (*continued*)

Date	4°E	3°E	2°E	1°E	0°	1°W	2°W	3°W	4°W	5°W	6°W	7°W	8°W	9°W	10°W
1 May	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237
5	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237
10	1140	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236
15	1140	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236
20	1140	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236
25	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237
30	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237
1 June	1142	1146	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238
5	1142	1146	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238
10	1143	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239
15	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236	1240
20	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237	1241
25	1146	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242
30	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239	1243
1 July	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236	1240	1244
5	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236	1240	1244
10	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237	1241	1245
15	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242	1246
20	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242	1246
25	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242	1246
30	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242	1246
1 August	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242	1246
5	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242	1246
10	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237	1241	1245
15	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237	1241	1245
20	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236	1240	1244
25	1146	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242
30	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237	1241
1 September	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236	1240
5	1143	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235	1239
10	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237
15	1140	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236
20	1138	1142	1146	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234
25	1136	1140	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232
30	1134	1138	1142	1146	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230

Table II (*continued*)

Date	4°E	3°E	2°E	1°E	0°	1°W	2°W	3°W	4°W	5°W	6°W	7°W	8°W	9°W	10°W
1 October	1134	1138	1142	1146	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230
5	1133	1137	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229
10	1131	1135	1139	1143	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227
15	1130	1134	1138	1142	1146	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226
20	1129	1133	1137	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225
25	1128	1132	1136	1140	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224
30	1128	1132	1136	1140	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224
1 November	1128	1132	1136	1140	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224
5	1128	1132	1136	1140	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224
10	1128	1132	1136	1140	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224
15	1129	1133	1137	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225
20	1130	1134	1138	1142	1146	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226
25	1131	1135	1139	1143	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227
30	1132	1136	1140	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228
1 December	1133	1137	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229
5	1134	1138	1142	1146	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230
10	1136	1140	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232
15	1139	1143	1147	1151	1155	1159	1203	1207	1211	1215	1219	1223	1227	1231	1235
20	1141	1145	1149	1153	1157	1201	1205	1209	1213	1217	1221	1225	1229	1233	1237
25	1144	1148	1152	1156	1200	1204	1208	1212	1216	1220	1224	1228	1232	1236	1240
30	1146	1150	1154	1158	1202	1206	1210	1214	1218	1222	1226	1230	1234	1238	1242

2 SUNSHINE RECORDERS

2.1 The Universal sunshine recorder Mk 3

The Universal sunshine recorder is of the Campbell–Stokes type and is available in three versions: the Mk 3A (Figure 1) for use in latitudes 0° to 40°, the Mk 3B for use in latitudes 25° to 45°, and the Mk 3C (as shown in Plate III) for use in latitudes 45° to 65°. Each version has a gun-metal base, A in Figure 1, provided with three legs, drilled to take screws for fixing purposes. Carried on the main base is a sub-base B consisting of a triangular gun-metal plate which in turn carries the bowl mounting. The sub-base has three adjusting screws so that it can be levelled accurately and provision is made for small adjustments of the sub-base azimuth relative to the main base. The bowl C is in the form of one half of a belt cut from a hollow gun-metal sphere.

For the Mk 3A recorder the belt is first cut in half at right angles to the end faces and then one pair of corresponding corners is cut away along a plane passing through the centre of the bowl at an angle of 30° to the previous cut (Figure 2(a)). For the Mk 3B and Mk 3C recorders the belt is cut in half along a plane passing through the centre of the bowl and at an angle of either 40° (Mk 3B) or 52° (Mk 3C) to a plane perpendicular to the end faces (Figures 2(b) and 2(c)). When the bowl is adjusted for a latitude equal to the angle of the cut, e.g. 52°, the ends of the bowl are horizontal.

The sphere support is in the form of a semicircular gun-metal arc, D in Figure 1, provided with an extension to allow two arcs to be made from one casting, of nearly rectangular cross-section attached symmetrically to the back of the bowl and concentric with it. A capstan-headed screw clamps the arc to its support and allows a range of movement from 0° to 65°. This movement is divided into two equal portions, the change from one portion to the other being made by inserting the screw in one of two holes. One side of the arc support bears an index mark to indicate the latitude setting. At each end of the arc is fitted a brass screw, one of which fits over a ball-ended boss E and the other into a cup-shaped boss F fitted on to the sphere at opposite ends of a diameter.

As flat pieces of card cannot be made to fit perfectly into a spherical surface the inner face of the bowl is flanged to take three different types of card, one type for use in periods about the equinoxes, one type for summer and one type for winter. A cross-section of the bowl is shown in Figure 3. When in position the equinoctial card forms part of a cylinder surrounding the sphere, while the summer and winter cards form part of the surface of two cones. The semi-vertical angle of these cones is 16° and their axes are parallel to the axis of the cylindrical surface. These surfaces are only tangential to the ideal spherical inner surface, but they have the advantage that flat pieces of card can be made to fit them accurately; they are within 0.05 mm of the ideal surface (over the parts actually used for recording). The positions occupied by the different sets of cards overlap so that a record can always be obtained without using the extreme edge of the cards. The cards are kept firmly in position by means of a clamping screw which is screwed into one of the three holes in the upper edge of the bowl (according to the type of card in use). The screw is attached to the sub-base by a length of brass chain.

Sphere. One of the most important optical properties of a spherical lens is the fact that a parallel beam of light, after passing through the lens, does not converge to a single 'focus'. The rays of light converge to a number of points, all of which lie within a space bounded by a surface of roughly conical form (the 'focal caustic surface') whose axis passes through the centre of the sphere and is parallel to the incident beam of light. The base of the cone is in contact with the rear surface of the sphere, and the apex of the cone lies on the axis at a point approximately 25 mm behind the sphere in the case of the Universal sunshine recorder.

All the convergent light emerging from the sphere is confined within the focal caustic surface; outside this region the light is divergent. Consequently the apex of the cone is a point of discontinuity in regard to the optical or thermal effects of the emergent light. If a

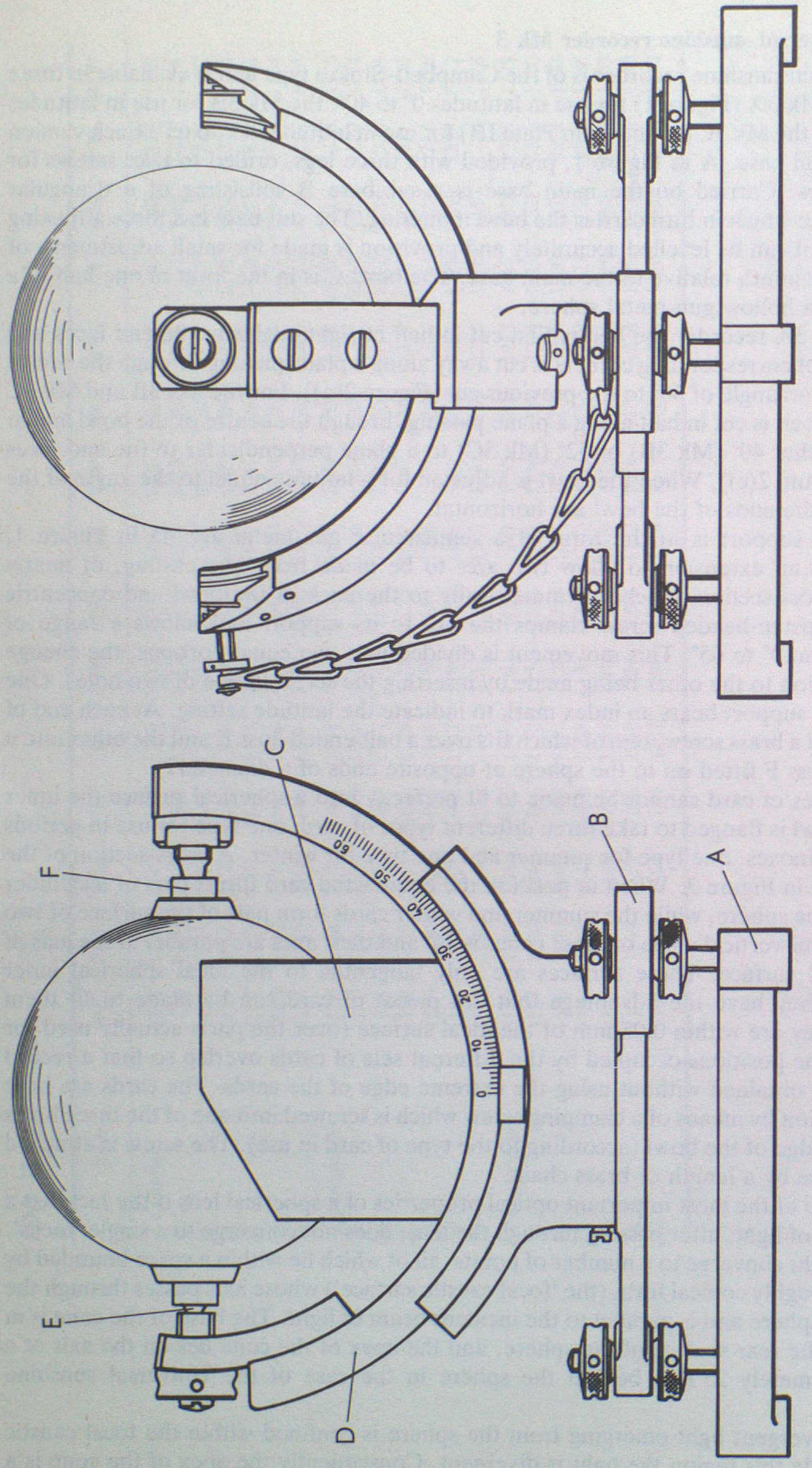


Figure 1. Universal sunshine recorder Mk 3A.

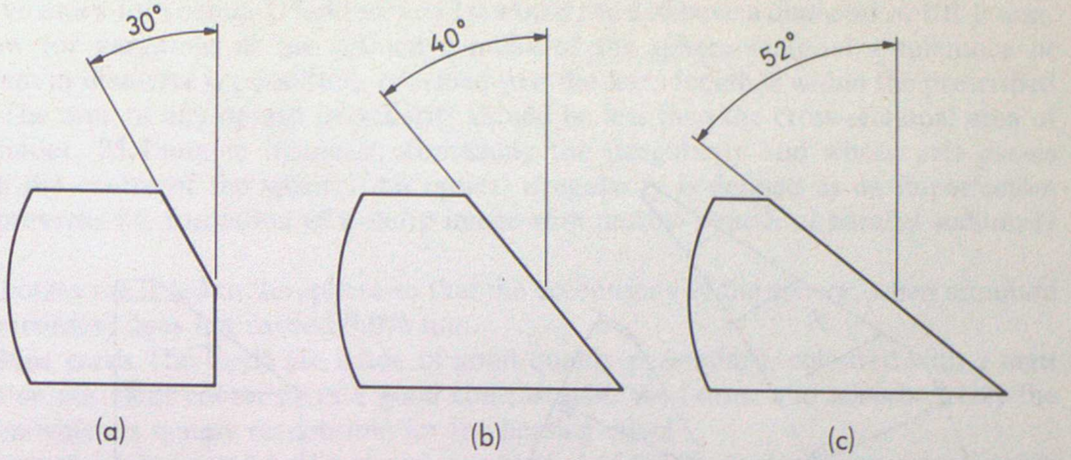


Figure 2. Bowls for the Mk 3A, Mk 3B and Mk 3C Universal sunshine recorders.

sunshine card is moved slowly towards the rear surface of the sphere in sunshine, there will be practically no tendency for the card to burn until the card reaches the apex of the caustic surface when burning will suddenly commence. The maximum concentration of rays, and therefore the burning power, is to be found rather nearer the sphere.

From the above considerations it can be seen that the focal length of the sphere must comply with a specified value to within narrow limits and, if variations from the specified value do occur, that too short a focal length will be a much more serious fault than too long a focal length.

The sphere is made of uniform well-annealed glass. The glass should be colourless or of a pale yellowish tint and free from striations and surface defects in that part of the sphere in use when mounted on the recorder. Its focal length is defined as the distance from the centre of the sphere to the point at which a narrow pencil of parallel sodium D light is brought to a focus; it is found from the mean of measurements along any four arbitrarily selected axes, none of which should be nearer than 5° of arc to the axis of the sphere mounting. The mean focal length should be 74.9 ± 0.3 mm and the focal length along any single axis should be 74.9 ± 0.5 mm. For a sphere to have a focal length of 74.9 mm and a

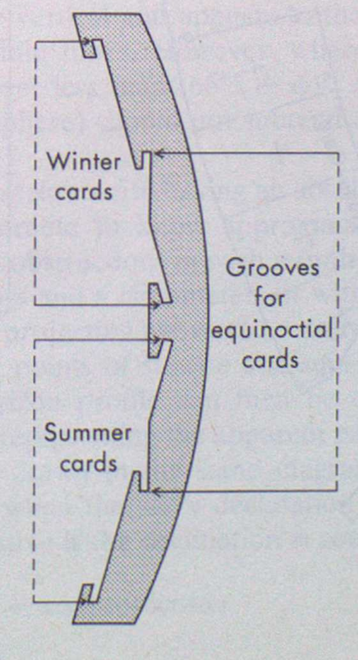


Figure 3. Cross-section of sunshine recorder bowl.

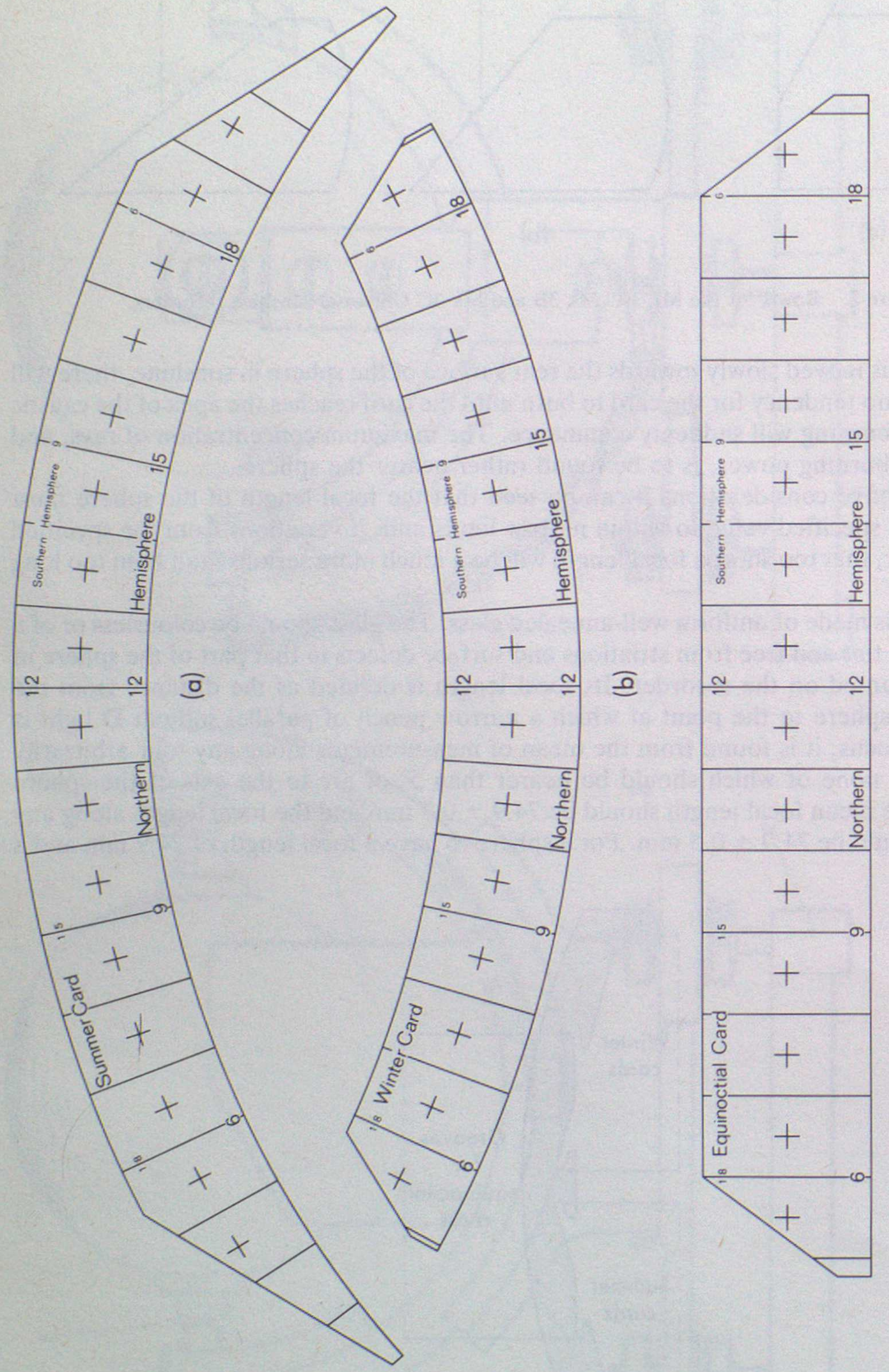


Figure 4. Sunshine cards.

refractive index for sodium D light of 1.512 it would need to have a diameter of 101.6 mm. To allow for variations in the refractive index of the sphere material a tolerance of ± 1.3 mm in diameter is permitted, provided that the focal length is within the prescribed limits. The area of any optical irregularity should be less than the cross-sectional area of any cylinder, 25.4 mm in diameter, containing the irregularity and whose axis passes through the centre of the sphere. An optical irregularity is defined as an imperfection which prevents the formation of a sharp image with narrow pencils of parallel sodium D light.

Two bosses are fitted to the sphere so that the eccentricity of the sphere, when mounted in the recorder, does not exceed 0.076 mm.

Sunshine cards. The cards are made of good quality pasteboard, coloured with a matt finish blue ink. This colour gives a good contrast with the burns, and absorbs freely the radiation which is mainly responsible for the heating effect.

It is important that a standard material should be used for the cards to ensure consistency in the rate of burning. A strict limit also has to be placed on their changes in dimensions when wet, and on subsequent drying, to reduce to a minimum the change in scale value, the tendency for the cards to jam in the recorder, or the tendency to become too small and thus become displaced. Three types of card (Figure 4) are used in the recorder; the long curved summer cards fit into the bottom set of recorder flanges, the short curved winter cards fit into the upper set of flanges, and the straight equinoctial cards fit into the central flanges. White hour lines are printed on the cards at right angles to the long edges and symmetrically placed about the centre noon mark. The crosses indicate points on the centre line of the cards. The time-scale of the cards varies from 17.5 mm h^{-1} at the solstices to 19 mm h^{-1} at the equinoxes.

Installation and adjustment

(a) *Exposure.* In the British Isles a free horizon is required in the approximate ranges north-east through east to south-east, and north-west through west to south-west. To the south (in the northern hemisphere) the elevation of any obstruction should not exceed an angle equal to $(66\frac{1}{2} - \phi)°$, where ϕ is the latitude. Between south and south-west and between south and south-east the permissible elevation of an obstacle changes evenly between the above limit and zero, but, in general, obstacles whose elevations above the horizon do not exceed 3° may be ignored as the sunshine is rarely strong enough to record when the sun is at a lower elevation than this. It should be noted that in latitudes of less than 23½° the sun passes the vertical and appears to the north of the instrument (in the northern hemisphere) at certain times. However, where this is so, the sun's maximum elevation at local noon is never less than $(66\frac{1}{2} + \phi)°$; consequently obstructions to the north (in the northern hemisphere) should not subtend angles of elevation of more than $(66\frac{1}{2} + \phi)°$.

It is not always possible to secure a site having an absolutely uninterrupted exposure. In such circumstances it is desirable to know approximately how much of the possible sunshine may be obscured by obstructions in each month of the year. This can be done by first measuring with a compass and a clinometer, or with a theodolite, the elevation and azimuth of every obstruction projecting above the eastern, southern and western horizons between the azimuths of the points of sunrise and sunset at the summer solstice. From these measurements the horizon profile can then be drawn on squared paper. Lines (similar to those in Figure 5) representing the apparent path of the sun at different seasons for a particular latitude are drawn in the same diagram. The necessary equations for drawing the lines for a day when the sun's declination has the value δ (positive if the declination is north and negative if the declination is south) are

$$E = \sin^{-1}(\sin\phi\sin\delta + \cos\phi\cos\delta\cos\alpha)$$

$$\text{and } A = \sin^{-1}\left(\frac{\cos\delta\sin\alpha}{\cos E}\right)$$

where E = the sun's altitude,
A = the sun's azimuth in degrees from north,
ϕ = the latitude, and
α = the sun's hour angle (= 15° × time in hours from noon).

When such a diagram has been constructed the duration of sunshine cut off by a particular obstruction can be easily estimated. The diagrams in Figure 5 show the altitude and azimuth of the sun at each hour (LAT) for various latitudes from 60°N to 30°S. Each of the five curves A–E given in the diagrams is for a specific date (or dates) as indicated in Table III below; for any other date a curve must be interpolated which passes through the corresponding value for the sun's noon altitude, the noon altitude being equal to the co-latitude $(90 - \phi)°$ plus the declination of the sun. The sun's declination can be found from the *Nautical Almanac*. The dates corresponding to the five curves are given in Table III.

Table III. *Dates for the use of the various curves in Figure 5*

Date	Sun's declination	Hemisphere Northern	Hemisphere Southern
22 June	23½°N	A	E
21 April, 23 August	11¾°N	B	D
21 March, 23 September	0°	C	C
18 February, 25 October	11¾°S	D	B
22 December	23½°S	E	A

A = Summer solstice C = Equinoxes E = Winter solstice

When the diagrams are to be used in southern latitudes the hours of the day and the azimuths must be altered as well as the interchange of dates. An example of this is given in the diagram for 30°S (page 6–16).

(b) *Support.* The support on which the instrument is fixed must be perfectly rigid and not liable to warp or be otherwise affected by weather. Where a satisfactory exposure is available near ground level a brick or concrete pillar forms a suitable support. To avoid obstruction, however, it is often necessary to install the recorder on the roof of a building. Here, if necessary, an alternative form of support can be made by laying a 300 mm square of cement not less than 50 mm deep in which three wooden pegs are embedded, suitably positioned for the lugs in the main base of the instrument. If the wooden pegs are tapered with the broad end downwards and well painted where exposed they should be firm and unaffected by the weather. The front pair of lugs on the recorder's main base are 178 mm apart and should be aligned east–west. The remaining lug is 133 mm north (in the northern hemisphere) of the centre of the line joining the other two lugs.

(c) *Fitting the sphere.* The sphere should be offered up to the arc support so that the ball-ended screw on the arc fits into the cup-shaped boss, F in Figure 1, on the sphere. The cup-shaped screw should then be adjusted so that the cup fits snugly over the ball-ended boss E on the sphere. It is important that only the cup-shaped screw should be used for the purpose of fitting or removing the sphere.

(d) *Adjustment.* When setting up the sunshine recorder the following adjustments are necessary:

(1) The recorder must be levelled by using a spirit-level on the sub-base, first in the north–south direction and then in the east–west direction. The levelling screws, on which the sub-base is supported, should be used for this adjustment.

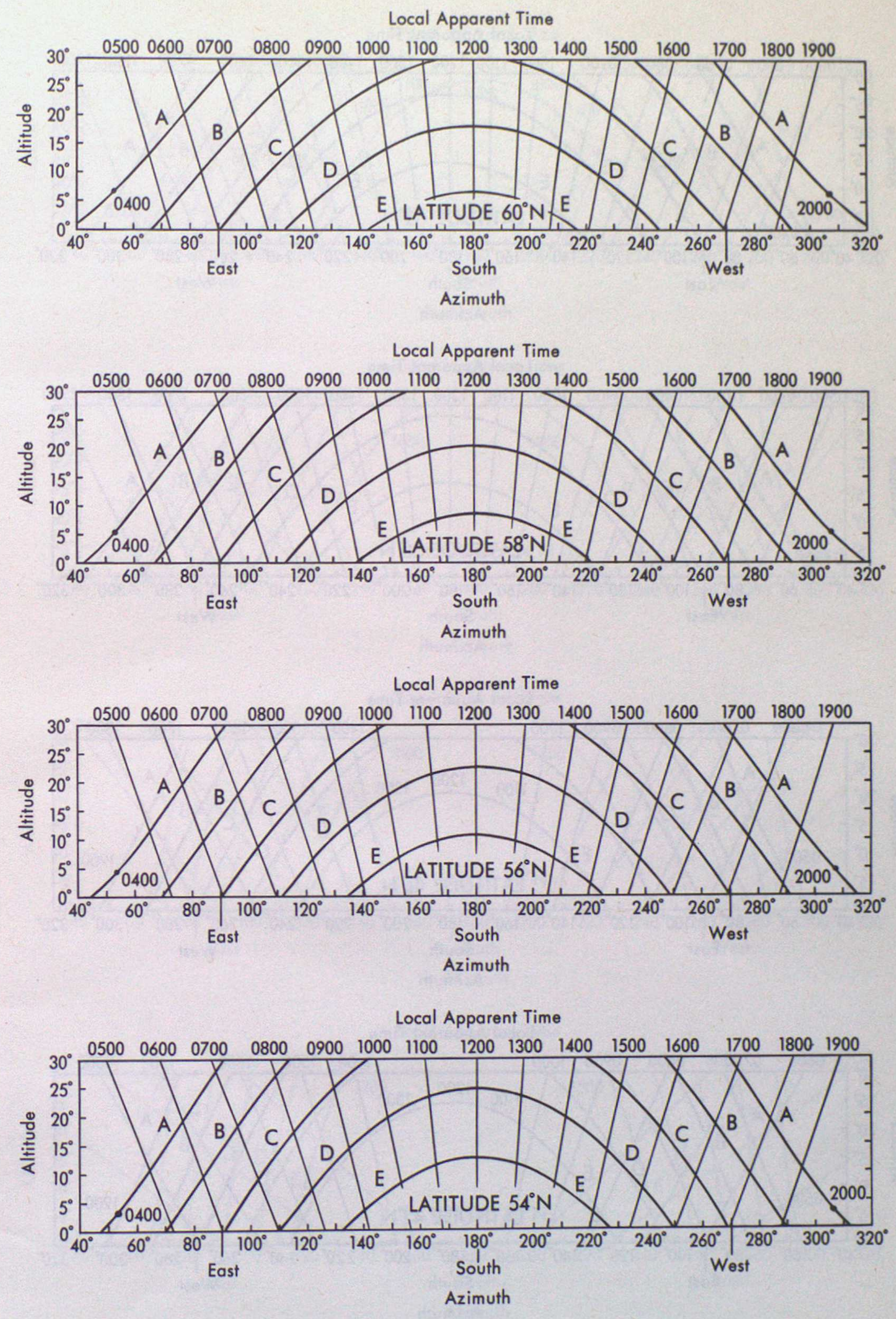


Figure 5. Variations of the sun's altitude and azimuth.

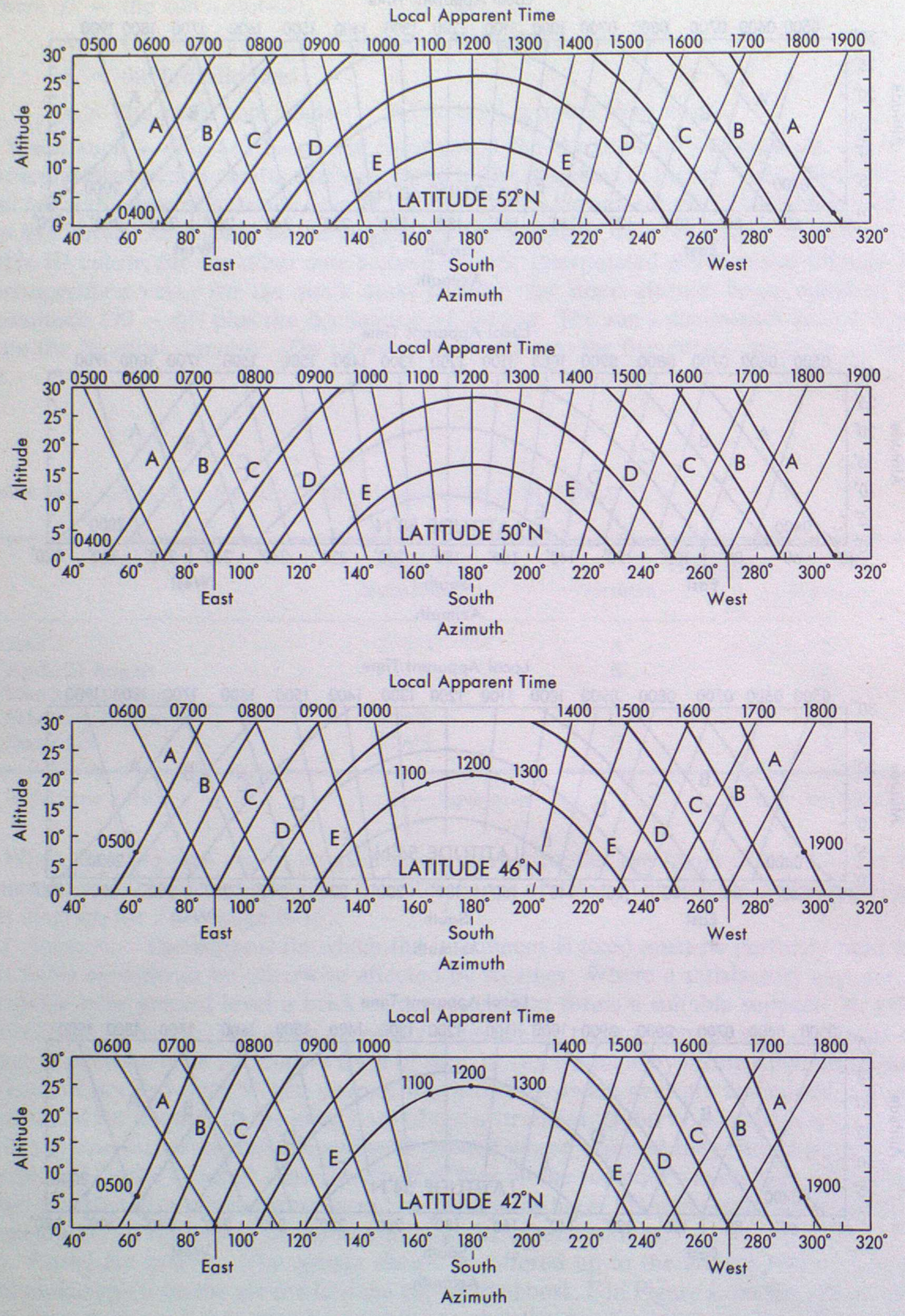


Figure 5. (*continued*).

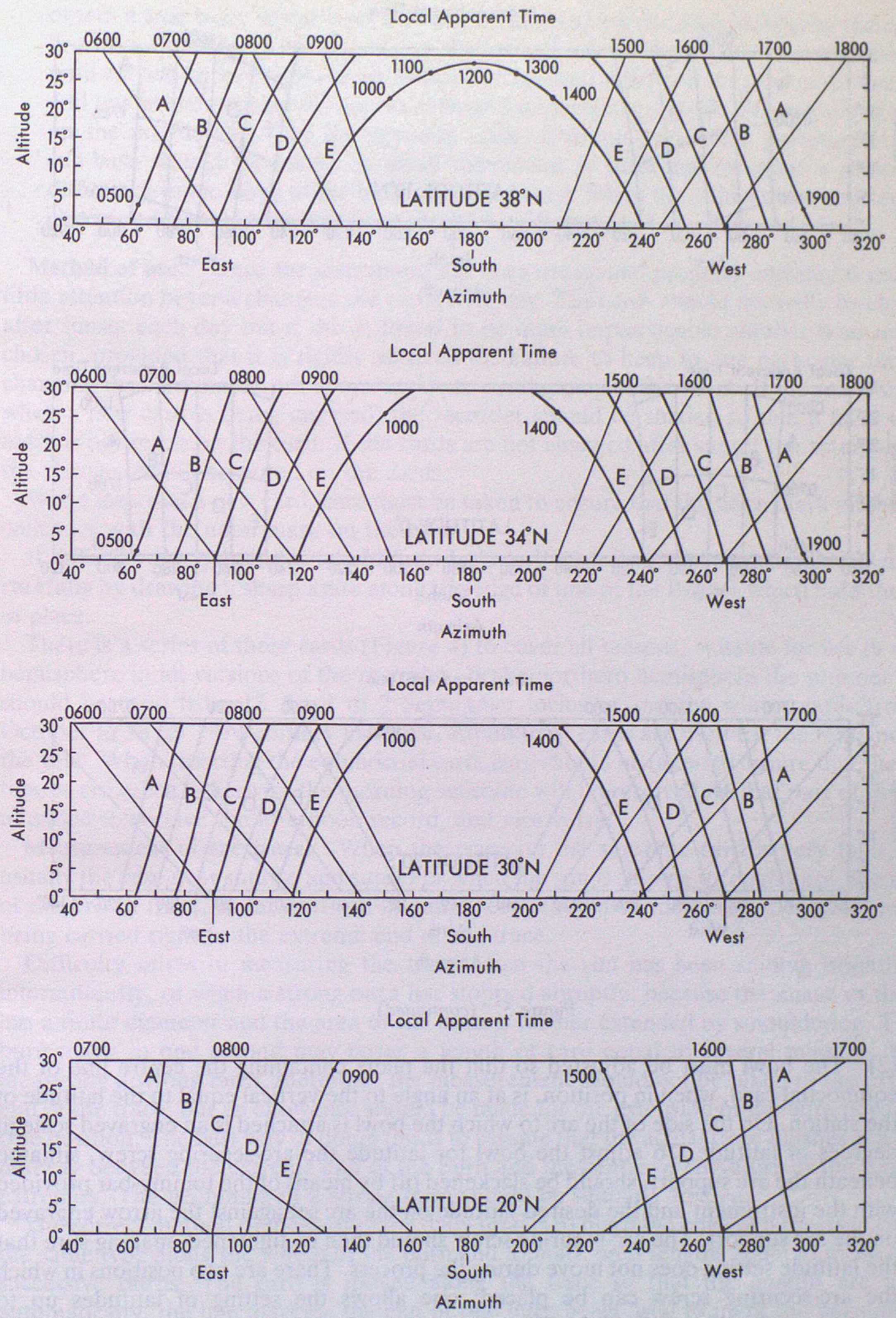


Figure 5. (*continued*).

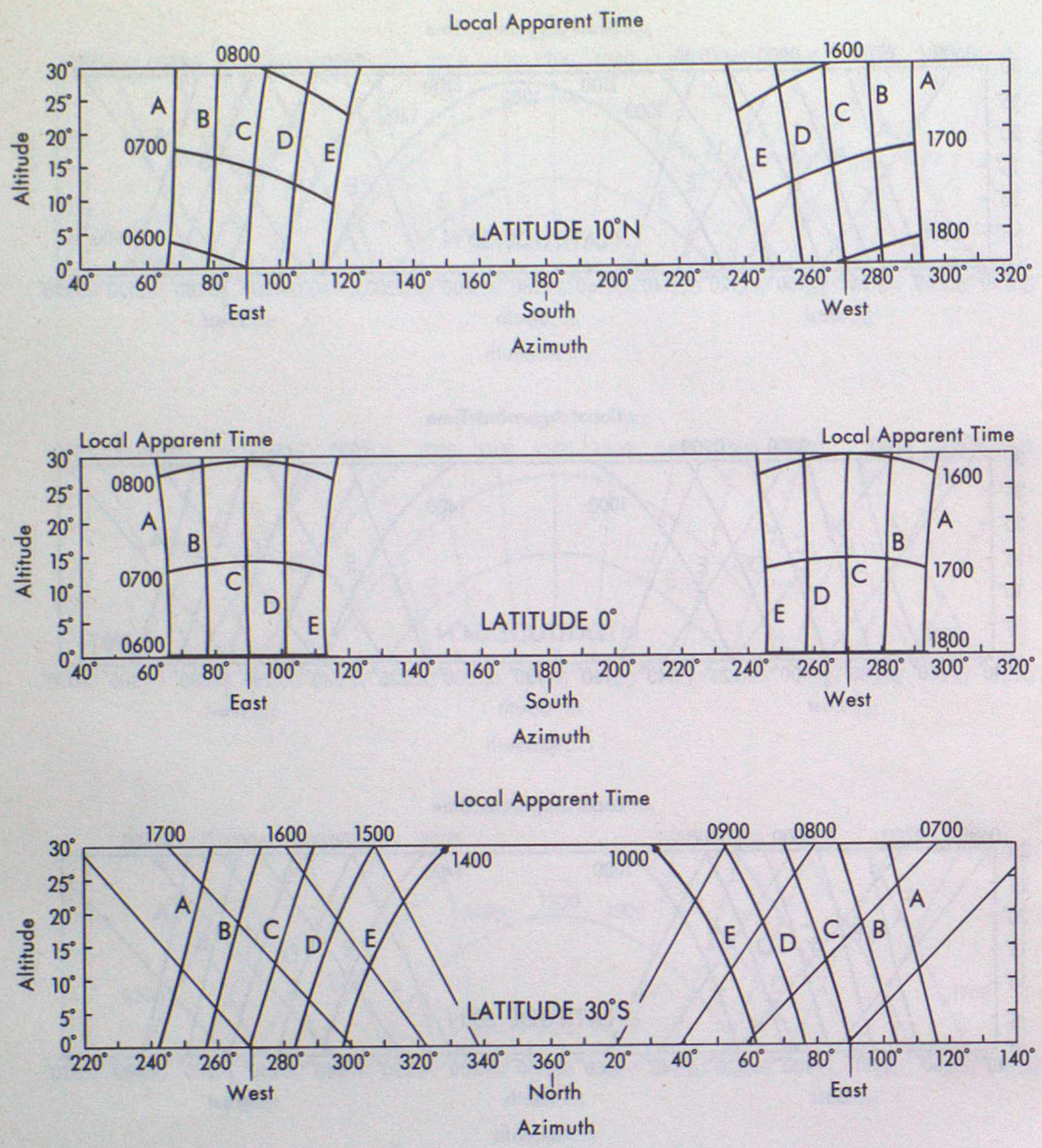


Figure 5. *(continued)*.

(2) The bowl must be adjusted so that the plane containing the centre line of the equinoctial card, when in position, is at an angle to the vertical equal to the latitude of the station. On the side of the arc to which the bowl is attached is an engraved scale in degrees of latitude. To adjust the bowl for latitude the arc-securing screw, situated beneath the arc support, should be slackened off by means of the tommy-bar provided with the instrument and the desired latitude on the arc set against the arrow engraved on the arc support. The arc-securing screw should then be tightened, making sure that the latitude setting does not move during the process. There are two positions in which the arc-securing screw can be placed: one allows the setting of latitudes up to approximately 35° and the other from approximately 30° upwards.*

(3) The vertical plane containing the centre of the sphere and the noon mark on the bowl must lie in the meridian. The best method is to align the sphere support as accurately as possible in the north–south direction, with the help of a compass, making due allowance for deviation, or by bearings from a map, and then to insert a card and

* The arc-securing screw is positioned correctly before the instrument is issued and this adjustment should not normally be required at the station.

obtain a trial burn. If the burn is found to travel along the card parallel to the centre line the adjustment is correct. If not, the recorder should be slightly turned in azimuth until correct burns are obtained. When the test burn is high on the card in the morning and low in the evening the sub-base should be turned clockwise (when looking down on the instrument). For the opposite error, a counter-clockwise movement of the sub-base should be made. A small movement is sufficient to cause a noticeable difference in the slope of the burn across the card. When the adjustment is correct the clamping screws on the sub-base should be tightened.

Method of use. Once the instrument has been set up and properly adjusted it requires little attention beyond changing the cards each day. The cards should normally be changed after sunset each day but if this is found to be quite impracticable another hour may be chosen, provided that it is rigidly adhered to. Failure to keep to one particular time for changing the card may result in errors due to overlapping of the burns. If the sun is shining when a new card is being inserted, the recorder should be shaded so that a false scorch mark is not made on the card. If the cards are not changed after sunset the actual time of the change should be noted on the cards.

When inserting a new card, care must be taken to ensure that the noon mark on the card coincides with the noon mark on the bowl.

If difficulty is experienced in withdrawing a card after rain, the card should be cut out carefully by drawing a sharp knife along the edge of one of the flanges which hold the card in place.

There is a series of three cards (Figure 4) to cover all seasons, suitable for use in either hemisphere in all versions of the recorder. In the northern hemisphere the summer cards should be used from 12 April to 2 September inclusive and the winter cards from 15 October to 28 (or 29) February inclusive. Equinoctial cards are used for the remainder of the year. When inserting the equinoctial card, care should be taken to ensure that the hour figures are erect, otherwise the morning sunshine will be received on that part of the card intended to receive the afternoon record, and vice versa.

Measurement of the trace. When the trace on the sunshine card is very faint, as is usually the case near sunrise and sunset or when the sun is shining through haze, the whole of the brown trace, as far as it can be fairly seen, should be measured, the measurement being carried right to the extreme end of the trace.

Difficulty arises in measuring the trace when the sun has been shining brightly but intermittently, or when a strong burn has stopped abruptly, because the image of the sun has a finite diameter and the area of the burn is further extended by smouldering. Thus a burn made in one second may cover a length of card equal to several minutes. When measuring a strong burn, therefore, the measurement should not be taken to the extreme end of the trace, but an allowance should be made for the extension of the burn beyond its true position. The best way of doing this is to assume that the actual trace finishes at a point midway between the extreme end of the burn and the centre of curvature of the rounded extremity. The beginning of a strong burn should be similarly treated.

The correct method of measuring the daily total is to place the edge of a reversed card of the same type along the length of the burn and to mark on it lengths equal to those of the successive burns. The card is moved along the trace so that the lengths are added automatically, the line marking the end of one burn being used to mark the beginning of the next. The total duration is then read off the time scale on the measured card, care being taken to make the measurement at the same level as the burn. Plate I shows the principles outlined above applied to the measurement of a typical sunshine trace. Readings are made to the nearest 0.1 hour.

Maintenance. Provided the support for the instrument is firm and does not warp, little maintenance is required apart from keeping the instrument clean. The glass sphere should be cleaned as required with a chamois-leather; great care must be taken that nothing abrasive is used. If snow or hoar frost settles on the instrument it should be removed as soon as possible. When changing to a new type of card any dirt accumulated in the grooves should be removed.

Accuracy and sources of error. The effects of various errors which may be due to faulty adjustment or manufacture are discussed below.

The enumeration of these possible errors in the adjustment of the bowl and the sphere show the necessity of careful testing and installation. The records obtained should be examined regularly to ensure that the adjustment has not changed; provided this is carried out, the instrument should give reliable and consistent records over a long period.

(a) *Errors of concentricity.* A small displacement of the sphere relative to the centre of the bowl can be considered as being made up of two components:

(1) a displacement in the plane of the celestial equator, and
(2) a displacement in the line through the centre of the bowl perpendicular to the celestial equator.

In case (1), the trace will be in the correct position at the equinoxes and will be slightly displaced and not parallel to the central line of the card at other times. For periods of sunshine covering the whole day the recorded duration will be too large if the sphere is too far from the bowl and too small otherwise. A displacement of the sphere from the bowl of 2.5 mm will increase a 12-hour sunshine record at the equinox by 16 minutes; it would be slightly less for other declinations. Adjustment of the Universal sunshine recorder for such a displacement is not possible as the position of the sphere is governed by the screws and bosses attaching it to the arc.

In case (2), the error in recorded duration is zero on the equinoctial card and is about 0.6 min h^{-1} on the summer and winter cards for a displacement of 2.5 mm (the error is positive on the summer cards and negative on the winter cards for an upward displacement). The trace remains parallel to the edges of the card but is displaced a distance d on the equinoctial card, and a distance which varies between $0.93d$ and $1.04d$ on the summer and winter cards, where d is the small displacement of the centre of the sphere. There is therefore a risk of some records being lost owing to the trace passing off the edges of the cards. Although it is possible to adjust the recorder for such a displacement it is not recommended that this adjustment be undertaken by the user.

(b) *North–south level and latitude error.* If the recorder is set to the incorrect latitude or is not level in the north–south direction there will be a small error, $\Delta\phi$ in Figure 6, in the

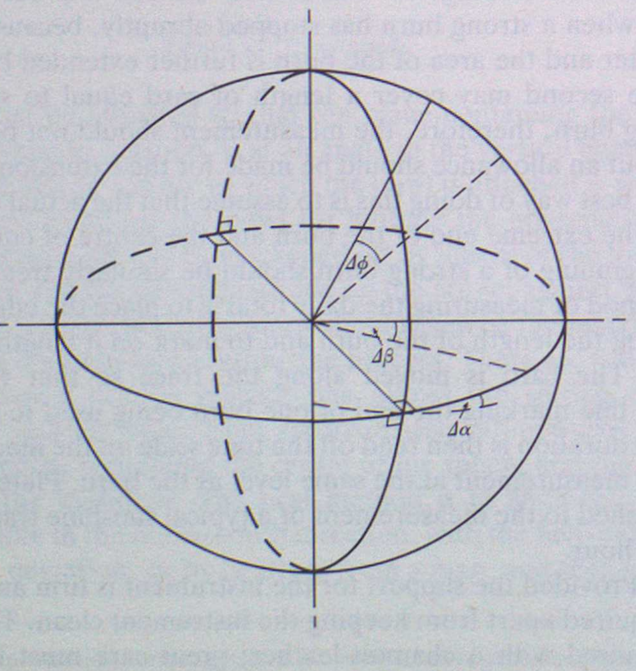


Figure 6. Sources of error in the sunshine trace.

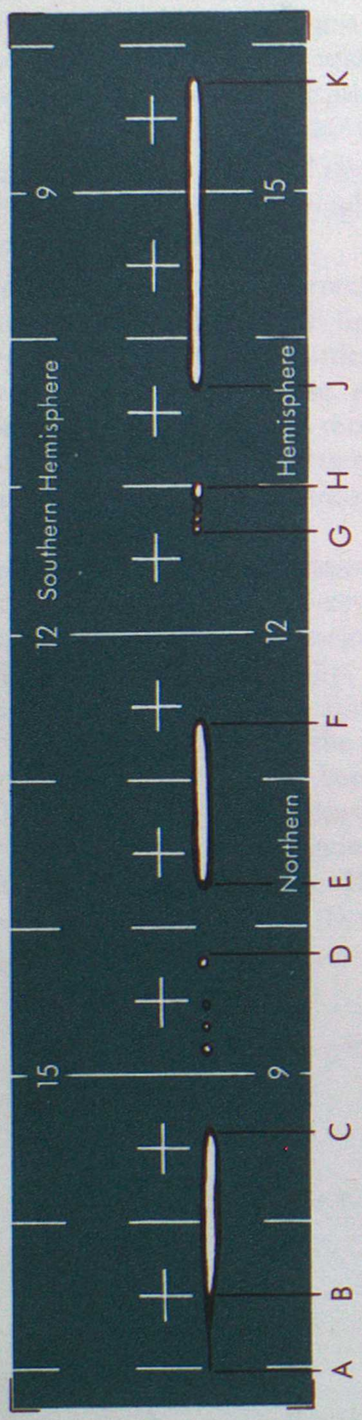


Plate I. Measurement of the sunshine trace.

The illustration shows a typical record on part of an equinoctial card. Marks, indicated by letters A to K, have been made to show between which points the measurements should be made.

The first portion A to B begins faintly after sunrise and slowly increases in width with the intensity of the sun's rays; the measurement is taken from the extreme end of the brown trace. The next portion B to C shows bright sunshine burning completely through the card and the measurement is taken to a point about half-way between the centre of curvature and the extreme visible limit of the burn. From C to D the record consists only of small circular burns; being truly circular these are not measured even when the card is burnt right through. Portions E to F and J to K show continuous bright sunshine and have rounded ends; allowance is made for the spread of the burn by measuring between points about half-way between the centres of curvature and the extreme visible limits of the burns. Finally, portion G to H consists of a series of small circular burns and an elongated burn joined together, no uncharred blue card being visible between them; this is measured in the same way as the continuous burns E to F and J to K.

The hourly amounts are: 07–08 h (Local Apparent Time) 1·0; 08–09 h ·6; 10–11 h ·7; 11–12 h ·4; 12–13 h ·3; 13–14 h ·3; 14–15 h 1·0; 15–16 h ·8; and the total for the day is 5·1 hours.

plane of the geographical meridian. This will give a corresponding error, Δa, in the position of the image on the card as recorded by the time-scale; Δa is zero at noon and at the equinoxes. If $\Delta\phi$ is 2° and δ (the declination) is 23½°N, then Δa is nearly 4 minutes at 0600 and 1800 LAT (negative at 0600 and positive at 1800) and this is the magnitude of the error in recorded duration of continuous sunshine from 0600 to 1200, or 1200 to 1800. The error would be opposite in sign in winter from that given above for summer. The error $\Delta\phi$ affects the curvature of the trace (Figure 7(a)) which is either too low or too high on the card and not parallel to the central line, appearing curved on the equinoctial card. Assuming the recorder is adjusted for the correct latitude, if the trace is concave upwards and too low, the south edge of the recorder is lower than the north edge and vice versa.

(c) *East–west level error.* If the recorder is not level in the east–west direction there will be an error, $\Delta\alpha$, in the plane at right angles to the meridian (Figure 6). This will give a corresponding error, Δb, in the position of the image on the card as recorded by the time-scale. For a given latitude, Δb has a numerical minimum at the equinoxes and at 0600 and 1800 LAT, and a maximum at 1200 LAT. If $\Delta\alpha$ is 2°, ϕ is 55° and δ is 23½°N, Δb is 7¼ minutes at 1200 and 4½ minutes at 0600 and 1800, giving an error in recorded duration of continuous sunshine from 0600 to 1200 and 1200 to 1800 of + 2¾ minutes and − 2¾ minutes respectively. The recorded duration of sunshine from 0600 to 1800 will not be affected. The error does not affect the curvature of the trace appreciably, but it causes the trace to cross its true position at an angle equal to $\Delta\alpha \sin\phi \sec\delta$. If $\Delta\alpha = 2°$, $\phi = 55°$ and $\delta = 23½°$, this angle is approximately 1¾°. If the trace is higher on the card in the morning than in the evening the east side of the bowl is higher than the west side (Figure 7(b)) and vice versa.

(d) *Azimuth error.* If the line passing through the centre of the sphere and the noon line on the bowl are not aligned due south the recorded duration of sunshine will be correct but the trace will not be parallel to the edges of the card (Figure 7(b)). The angle between the true and actual course of the trace is given by $\Delta\beta \cos\phi \sec\delta$, where $\Delta\beta$ is azimuth error (Figure 6). If $\Delta\beta = 2°$, $\phi = 55°$ and $\delta = 23½°$, this angle is 1¼°. The indicated time will be incorrect by an amount equal to 4 minutes per degree error. If the trace is higher on the card in the morning than in the evening the bowl faces east of south and vice versa.

It will be noticed that the errors due to azimuth and the east–west level produce similar effects, consequently it is possible for compensating errors of level and azimuth to produce an apparently correct trace. For this to occur the whole instrument must be rotated about the polar axis. The effect of such a movement is to cause incorrect timing which, unless very serious, is likely to pass undetected.

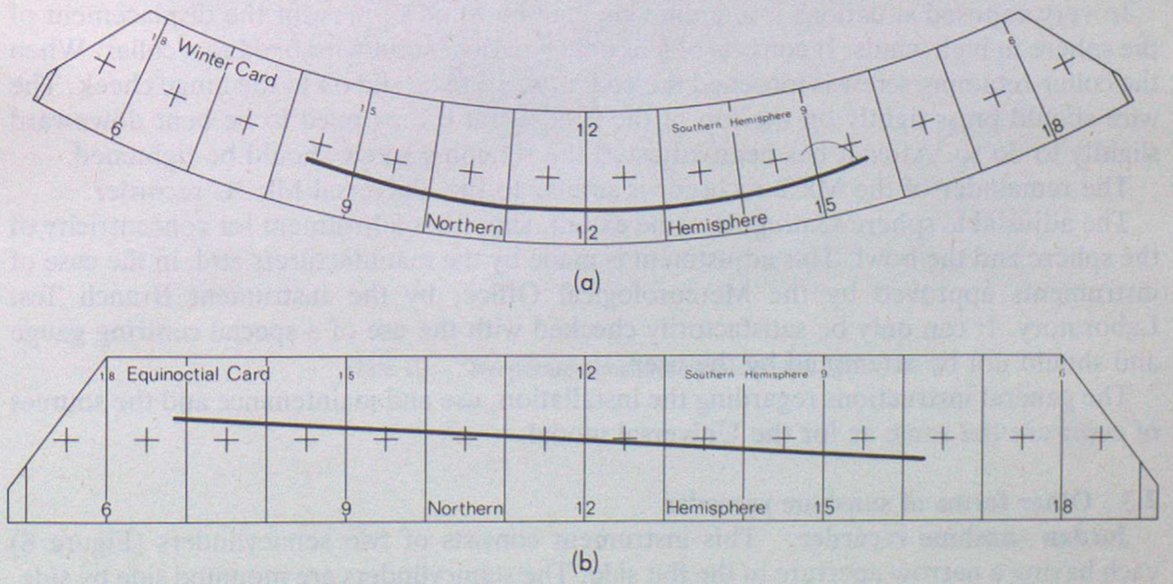


Figure 7. Errors in the sunshine trace.

(e) *Errors in the focal length of the sphere.* These are not likely to be serious for spheres approved by the Meteorological Office because of the strict tests mentioned earlier. Imperfect focusing results in a thicker and less intense burn and also, when the radiation is weak, the possibility of some loss of record.
(f) *Errors in the size of the bowl.* If the bowl is larger than the standard dimensions but is used with standard cards, the amount of sunshine recorded will be too large. The size of the bowl is usually checked by inserting a brass template, representing the equinoctial card, with the hour lines marked on it at the correct distances apart, and measuring the distance apart of the 0600 and 1800 lines. This should be 145.5 mm. A further two templates, representing summer and winter cards, are used to check the distances of the corresponding central lines from the equinoctial central line.
(g) *Errors in the cards.* Errors in the printing of the cards or change in size with humidity will give corresponding errors in the indicated duration of sunshine. The Meteorological Office specification for the cards requires that their lengths must not change measurably after immersion in water for 18 hours and must not contract by more than 1 per cent on redrying. The width should not increase by more than 2 per cent on immersion or decrease on redrying to less than 99 per cent of the original width.
(h) *Errors due to loss of light in the sphere.* The spheres are normally very stable but their transparency does decrease gradually with age. The condition of the sphere determines the minimum value of the intensity of the incident radiation which will give a trace on the card. Upon this value depends the time at which the trace starts on clear mornings or ceases on clear evenings.

2.2 Temperate sunshine recorder Mk 2

The temperate sunshine recorder Mk 2 (Plate II), intended for use in the latitude range 45° to 65°, has now been largely superseded by the Universal sunshine recorder Mk 3C (Plate III).

The bowl mounting consists of a tongue moving in a hinge cheek, so that the bowl may be rotated about an axis though its centre, perpendicular to the hinge cheek. The position of the bowl relative to the sub-base can be altered by slackening the lock-nut on the hinge pin and moving the tongue in the hinge cheek. The bowl should be set so that the reading of the scale on the hinge cheek is the latitude of the station.

The sphere seating consists simply of a small horizontal cup, with the same radius as the sphere, carried on a short pillar. Its position can be adjusted both horizontally and vertically after slackening the appropriate lock-nuts.

In very exposed situations a retaining clip can be fitted to prevent the displacement of the sphere in high winds. It consists of a double length of stout wire fixed to a collar. When the collar-retaining screw is loosened the collar itself can be slid on to the hinge cheek. The wire should press lightly on the top of the sphere but it may need to be bent downward slightly to do so. After it has been adjusted the retaining screw should be tightened.

The remainder of the Mk 2 recorder is similar to the Universal Mk 3C recorder.

The adjustable sphere seating, to some extent, simplifies adjustment for concentricity of the sphere and the bowl. This adjustment is made by the manufacturers and, in the case of instruments approved by the Meteorological Office, by the Instrument Branch Test Laboratory. It can only be satisfactorily checked with the use of a special centring gauge and should not be attempted by the user.

The general instructions regarding the installation, use and maintenance and the sources of error are the same as for the Universal model.

2.3 Other forms of sunshine recorder

Jordan sunshine recorder. This instrument consists of two semicylinders (Figure 8) each having a narrow aperture in the flat side. The semicylinders are mounted side by side, one with its aperture facing eastwards and the other westwards, on a levelling base plate

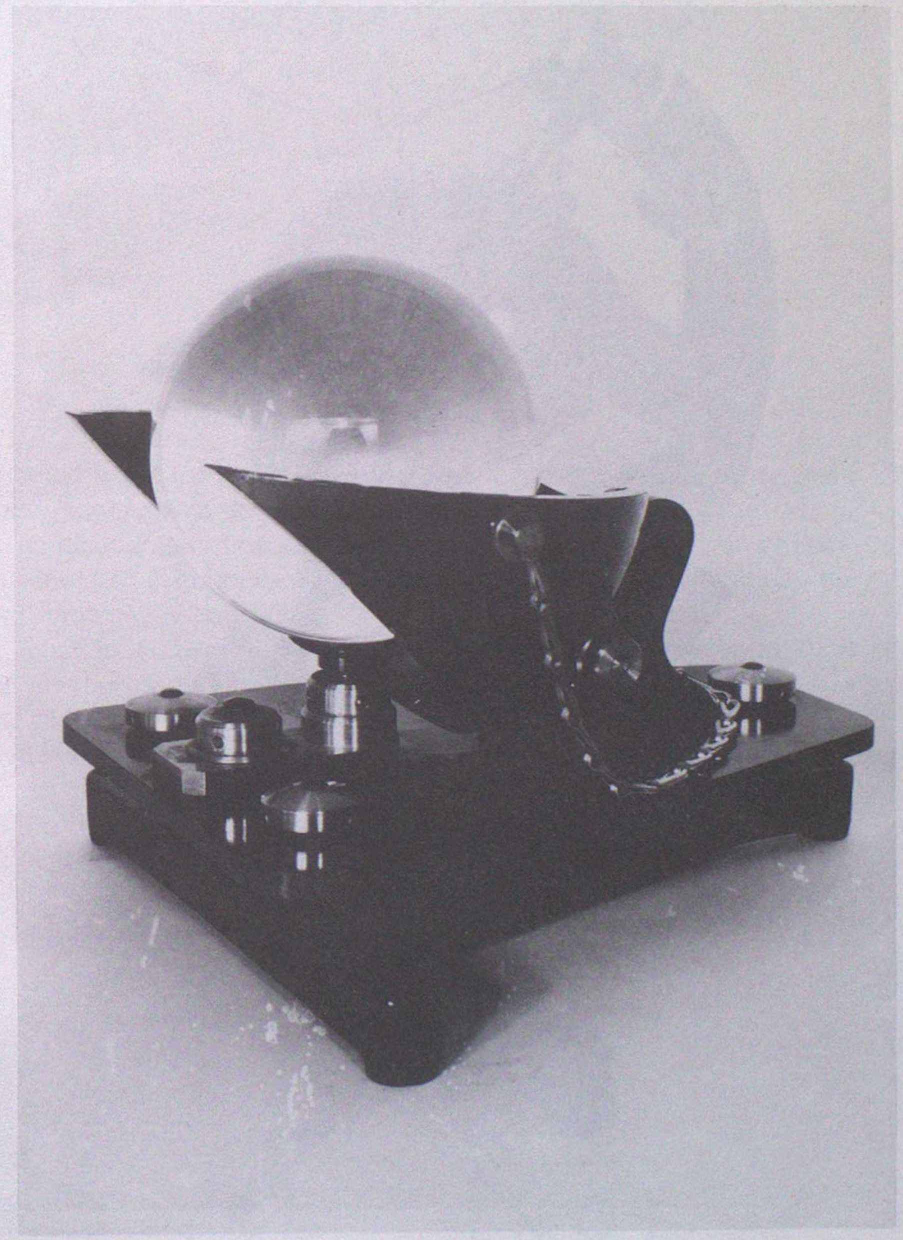


Plate II. Temperate sunshine recorder Mk 2.

Plate III. Universal sunshine recorder Mk 3C.

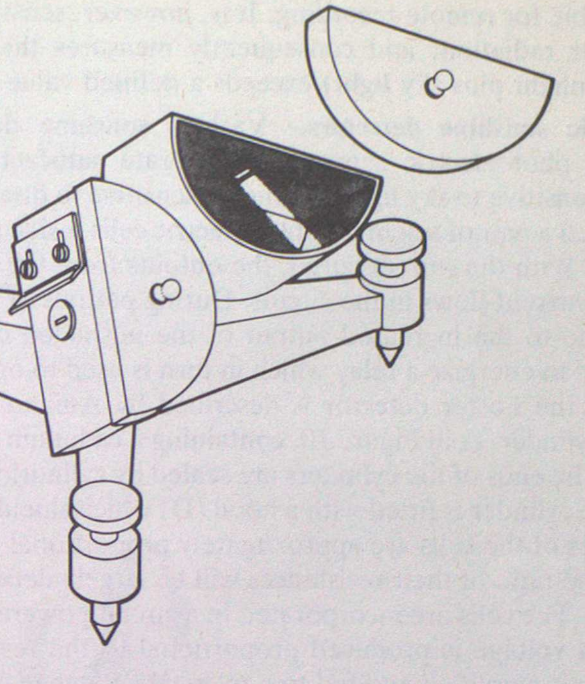


Figure 8. Jordan sunshine recorder.

which can be adjusted for latitude by means of a graduated arc. The record is obtained on photographic paper, such as the 'blueprint' type, placed round the curved wall of each cylinder. The measurement of the records is open to considerably more uncertainty than is the measurement of Campbell–Stokes records. It is also difficult to keep the sensitivity of the photographic paper constant.

Marvin sunshine recorder. The Marvin sunshine recorder (Figure 9) is essentially a differential air thermometer with one clear bulb and one black bulb in an evacuated glass jacket. The bulbs are separated by a column of mercury and alcohol that closes an electric circuit when sufficient radiation falls on the instrument. One advantage of this recorder is

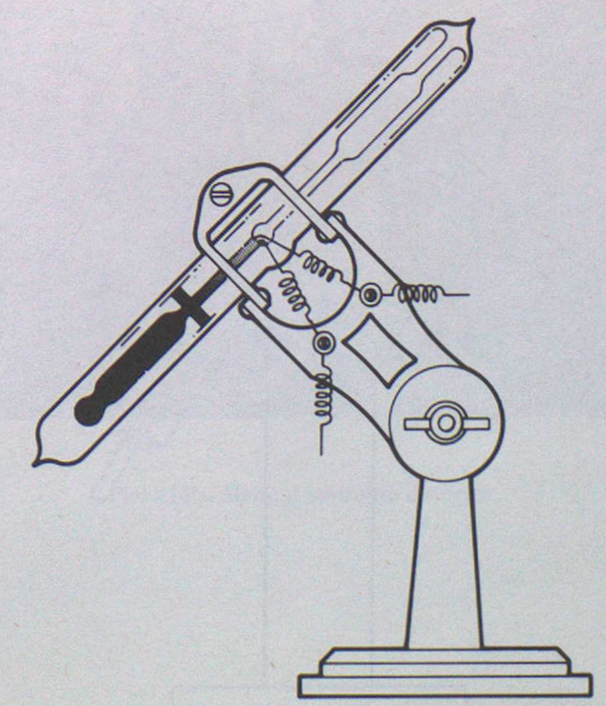


Figure 9. Marvin sunshine recorder.

that it is suitable for remote recording. It is, however, sensitive to diffuse radiation as well as direct solar radiation, and consequently measures the time during which the total insolation (sunlight plus sky light) exceeds a defined value.

Photoelectric sunshine detectors. Various sunshine detectors have been designed incorporating photoelectric sensors. To operate satisfactorily, such detectors should, ideally, be insensitive to sky light and highly sensitive to direct sunlight. Foster and Foskett (1953) mounted a pair of selenium photoelectric cells inside a translucent tube with a shade over one cell. With the sun obscured, the outputs from the two cells, due to sky light, are equal and no current flows in the circuit. During periods of sunshine, however, there is an imbalance, due to the increased output of the unshaded cell, and a current flows. This current is used to energize a relay which in turn is used to operate a pen on a recorder. An adaptation of the Foster detector is described by Amano *et al.* (1972). The instrument consists of a cylinder, A in Figure 10, containing a cadmium sulphide photoresistor cell (B) at each end. The ends of the cylinders are sealed by cylindrical, diffuse glass covers (C) and one end of the cylinder is fitted with a hood (D) which shields one cell from direct sunlight. The resistances of the cells are approximately proportional to the intensity of the incident light so that the ratio of their resistances will be largely dependent on the resistance of the unshaded cell. The cells are incorporated in a circuit powered by a constant current source and an output voltage is produced proportional to the resistance ratio of the cells. The output voltage is amplified and fed to a relay which, when activated, operates a recording pen. The operating voltage of the relay can be varied to suit the chosen threshold value of the intensity of solar radiation for the measurement of sunshine.

In the Haenni sunshine detector (Plate IV) a series of solar cells is mounted inside a translucent tube and at any time a small area of the cells is shaded by a rotating segment.

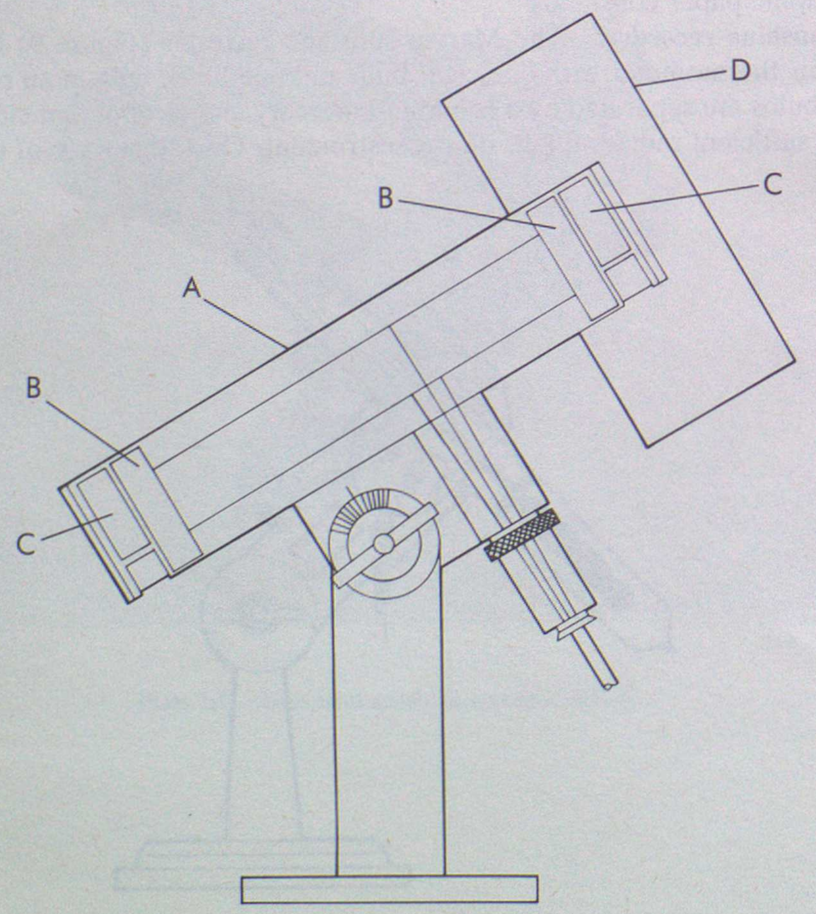


Figure 10. Shiko-type sunshine recorder.

Plate IV. Haenni sunshine detector.

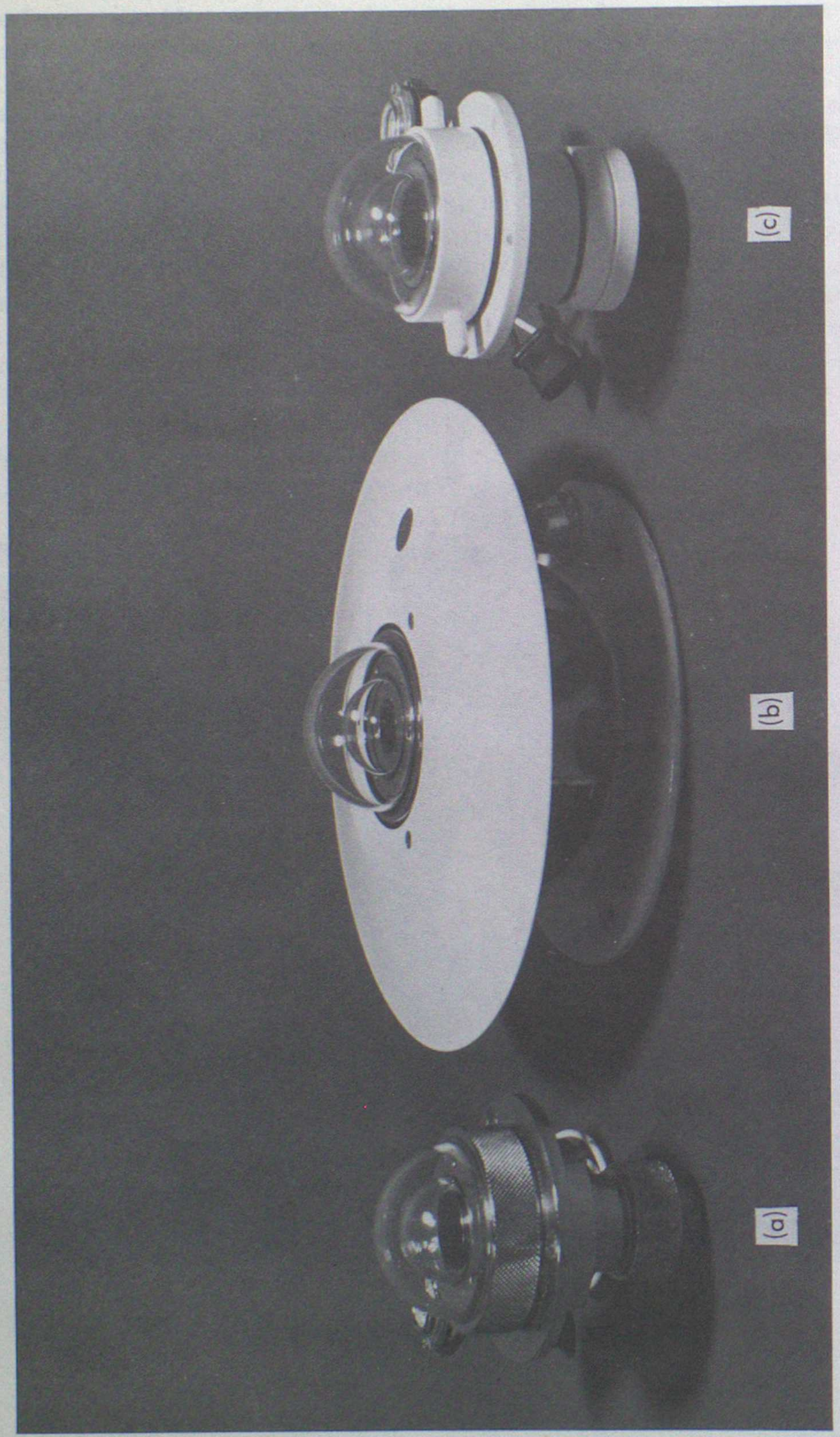


Plate V. (a) Kipp CM5, (b) Eppley precision spectral, and (c) Kipp CM2 pyranometers.

With an overcast sky the output from the cells is unchanging, whereas during periods of sunshine the output is in the form of pulses varying in amplitude from about −5 V to +5 V. The pulse amplitude is compared with an adjustable reference voltage and, if it exceeds the reference voltage, is interpreted as sunshine and transmitted as a binary signal to a suitable recorder.

3 MEASUREMENT OF SOLAR AND TERRESTRIAL RADIATION*

3.1 General

As short-wave radiation from the sun passes through the earth's atmosphere it is modified by the following processes:

(a) Absorption, scattering and reflection by cloud.
(b) Absorption by atmospheric gases, particularly oxygen, ozone, carbon dioxide and water vapour.
(c) Scattering and diffuse reflection from particles (e.g. dust and smoke) of a size comparable with, or larger than, the wavelength of light.
(d) Scattering by molecules of air and particles smaller than the wavelength of light.

As a result of the scattering processes, solar radiation received on a horizontal surface comprises a direct component and a diffuse component which, when measured together, are referred to as the global solar radiation. The remaining component of the short-wave radiation budget at the earth's surface is that portion of the global solar radiation which is reflected from the surface. At the earth's surface nearly all the short-wave solar radiation is confined between the wavelengths 0.3 μm and 3 μm.

Long-wave terrestrial radiation comprises the downward atmospheric component (e.g. downward emission by the atmospheric gases, particularly carbon dioxide and water vapour) and the upward terrestrial component (i.e. upward emission and reflection by the terrestrial surface and the atmospheric gases). For practical purposes the wavelength range of the long-wave terrestrial radiation is usually taken to be 4 μm to 50 μm.

The four components, global and reflected short-wave radiation and downward and upward long-wave radiation, can be combined in a single measurement to give the difference between downward and upward short- and long-wave radiation. The result is termed the net radiation.

3.2 Definitions and units

The power emitted or received in the form of radiation is termed the radiant flux. Irradiance is defined as the radiant flux per unit area incident on a surface; irradiation, the time integral of irradiance, is a numerical measure of the energy falling on unit area of a surface.

The preferred SI unit for irradiance is the watt per square metre (W m^{-2}), but for meteorological purposes the World Meteorological Organization (1971) recommends the milliwatt per square centimetre (mW cm^{-2}). The relation between various units is shown in Table IV.

The orientation of the surface must obviously be specified, and in practice the irradiance is mostly measured on two plane surfaces. These are a horizontal surface and a surface normal to the line joining the place of observation to the instantaneous position of the sun; in the latter case it is usual to restrict the observation to radiation coming from directions lying within about 2½° of the direction of the centre of the sun.

* Terrestrial radiation is the radiation emitted by the earth and its atmosphere whereas terrestrial surface radiation is the radiation emitted by the surface of the earth.

Table IV. *Relation between different units of radiant flux per unit area*

$W\ m^{-2}$	$mW\ cm^{-2}$	$kW\ m^{-2}$	$cal\ cm^{-2}\ min^{-1}$	$BTU\ ft^{-2}\ h^{-1}$	$BTU\ ft^{-2}\ min^{-1}$
1	0.1	10^{-3}	1.433×10^{-3}	0.316	5.29×10^{-3}
10	1	10^{-2}	1.433×10^{-2}	3.16	5.29×10^{-2}
10^3	10^2	1	1.433	3.16×10^2	5.29
698	69.8	6.98×10^{-5}	1	2.206×10^2	3.692
3.16	0.316	3.16×10^{-3}	4.52×10^{-3}	1	1.672×10^{-2}
189	18.9	1.89×10^{-5}	0.271	59.72	1

3.3 Reference scales

The relationship between radiation reference scales is discussed in detail by May (1980) and only a brief résumé is given here. For many years radiation measurements were based on two main standard instruments, the Ångström and the silver-disc (Smithsonian) pyrheliometers (see pages 6–27 and 6–41). In 1956 an International Radiation Conference recommended the adoption of a new scale, the International Pyrheliometric Scale (IPS 1956). To express measurements on the IPS 1956, measurements made according to the 1905 Ångström scale were increased by approximately 1.5 per cent, and measurements made according to the 1913 Smithsonian scale were decreased by approximately 2 per cent. At each 5-yearly international comparison of instruments, these corrections were updated; the updated values were not always universally accepted. Eventually, in 1975, the World Meteorological Organization recommended that cavity radiometers (see page 6–26) should provide the world reference and that a new scale, the World Radiometric Reference (WRR), should be established. This was adopted internationally in 1981, though the Meteorological Office exercised the option of adopting it a year earlier, from 1 January 1980.

3.4 Instruments for measuring radiation

Instruments used for measuring radiation are known collectively as radiometers and are classified as follows:

(a) Pyranometers and bimetallic actinographs: instruments for measuring the solar radiation received within a 180° field of view and suitable for the measurement of global or diffuse solar radiation.

(b) Pyrheliometers: instruments for measuring direct solar radiation at normal incidence; they can be either primary standard instruments or instruments scaled by reference to a primary instrument.

(c) Net pyrradiometers (sometimes termed radiation balance meters): instruments used to measure the net flux of downward and upward long- and short-wave radiation.

(d) Pyrgeometers (sometimes termed infra-red radiometers): instruments intended for measuring downward atmospheric radiation on a horizontal upward-facing surface at the ambient temperature, but may also be used in an inverted position to measure upward radition.

A brief description is given below of one or more of the instruments in each of the above classes.

Pyranometers (thermopile instruments). In a thermopile instrument a thin blackened surface, supported inside a relatively massive well-polished case, is exposed to the radiation; the difference in temperature between the surface and some reference point or points inside the instrument case is measured by several thermo-junctions arranged in series. The blackened surface rises in temperature until its rate of loss of heat by all causes is equal to the rate of gain of heat by radiation. If this rise in temperature is to be a function only of the irradiance, the rate of loss of heat for a given temperature difference must be

independent of the external conditions, such as the ambient temperature or the airflow past the instrument. It is also desirable that the rise in temperature should be directly proportional to the irradiance; in practice this means that convection currents in the case must be avoided. The time-constant should also be kept conveniently small.

Moll–Gorczynski pyranometer. In this type of pyranometer the thermopile (Figure 11) consists of alternate thin strips of manganin and constantan, with one set of junctions along the centre line of the surface (the 'hot' junctions) while the remaining ('cold') junctions are in good thermal contact with the relatively massive supporting posts. The posts are insulated electrically but not thermally from the base plate. The surface of the thermopile is blackened and enclosed in two concentric glass hemispheres, and the whole instrument is supported in a solid metal case. A single dome, whilst protecting the thermopile from the effects of wind, precipitation and contaminants, is affected by ambient temperature, giving rise to radiative exchanges between the thermopile and the dome. The addition of a second (inner) dome reduces this radiative exchange, though there is still a tendency for convective heat transport in the air between the thermopile and the inner dome. The top surface of the instrument case between the two hemispheres is highly polished to reduce the absorption of radiation. The instrument is mounted centrally in a guard plate which shields the remainder of the instrument from direct radiation and prevents radiation from below from entering the hemispheres and being reflected on to the thermopile.

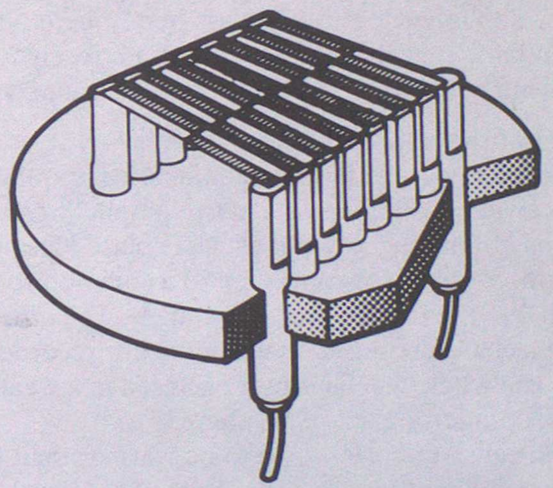


Figure 11. Thermopile of a Moll–Gorczynski pyranometer.

Heat transfers readily from the cold junctions to the instrument body so that, when the thermopile is exposed to solar radiation, the temperature of the cold junctions remains near to that of the instrument body. On the other hand, heat transference from the hot junctions is slow and their temperature rises until equilibrium is reached by radiative and conductive exchanges. As a consequence, an electromotive force is set up across the thermopile proportional to the difference in temperature between the hot and cold junctions.

Kipp pyranometer. The Kipp 'solarimeter' is an instrument of the Moll-Gorczynski type used throughout the United Kingdom radiation network. Two versions are used (Plate V), the CM2 (studied in detail by Bener, 1951 and Latimer, 1962) and the CM5.

The pyranometer consists of a thermopile mounted under two hemispherical glass domes, accurately ground, attached to a metal base ring by sealing compound. There are holes in the annulus between the two domes so that air can circulate between the domes and the body of the instrument. In the case of the CM5 the outer dome is sealed against the atmosphere by an O-ring which is compressed between the base ring of the dome and the body of the sensor when the dome is secured by a knurled clamp ring.

A desiccator is incorporated in the body of the CM5 to keep the air under the domes free from moisture. It is removed by unscrewing the knurled clamp ring (shown at I in Figure 17, page 6–35) at the bottom of the body. From the base of the CM2 protrudes a 'drying tube' to which a desiccator can be attached.

A spirit-level is fitted to the flange of pyranometers used in the Meteorological Office network during the radiometric levelling process (see page 6–35). The spirit-level can be viewed through an aperture in the guard plate; the aperture is normally closed by a cover which pivots on the under-side of the guard plate. The instrument has a time-constant (to within 1 per cent of full scale) of 30 seconds and a typical value of the sensitivity is 0.115 $mV\ mW^{-1}\ cm^{-2}$.

Eppley precision spectral pyranometer (Plate V). The sensor of this pyranometer is a circular 50-junction wire-wound plated (copper–constantan) thermopile. The sensor is enclosed in concentric clear-glass hemispheres, 30 mm and 50 mm in diameter. The outer hemisphere is interchangeable with another, either of glass absorbing in particular wavelength bands or with a deposited interference-type filter. These allow the separation of solar radiation into well-defined wavelength intervals. The instrument is fitted with a built-in desiccator and a guard plate, and incorporates a thermistor-controlled temperature-compensation circuit.

Eppley black and white pyranometer. This pyranometer has a radial wire-wound plated (copper–constantan) thermopile enclosed in a glass hemisphere 50 mm in diameter. The thermopile is a differential type with the hot-junction receivers blackened, and the cold-junction receivers whitened with a non-hygroscopic barium sulphate paint.

Bimetallic actinographs of the Robitzsch type. Several configurations of the bimetallic actinograph have been developed by different manufacturers but the principle of operation is the same in all. The receiving surface consists of two parallel, rectangular, white-painted, shielded or polished strips of bimetal between which is placed a similar strip of blackened bimetal. At one end the three strips are connected to a common rod, while the other ends of the white strips are fixed to the frame of the instrument. The other end of the black strip is connected to a lever mechanism and its movements are recorded by a pen on a chart placed on a chart drum. The whole mechanism is enclosed in a weatherproof case with the sensitive elements exposed under a glass hemisphere.

Absorbed radiation will cause the black strip to be warmer than the white strips and its increased curvature will result in a displacement of the pen. However, changes in ambient temperature will, ideally, produce identical temperature changes in both the black and white strips, resulting in no change in position of the pen.

This instrument is much simpler to operate than a thermopile instrument but it has a relatively large time-constant (5 to 10 minutes as opposed to less than 30 seconds for most thermopile instruments), and the effect of friction between the recording chart and the pen is somewhat greater than in, say, a bimetallic thermograph. The instrument is not considered suitable for measuring the instantaneous value of the radiation intensity, but it can be used for daily totals. A Meteorological Office version of this instrument is described on page 6–39.

Pyrheliometers

Kendall pyrheliometer Mk 6. The Kendall pyrheliometer Mk 6 (Plate VI) is a development of an instrument originally designed to aid calibration of a simulated sun for the testing of spacecraft (Kendall and Berdahl, 1970). It is a self-calibrating, cavity-type instrument of high accuracy, the most essential part of which is an internally blackened cavity, A in Figure 12, constituting a small black body. A thermal resistor, connected thermally between the cavity and the main body of the instrument, conducts heat produced in the cavity to the main body. The heat flux through the thermal resistor B, produced by

Plate VI. Kendall pyrheliometer Mk 6.

Plate VII. Ångström pyrheliometer.

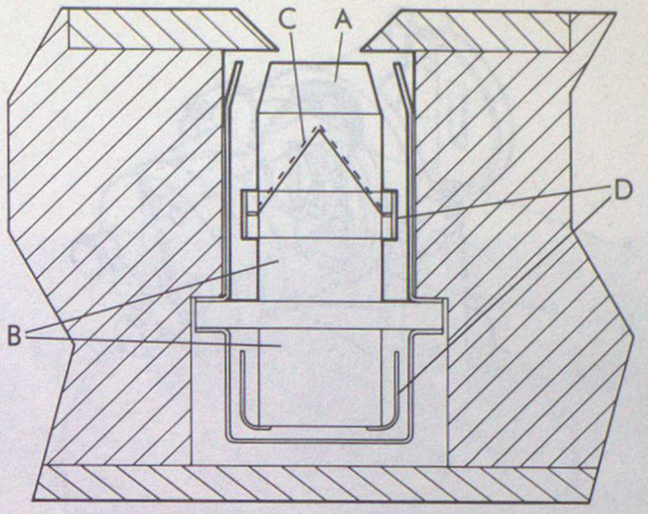


Figure 12. Kendall pyrheliometer Mk 6.

either incoming radiation or the electrical calibration heater C built into the cavity, causes a temperature drop across the thermal resistor which is measured by a thermopile D. By accurate measurement of the electrical power to the calibration heater, together with the thermopile response, the instrument can be calibrated without reference to other standards.

The pyrheliometer is used with a control unit which displays the output on a digital voltmeter in a choice of units, for example mW cm^{-2}, and which enables calibration and operational checks to be carried out.

The overall uncertainty of the measurements made when using the instrument is $\leqslant 0.5$ per cent and, essentially, arises from uncertainties in

(a) the area of the cavity aperture,
(b) the effective absorptivity of the cavity, and
(c) the equivalency and power measurement of the electrical calibration heater.

Ångström pyrheliometer. In the Ångström pyrheliometer (Plate VII) identical strips of blackened platinum, A in Figure 13, are similarly mounted, except that one strip is exposed to radiation while the other strip is shaded. The shaded strip is heated electrically until it is at the same temperature as the exposed strip. Under steady-state condition (both strips at the same temperature) the electrical energy used for heating equals the absorbed solar energy. Two thermo-junctions B, one on the back of each strip, are connected in series with a sensitive galvanometer and are used to determine equality of temperature. The heating current is determined by measuring the voltage across a standard resistor (Figure 13). The intensity I of the direct radiation is calculated from $I = \mathrm{k}\, i^2$, where i is the heating current and k a dimensional and instrumental constant. Such an instrument is, in theory, an absolute instrument as all the relevant factors can be measured, but small corrections have to be made for the imperfect absorptivity of the exposed strip and the slightly different exposure of the shielded strip. Most instruments are compared with a standard instrument of the same type, or against another type of primary instrument (e.g. a cavity radiometer), and a calibration figure obtained. When making an observation each strip is exposed in turn, and a mean value found for the current required.

Silver-disc pyrheliometer. The silver-disc pyrheliometer consists essentially of a blackened silver disc, A in Figure 14, supported by fine steel wires inside a copper shell. A mercury-in-glass thermometer is used to measure the temperature of the disc, the thermometer bulb being placed in a mercury-filled cavity in the disc. Diaphragms (B) are used to limit the angle of acceptance of the instrument to approximately 6°, and a shutter (C) is provided to exclude radiation altogether. The principle of the instrument is that the initial rate at which the silver disc is heated by the radiation is found by measuring the rate

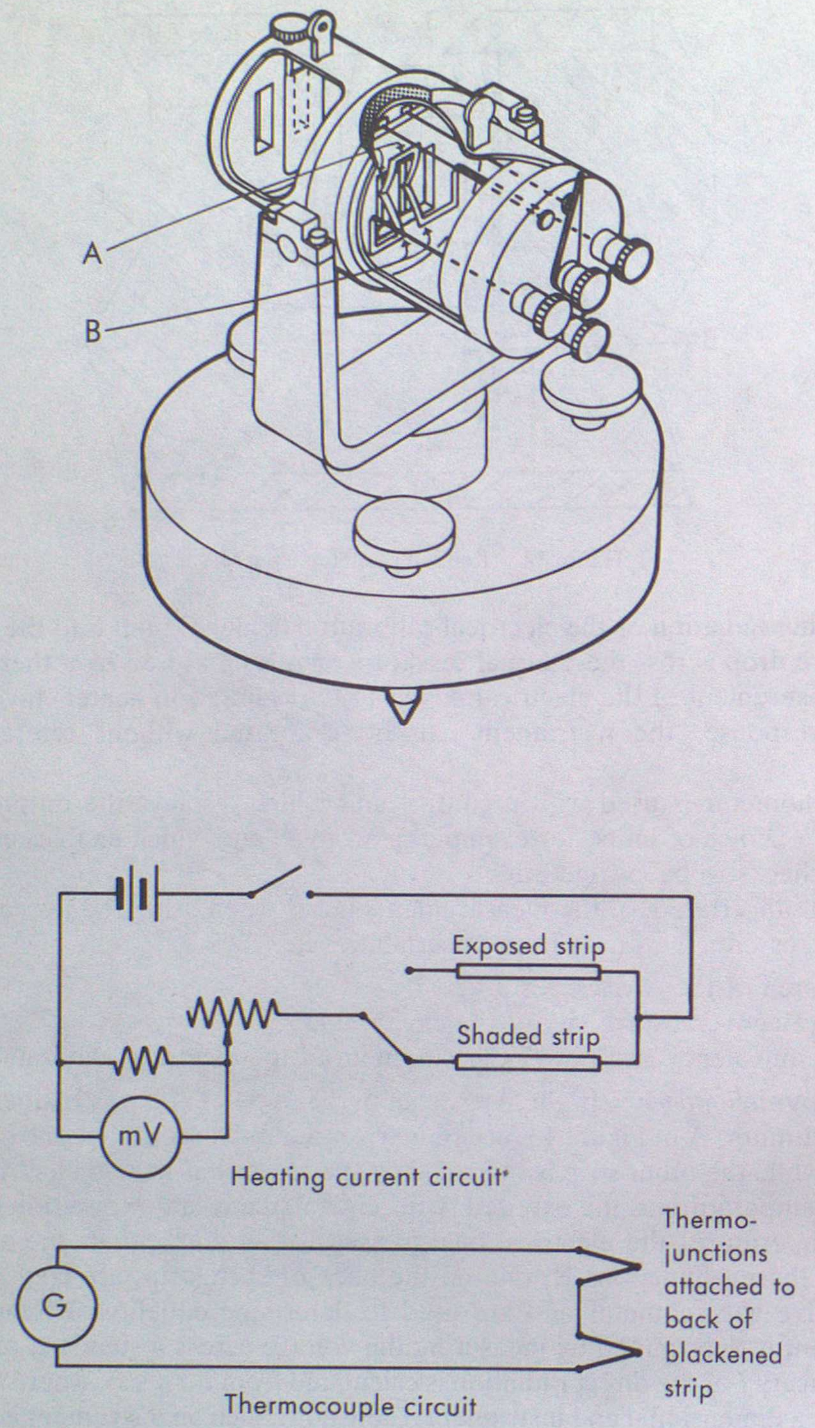


Figure 13. Ångström pyrheliometer.

of change of the disc temperature. By allowing radiation to fall on the disc at regular intervals and measuring the corresponding changes in temperature of the disc, the intensity of radiation I can be obtained using

$$I = (\mathrm{d}T/\mathrm{d}t)\ [\,1 + \mathrm{B}(T_m - T_d) - \mathrm{C}(T_a - T_s)\,]$$

where $\mathrm{d}T/\mathrm{d}t$ = the rate of rise of temperature of the disc,
T_m = the mean temperature of the disc during exposure,
T_a = the air temperature,
T_d = the standard disc temperature,
T_s = the standard temperature of the thermometer stem,
and B and C are constants.

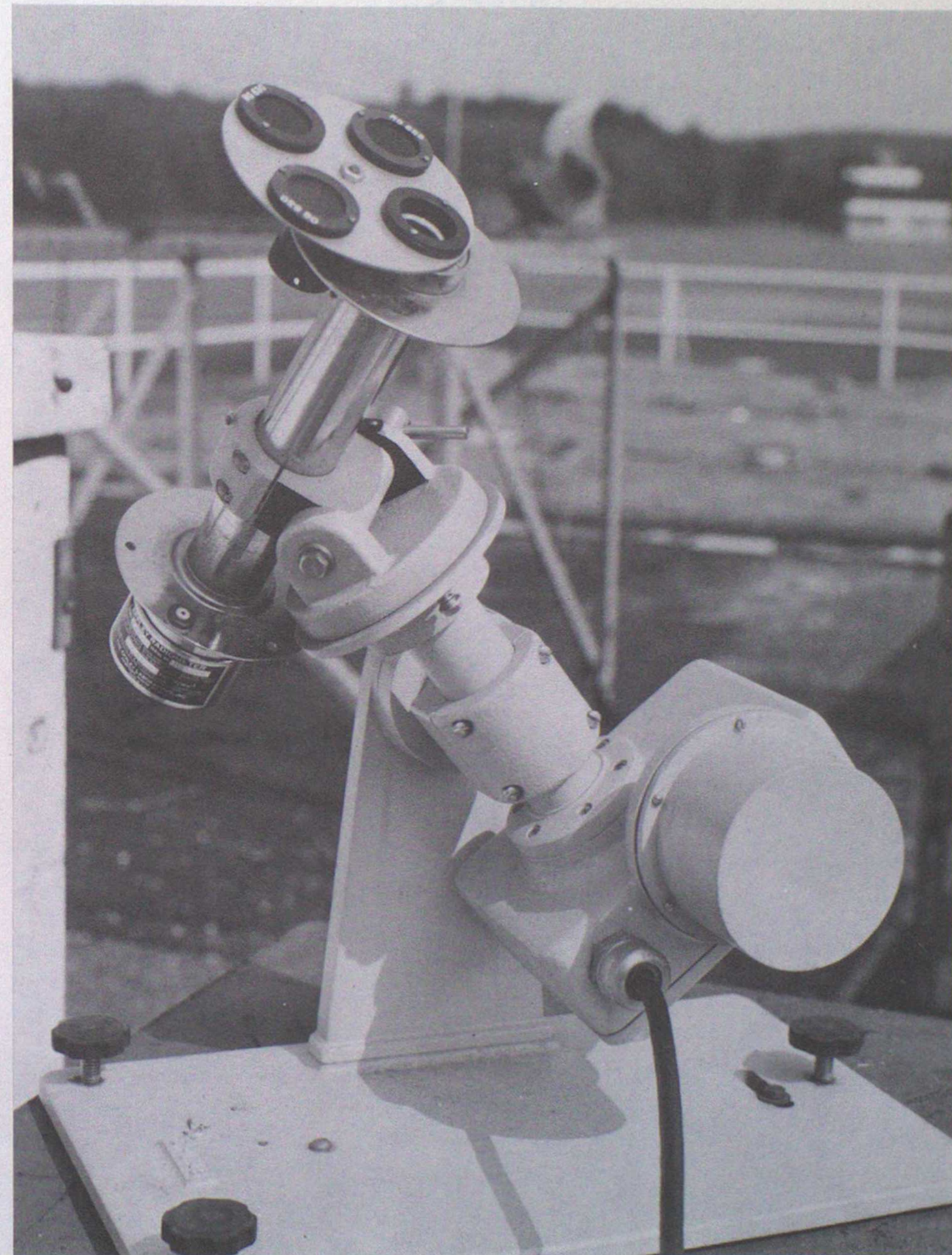


Plate VIII. Eppley normal incidence pyrheliometer.

Plate IX. Linke-Fuessner pyrheliometer.

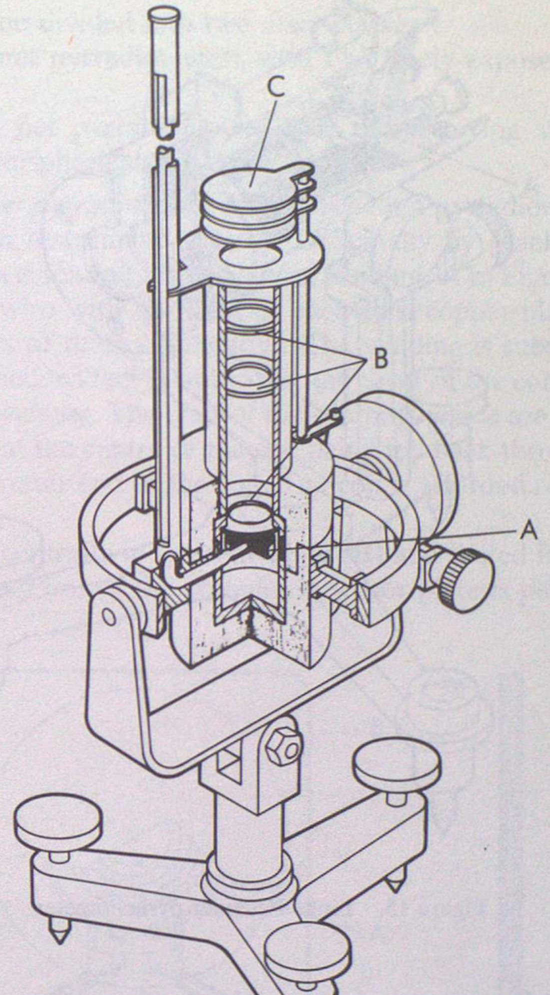


Figure 14. Silver-disc pyrheliometer.

Eppley normal incidence pyrheliometer (Plate VIII). This instrument is, in some respects, a thermo-electric version of the silver-disc pyrheliometer. The sensitive element is a wire-wound thermopile mounted at the base of an internally blackened brass tube. The tube is filled with dry air at atmospheric pressure and sealed at the viewing end with a removable insert incorporating a crystal quartz window. Two flanges, one at either end of the tube, are provided with a sighting arrangement for aiming the instrument directly at the sun. Fitted to the viewing end is a rotatable disc incorporating four apertures, three of which can accommodate filters.

The instrument has a sensitivity of about 0.08 mV mW^{-1} cm^{-2} and a time-constant of 1 second.

Linke-Feussner pyrheliometer. This pyrheliometer (Plate IX) comprises a Moll thermopile (see page 6–25), A in Figure 15, mounted in a thick copper shell consisting of a series of concentric, conical, milled rings which are screwed upon one another. The heavy mass of the body prevents air currents from unduly affecting the sensor and minimizes any temperature rise due to direct solar radiation, thus maintaining a uniform temperature in the vicinity of the sensor. The thermopile originally used contained 18 thermo-junctions but later models incorporate a thermopile which is divided into two equal sections, each consisting of 20 thermocouples, connected in opposition. Both sections are affected equally

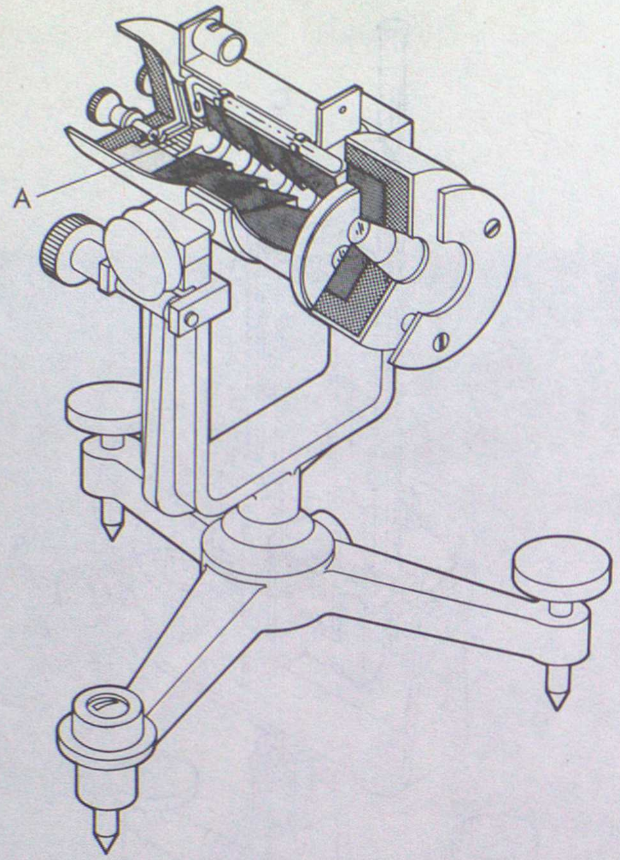


Figure 15. Linke-Feussner pyrheliometer.

by convective heat exchange occurring near the sensor surface, but one of the sections is shaded from the radiation being measured, thus acting as a compensating device. In addition to its more general use as a pyrheliometer, the instrument, which is fitted with a series of filters, can be used for measuring terrestrial surface radiation and atmospheric radiation.

Net pyrradiometers and pyrgeometers. All radiometers measure the energy exchange between a sensor and its immediate surroundings. With pyranometers and pyrheliometers the long-wave radiation exchange is mainly with the instrument case and is negligible when compared with the effect of solar radiation. However, when measuring the flux of long-wave radiation the sensor must exchange radiation freely with all parts of the appropriate hemisphere. A completely uncovered matt-black receiving surface, though meeting this requirement, is subject to other forms of heat exchange, mainly convective. The problem of eliminating convective effects, or at least making them constant, has been approached in four ways:

(a) Enclosing the sensor in a cover transparent to long-wave radiation (Schulze, 1953; Däke, 1972).
(b) By using a constant level of forced ventilation large enough to swamp natural convection due to the wind (Gier and Dunkle, 1951)
(c) By incorporating a compensating surface, which is largely unaffected by radiative exchanges but which is exposed to identical convective heat exchanges as the exposed surface, and measuring the energy required to maintain the two surfaces at the same temperature (Ångström, 1905).
(d) By making the radiometer response time long, so that short-period variations of the convective heat loss are smoothed out, and correcting the instrument readings for the effect of long-term wind-speed variations.

Net pyrradiometers may be divided into two main classes:
(a) Plate or unshielded net pyrradiometers with two freely exposed receiving surfaces, and
(b) Window or shielded net pyrradiometers with the receiving surfaces protected by curved, generally hemispherical, windows.

Meteorological Office net pyrradiometer Mk 8. The net pyrradiometer Mk 8 (Plate X) is the latest version of an instrument described originally by MacDowall (1955). In its present form, the sensor is essentially a coiled wire winding, A in Figure 16. The winding is formed from constantan wire with one half of each turn copper-plated, so forming two diametrically opposite sets of thermo-junctions. The winding is subsequently coiled with the two sets of thermo-junctions facing outwards; the turns of the coil are interleaved with a thermal and electrical insulator. The ends of the winding, which are copper-plated, act as the output leads, the end at the centre of the coil being fed back through the centre of the winding to emerge at the outer end of the coil. The coil is afforded rigidity and protection by embedding it in plastic.

The sensor is mounted centrally in a plastic plate (B) and sealed in place with a copper plate on each face. The exterior of the completed sensor plate is painted matt black.

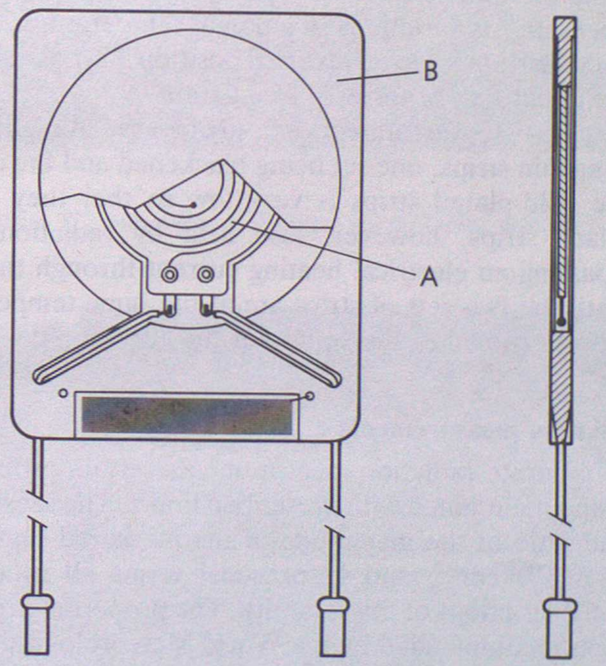


Figure 16. Sensor plate of a Meteorological Office net pyrradiometer Mk 8.

In use the sensor plate is located at the end of a duct, A in Plate X, ventilated by a blower B at the other end of the duct in such a way that each surface of the plate receives equal ventilation. The heat exchange between the surfaces of the plate and the ambient air is then independent of the wind velocity.

Funk-type net pyrradiometer. This instrument (Plate XI), as described by Funk (1959), comprises essentially a polythene windshield, in the form of two hemispheres, surrounding the actual sensor. The sensor consists of a rectangular plastic former on which is wound fine constantan wire, one half of each turn being copper-plated. The winding, covered on each face with a thin plastic sheet, is sandwiched between two aluminium plates whose exterior surfaces are painted matt black.

The polythene from which the windshield is formed is very thin and so the windshield requires inflation in order to retain a hemispherical shape. Nitrogen is used as the inflation gas; it has to be renewed frequently to avoid condensation inside the hemisphere due to the relatively high water-vapour permeability of polythene; in some versions a continuous flow of gas is maintained. The hemispheres, because of gradual photo-oxidization, require periodic replacement.

Eppley pyrgeometer. The Eppley pyrgeometer is a precision spectral pyranometer (see page 6–26) modified for the measurement of long-wave radiation only. The glass hemispheres of the pyranometer are replaced by a single hemisphere 30 mm in diameter, manufactured from a crystalline form of the mixed bromide–iodide of thallium, which is coated on the inner surface with a vacuum-deposited interference filter and on the outer surface with a weather-proof coating. This composite envelope isolates the sensor from short-wave radiation, exhibiting a sharp transition between about 3 μm and 4 μm from complete 'opaqueness' to maximum 'transparency'.

The output from the sensor represents the net radiation flux at the sensor surface. However, the radiation emitted by the sensor is dependent mainly on the sensor temperature. A thermistor-battery-resistance circuit is therefore incorporated in the instrument to compensate for sensor temperature. The thermistor senses the temperature of the thermopile and in so doing controls a voltage which can be introduced between the thermopile output and the measuring device to provide a measurement of the incoming radiation received at the thermopile surface. An additional thermistor-controlled circuit is incorporated to compensate for variations in ambient temperature.

By mounting a second instrument in an inverted position it is possible to determine, from the two instruments, the net flux of terrestrial radiation.

Ångström pyrgeometer. This instrument can only be used at night. The sensor consists of two sets of thin manganin strips, one set being blackened and the other set gold-plated. The emissivity of the gold-plated strips is very low so that they assume the ambient temperature. The black strips, however, lose heat by radiation, the cooling being compensated for by passing an electrical heating current through the strips. The heating current is adjusted until the two sets of strips are at the same temperature, when the net outward radiation is proportional to the square of the current.

3.5 Accuracy of radiation measurements

In order to ensure accurate radiation measurements certain properties of radiometers need to be evaluated and maintained with prescribed limits. The sensitivity of a radiometer may be defined as the ratio of the magnitude of the measured signal to the appropriate irradiance, e.g. $mV\ mW^{-1}\ cm^{-2}$, and in practical terms all other properties can be considered as producing variations of this quantity. The properties are described below and the prescribed limits, as recommended by the World Meteorological Organization (1971), are given in Table V.

Stability. Ageing of the coating of a thermopile, or corrosion of electrical and thermal contacts, can cause instabilities in radiation measurements. The stability of a radiometer is usually quoted as a relative variation in sensitivity per year.

Non-linearity. Non-linearity is normally quoted in terms of the percentage departure of the measured values from a nominal value. For thermopile radiometers the major factor affecting linearity is the manner in which the magnitude of the difference in temperature between the hot and cold junctions determines the heat conduction and the voltage produced.

Temperature coefficient. Any changes in the temperature of a thermopile cold junction, brought about by changes in ambient temperature, will effectively alter the sensitivity of the instrument. Some instruments are provided with built-in temperature-compensation circuits in an effort to maintain a constant sensitivity over a large range of temperatures (Collins and Walton, 1967; Weaving, 1975). The temperature coefficient is expressed as the percentage change in sensitivity per degree change in the temperature of the instrument.

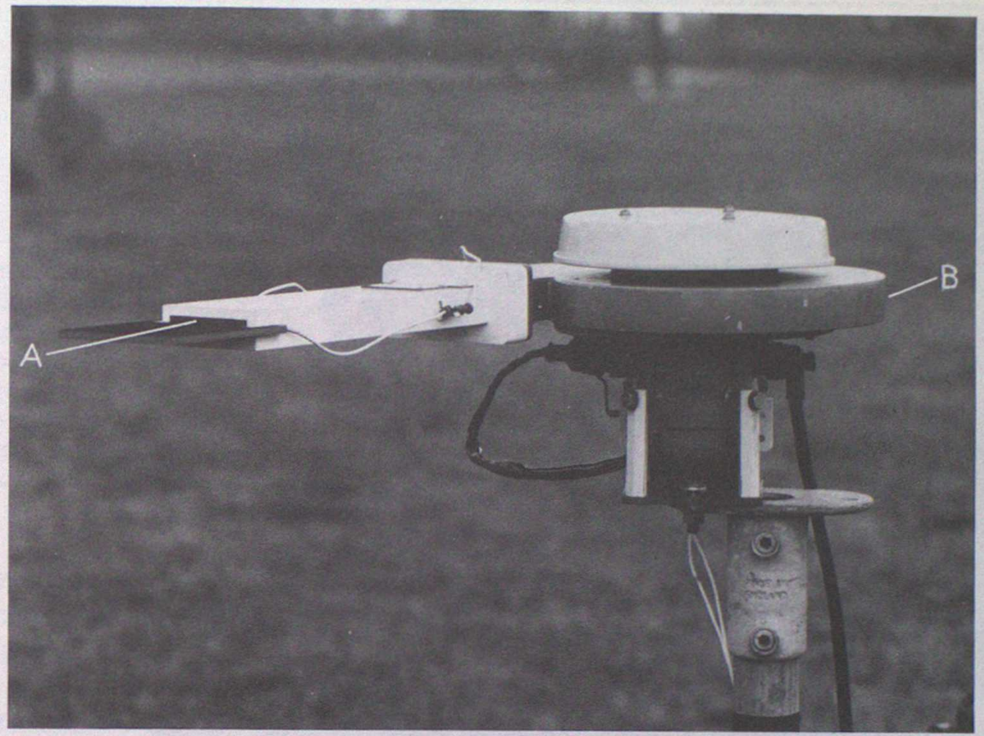


Plate X. Meteorological Office net pyrradiometer Mk 8.

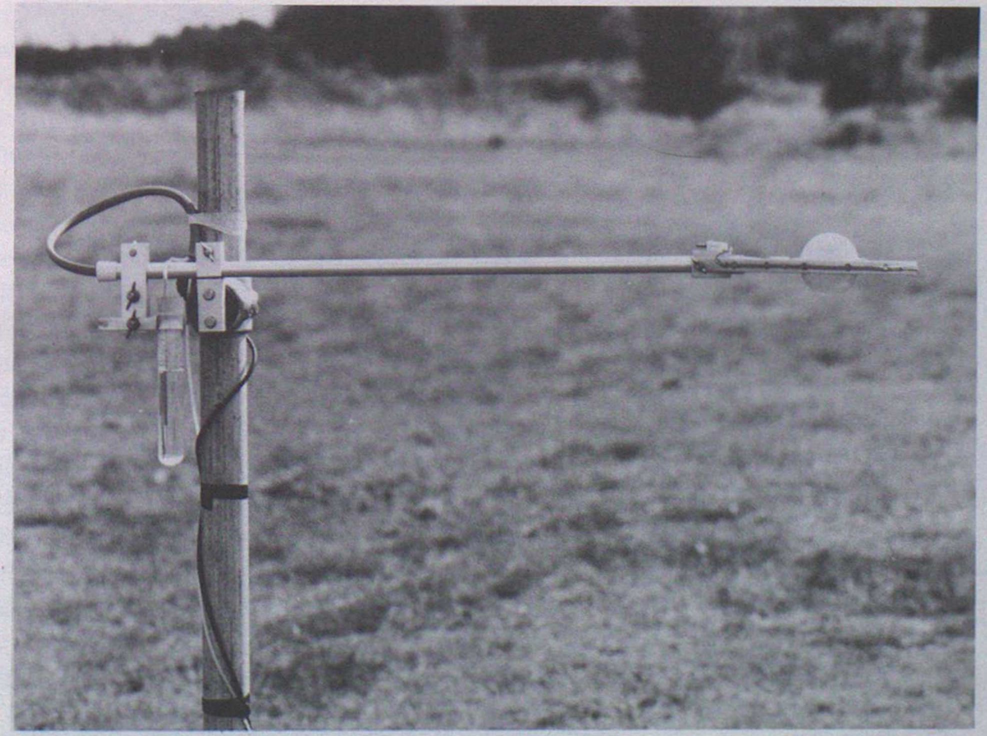
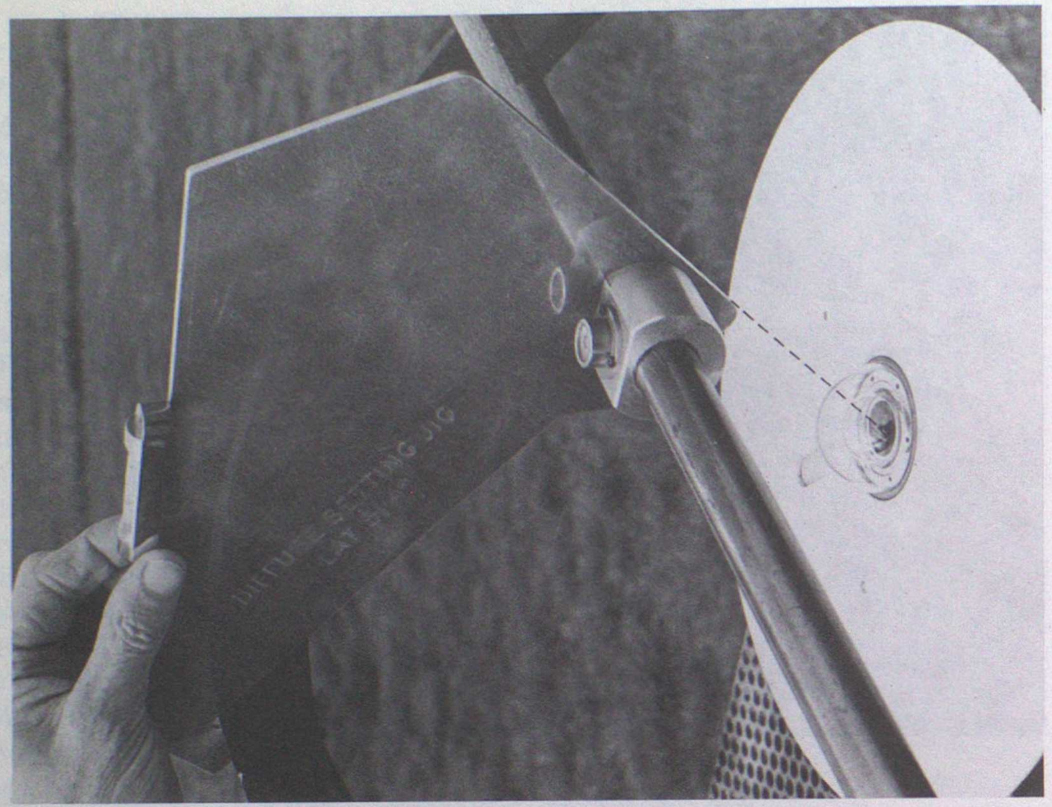


Plate XI. Funk-type net pyrradiometer.



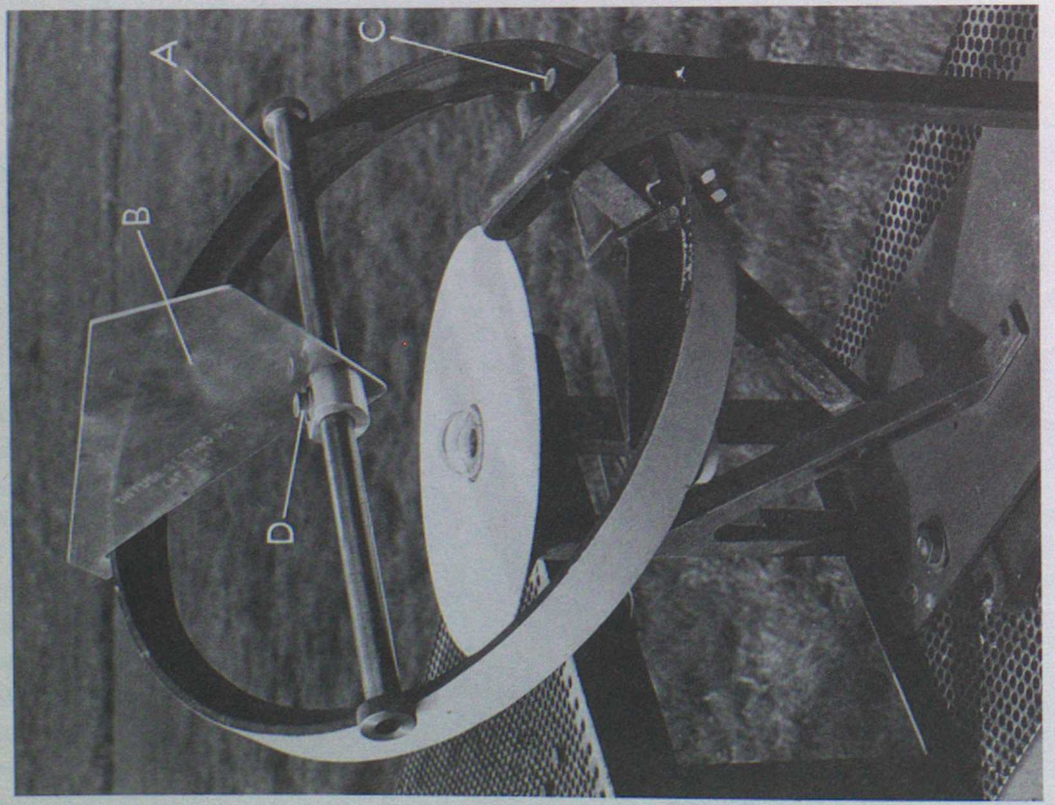


Plate XII. Diffuse mounting jig.

Table V. *The WMO classification of accuracy of radiometers*

		Reference standard pyrhelio-meter	Secondary instruments							
			Pyrheliometers		Pyranometers			Net pyrradiometers		
			1st class	2nd class	1st class	2nd class	3rd class	1st class	2nd class	3rd class
Stability	%	±0.2	±1	±2	±1	±2	±5	±1	±2	±5
Linearity	%	±0.5	±1	±2	±1	±2	±3	±1	±2	±3
Temperature	%	±0.2	±1	±2	±1	±2	±5	±1	±2	±5
Time-constant	s	25	25	60	25	60	240	30	60	120
Selectivity	%	±1	±1	±2	±1	±2	±5	±3	±5	±10
Cosine response	%	–	–	–	±3	±5–7	±10	±5	±10	±10
Azimuth response	%	–	–	–	±3	±5–7	±10	±5	±10	±10

Time-constant. During the time taken by a radiometer to respond to 63 per cent of a step change in radiation intensity, the output, and thus the sensitivity, of the instrument will vary until a steady state is reached. As a rule the 95 per cent response time is about three to four times the value of the time-constant.

Variations in spectral response. Errors can be caused by a departure of the sensor response from the required spectral range. Instruments with thermopiles coated with a suitable optical black, and fitted with hemispheres having the required level of spectral transmission, usually present no problem in this respect.

Variations of response with the angle of incidence and the azimuth. The dependencies of the response of the sensor on the solar elevation and the azimuth are known as the cosine response and the azimuth response respectively.

Cosine response. Ideally the response of a sensor should be proportional to the cosine of the angle of incidence of the incident radiation. Departures from the cosine response in pyranometers are mainly the result of optical refraction in the hemispheres and unevenness in the thermopile surface.

Azimuth response. Assuming the angle of incidence remains constant, the sensitivity of a sensor should ideally be independent of the azimuth. With pyranometers, marked variations in response with change in azimuth can occur due to the effects of optical refraction, inhomogeneities in the hemispheres, and of the construction or geometry of the thermopile. In general, the 'azimuth error' increases with the angle of incidence.

The two effects are related inasmuch as the cosine response can vary with azimuth.

Variation of response with angle of inclination. When measurements are made with a sensor mounted in a vertical or inclined plane, account has to be taken of the change in sensitivity compared to a sensor mounted in a horizontal plane (Goldberg, 1980; Flowers, 1977). This change in sensitivity is brought about by the effects of convective heat transport in the air between the thermopile and the inner hemisphere of a pyranometer.

Additional inaccuracies can arise owing to lack of maintenance, incorrect exposure (see below), and the fact that hourly irradiations are usually calculated from 60 measurements of irradiance and are therefore only estimates of the true values.

3.6 Exposure of radiometers

Ideally, the site chosen for a radiometer should be free from any obstruction above the plane of the sensor. In practice it is usually a question of obtaining a site as free as possible from obstructions, the aim being to expose the instrument so that no shadow is cast upon it at any time and it will not be affected by reflected sunlight or by artificial radiation. If possible, no obstruction should exceed 3° in elevation, but if this condition cannot be met it should be borne in mind that directions from north-east through east to south-east, and from north-west through west to south-west, are the most critical.

For pyranometers and upward-facing pyrgeometers a flat roof often provides a suitable location for mounting the instrument support. If such a site is unavailable the support should be mounted some distance from buildings and other obstructions such that the above criteria are fulfilled.

The site chosen for a net pyrradiometer or a downward-facing pyrgeometer should have a surface that is representative of as wide an area as possible of the surroundings; an artificial surface should be avoided. A practical height for mounting the instrument is between 1 m and 2 m above the ground, though this may be increased where possible so that the measurements are representative of a larger area.

For records to be of value, changes in site exposure should be kept to a minimum. Slow changes in exposure, such as the growth of trees, are not immediately identifiable. When the equipment is installed it is therefore advisable to make a detailed site plan, similar to that for a sunshine recorder (see page 6–11), showing the elevation and extent of any obstructions. The plan should be reviewed every few years, any changes of exposure noted and, if possible, remedial action taken to minimize any obvious trends..

3.7 Measurement of the intensity of global and diffuse solar radiation on a horizontal surface — using a Kipp pyranometer

The Kipp pyranometer is described on page 6–25. When used for measuring global solar radiation, within the Meteorological Office network, it is mounted on a global solar radiation mounting Mk 2 (Figure 17). The mount is in three main parts:

(a) A casting (C) with three holes in the base so that it can be fixed to a stable platform. Rising from the base are three pillars which support the next item.
(b) A pyranometer mounting plate (E) with levelling screws (F) to level the pyranometer.
(c) A guard plate (A), with height adjusters (G) mounted on the pyranometer mounting plate.

The assembled mount is approximately 150 mm high and 300 mm wide.

The diffuse solar radiation pyranometer mounting is shown in Figure 18. The direct radiation from the sun is cut off by a shadow band, a circular metal ring carried on an adjustable arm. The arm is pivoted about a horizontal axis so that its angle to the horizontal can be set equal to the latitude of the site. Movement of the ring up or down the arm can then be made to allow for the change in the sun's declination.

At Meteorological Office sites the pyranometer is used with a potentiometric chart recorder, scaled in millivolts, in parallel with data-logging equipment. The Meteorological Office data-logging equipment MODLE 1, now obsolescent, logged the data on punched paper tape and the MODLE 3 logs the data on magnetic tape.

Installation. In selecting a site for the pyranometer careful consideration should be given to the exposure (see page 6–33). At Meteorological Office stations an exposure diagram for the full 360° azimuth should be prepared, and be approved by the National Radiation Centre, before the instrument is installed.

A horizontal platform about 300 mm square is required for each pyranometer mounting, global or diffuse. The base of the mounting should be used as a template for placing the holes for the mounting's securing bolts. The platforms and their supports should be strong enough to hold the mountings securely in the strongest wind likely to be experienced at the sites.

The pyranometer thermopile is rectangular and, in order that its calibration should apply, the long side of the thermopile must be aligned east-west. With the CM5 (see (a) in Plate V) this is achieved by installing the pyranometer with the aperture from which its output leads emerge facing north. With the CM2 (see (c) in Plate V) a black line painted on the pyranometer flange should point north.

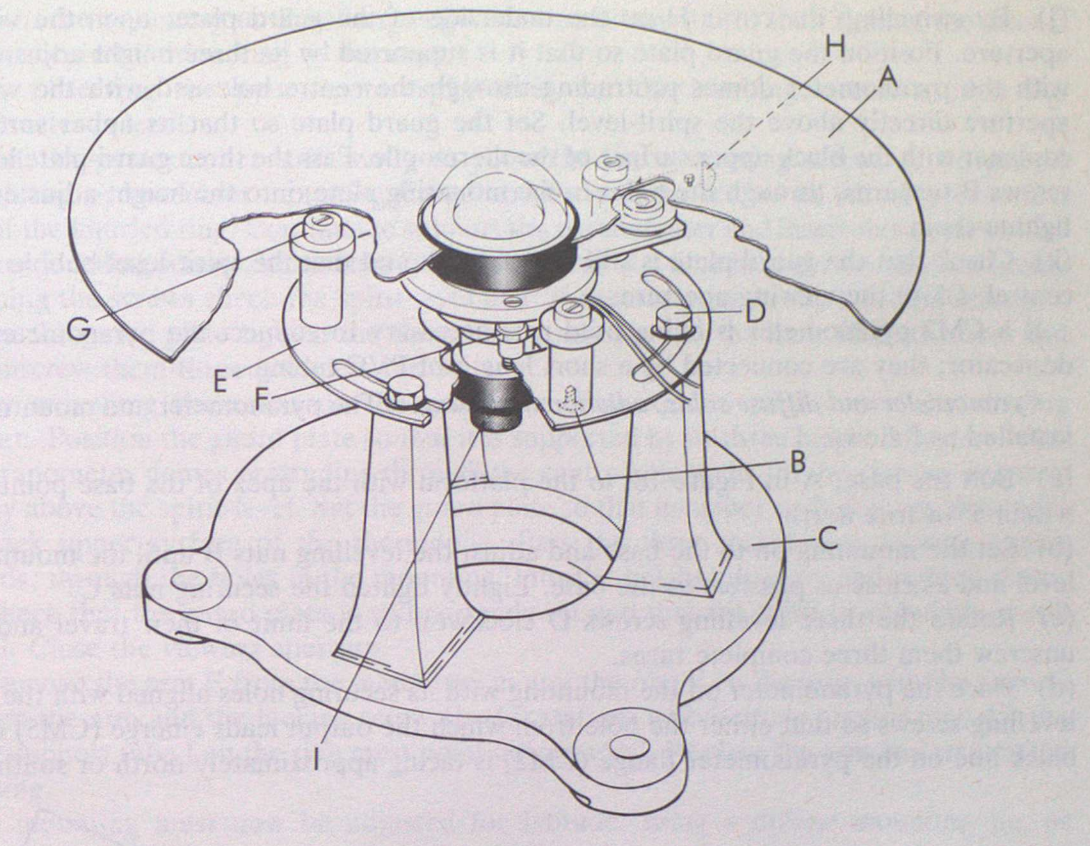


Figure 17. Global solar radiation mounting Mk 2.

All studding, bolts and nuts should be lightly greased when assembling and adjusting the pyranometer.

Pyranometer and global solar radiation mounting Mk 2. The pyranometer and mounting are installed as follows:

(a) Remove the guard plate, A in Figure 17, by unscrewing the three screws B.
(b) Fix the base C of the mounting to the platform so that two of the fixing holes are aligned north–south and the remaining fixing hole points to west.
(c) Slacken the three bolts D holding the plate E and turn the plate so that the three bolts are in the middle of the curved slots.
(d) Rotate the three levelling screws F clockwise to the limit of their travel and then unscrew them three complete turns.
(e) Place the pyranometer on the mounting with its securing holes aligned with the three levelling screws so that either the hole from which the output leads emerge (CM5) or the black line on the pyranometer flange (CM2) is facing approximately north.
(f) Turn the plate E until the output lead exit or the black line faces within 2° of true north, then tighten the bolts D to secure the plate to the base. This adjustment can take account of any small azimuth error in the fixing of the base on its platform.
(g) By observing the pyranometer spirit-level, set the levelling screws so that the pyranometer is level.
(h) Lift the pyranometer sufficiently to allow the three securing screws to be passed down through the pyranometer mounting flange and their heads settled in the counter-bores, clear of the knurled ring. Continue to support the pyranometer and insert those screws into the three levelling screws, tightening them a few turns at a time in sequence. Before finally tightening the screws check the spirit-level and, if necessary, reset the levelling screws.
(i) On the guard plate tighten the three height adjusters G to the limit of their travel and then unscrew them three complete turns.

(j) By swivelling the cover H on the underside of the guard plate, open the viewing aperture. Position the guard plate so that it is supported by its three height adjusters G, with the pyranometer domes protruding through the centre hole and with the viewing aperture directly above the spirit-level. Set the guard plate so that its upper surface is coplanar with the black upper surface of the thermopile. Pass the three guard-plate locking screws B upwards, through the holes in the mounting plate, into the height adjusters and tighten them.
(k) Check that the guard plate is still correctly set and that the spirit-level bubble is still central. Close the viewing aperture.

If a CM2 pyranometer is being used it is necessary to connect the pyranometer to a desiccator; they are connected by a short length of PVC tubing.

Pyranometer and diffuse solar radiation mounting. The pyranometer and mounting are installed as follows:

(a) Bolt the base, A in Figure 18, to the platform with the apex of the base pointing to within 5° of true north.
(b) Set the mounting on to the base and adjust the levelling nuts B until the mounting is level and as close as possible to the base. Lightly tighten the securing nuts C.
(c) Rotate the three levelling screws D clockwise to the limit of their travel and then unscrew them three complete turns.
(d) Place the pyranometer on the mounting with its securing holes aligned with the three levelling screws so that either the hole from which the output leads emerge (CM5) or the black line on the pyranometer flange (CM2) is facing approximately north or south.

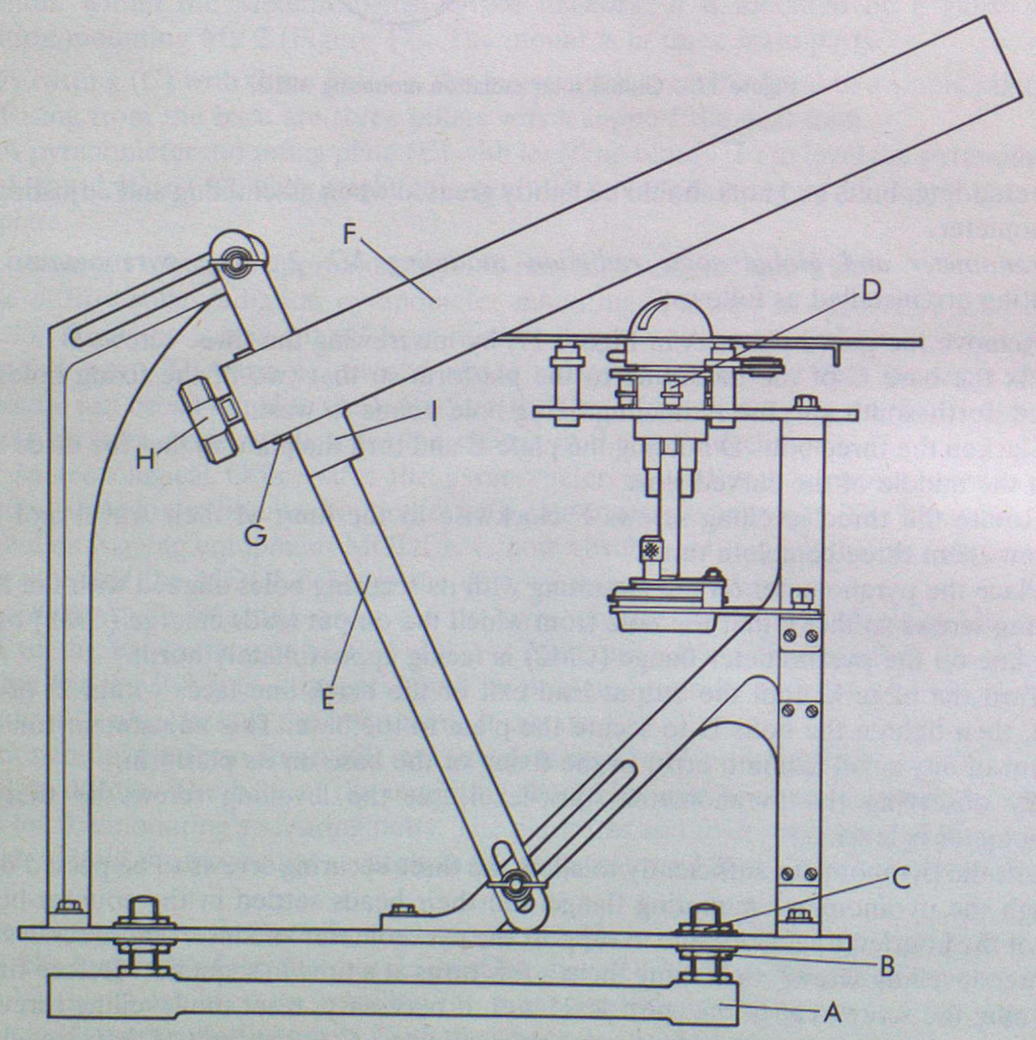


Figure 18. Diffuse solar radiation mounting.

(e) Turn the mounting until its long edge lies true north–south, then tighten the nuts C fully to secure the mounting to the base.
(f) By observing the pyranometer spirit-level, set the levelling screws so that the pyranometer is level.
(g) Lift the pyranometer sufficiently to allow the three securing screws to be passed through the pyranometer mounting flange and their heads settled in the counter-bores, clear of the knurled ring. Continue to support the pyranometer and insert those screws into the three levelling screws, tightening them a few turns at a time in sequence. Before finally tightening the screws check the spirit-level and, if necessary, reset the levelling screws.
(h) On the guard plate tighten the three height adjusters to the limit of their travel and then unscrew them three complete turns.
(i) By swivelling the cover on the underside of the guard plate, open the viewing aperture. Position the guard plate so that it is supported by its three height adjusters, with the pyranometer domes protruding through the centre hole and with the viewing aperture directly above the spirit-level. Set the guard plate so that its upper surface is coplanar with the black upper surface of the thermopile. Pass the three guard-plate locking screws upwards, through the holes in the mounting, into the height adjusters and tighten them.
(j) Check that the guard plate is still correctly set and that the spirit-level bubble is still central. Close the viewing aperture.
(k) Remove the arm E from the mounting; mount the ring F on the arm, with the shim G between the arm and the locking screw H; (for stations with latitude greater than 45° the square support tube I on the ring must point downwards). Replace the arm and ring on the mounting.

The mounting must now be adjusted for latitude, using a diffuse mounting jig, as follows:

(a) Check that the diffuse mounting jig is marked for the latitude of the site. Unscrew the boss from one end of the brass tube, A in Plate XII, insert the tube through the hole in plate B and replace the boss. Position the plate at the centre of the tube and secure in place by tightening the grub-screw in the plate boss.
(b) Move the ring to near the upper end of the arm and place the mounting jig on the ring so that the tube rests horizontally across the ring and the projection on the plate fits over the top of the ring.
(c) Slacken the wing-nuts C and adjust the position of the arm until the bubble in the spirit-level D is central, and the edge of the plate at right angles to the ring is in line with the centre of the thermopile (see right-hand photograph in Plate XII). Tighten the wing-nuts and check that the adjustment has not been disturbed.
(d) Both the top edge of the plate and the tube should now be horizontal and should be checked, using an ordinary spirit-level. If found not to be horizontal, the spirit-level on the jig should be regarded as suspect and the mounting adjustment repeated, using an ordinary spirit-level.

The ring can now be set so that its shadow covers the whole of the outer dome of the pyranometer.

Maintenance. The following tasks should be performed carefully so that the pyranometer dome does not become marked or scratched. Objects should not be placed on the guard plate and when the pyranometer is removed from its mounting the dome should not be allowed to make contact with anything but a soft cleaning cloth or tissue. No attempt should be made to repair the pyranometer or to remove the dome. If it is suspected that the pyranometer is faulty a replacement should be fitted.

Daily inspection. The surface of the dome should be inspected and any deposit, e.g. dirt or precipitation, removed using a clean soft cloth or tissue. De-icing fluid may be used to remove ice but the dome must be dried carefully afterwards. Check that there is no condensation under the dome. Also check that the shadow of the diffuse mounting ring covers the whole of the outer dome of the pyranometer.

Monthly inspection. The desiccator should be removed and the colour of the silica gel checked: if it is blue, refit the desiccator. If any of the silica gel is pink, empty the desiccator, dry it, refill it with new (blue) silica gel and refit it on the pyranometer. A check should be made that the pyranometer is level.

When necessary, regrease the mounting nuts and bolts, and repaint the inner face of the ring on the diffuse mounting with matt black paint.

The exposure details on the site plan should be checked every few years and suitably amended if any change in exposure has taken place.

Correction of the pyranometer measurements. It may be necessary to correct the measurements of global and diffuse radiation to take account of obstruction to the solar beam by permanent obstacles. The quantity to be calculated is the fraction of the vertical component of the short-wave flux which is lost by obstruction. Since the pyranometer has a cosine response, radiation incident at angles of less than 3° to the horizon has very little effect, and consequently obstacles of similar elevation may be neglected.

To determine the correction accurately for diffuse radiation it would be necessary to make allowance for the variation in intensity of the diffuse radiation over the hemisphere, which depends on the condition of the sky at the time. This is not practicable so it is usually assumed that the diffuse radiation is uniform over the whole sky.

In order to determine the diffuse corrections, Blackwell (1954) developed a formula where θ is the elevation and ψ the azimuth of the obstacle and where an elementary area with co-ordinates (θ, ψ) will contribute a fraction $\sin\theta\cos\theta.d\theta d\psi/\pi$ to the total vertical component. To calculate the loss due to a fixed obstacle of finite size the outline of the obstacle should be mapped out on a $\theta-\psi$ diagram. Its projection on this diagram is divided into discrete areas over which θ does not vary by much more than 5°. Then the total loss due to the obstacle is given by

$$\frac{1}{\pi}\Sigma\,(\tfrac{1}{2}\overline{\sin 2\theta}.\Delta\theta\Delta\psi)$$

where $\overline{\sin 2\theta}$ is the mean value of $\sin 2\theta$ over each discrete area.

The diffuse radiation is, of course, only one component of the global radiation. In comparative terms, therefore, the effect of obstructions on diffuse radiation is less for global radiation; as a rough guide the necessary percentage correction to global radiation measurements is approximately two-thirds of the percentage correction to diffuse radiation. It is not practicable to apply a constant correction to the direct component of global radiation since this component varies with the time of year. However, if a chart recorder is available, a dip in the trace will be observed when the sun passes behind an obstruction and a correction can often be obtained by interpolation across the dip.

An additional correction must be applied to the diffuse radiation measurements to compensate for the diffuse radiation intercepted by the shadow-ring. The method is an extension of that described above to calculate the effect of permanent obstacles. Let the radius of the ring be R and the half width be d; let the latitude be ϕ, and δ the declination of the sun; then the general equation for the projection of the two rims of the ring on the $\theta-\psi$ diagram is:

$$\cos\theta\sin\psi\cos\phi + \sin\theta\sin\phi = \frac{R\tan\delta \pm d}{[(R\tan\delta \pm d)^2 + R^2]^{\frac{1}{2}}}$$

where ψ is measured positive from east through north. Substituting in this equation, at a series of values of θ (0°, 10°, etc.) will give pairs of values for ψ representing the two rims of the ring. This procedure is repeated for six days of the year (summer and winter solstices, the equinoxes and, say, 15 January and 15 May). When the outlines of the shadow-ring have been drawn in for the six typical days, the areas obtained are divided into convenient parts (say between $\theta = 0°$ and $\theta = 10°$ etc.) over which values of $\tfrac{1}{2}\sin 2\theta$ may be conveniently assigned. The final corrections

$$\frac{1}{\pi}\Sigma\,(\tfrac{1}{2}\sin 2\theta.\Delta\theta\Delta\psi)$$

are then computed and a curve drawn, giving the annual variation of this quantity which is symmetrical about the summer solstice.

The application of this correction results in a close correspondence between global and diffuse irradiances during overcast sky conditions, but when the sun shines through thin cloud, or when the sky is partly covered by cloud, the corrected value of diffuse radiation over an hour may be as much as 15 per cent less than the value that would be obtained by using a sun tracker to obscure the direct radiation.

Accuracy of solar radiation measurements. It is obvious that many factors influence the accuracy of solar radiation measurements when using the Kipp pyranometer. Because of the cosine response error, hourly irradiations early and late in the day can be in considerable error. A daily global solar radiation total will usually be more accurate than individual hourly figures, and of course the time of year has an influence.

Table VI gives an estimate of the various component errors in the United Kingdom network.

Table VI. *Estimation of the errors of daily global solar radiation measurement using a CM2 pyranometer*

Cause	% error	Cause	% error
Transference of standard	1.5	Cosine response	2
Calibration	2	Sampling	1
Temperature coefficient	2.5	Unspecified (includes	
Non-linearity	1	depression of the zero,	
Recorder	1	drift of calibration, etc.)	1

Taking the root mean square of these errors, the result is a total error of about 4–5 per cent. Some of the errors are not strictly random; for example, temperature has a seasonal trend and high irradiances will usually coincide with high temperatures so that the temperature and non-linearity errors are complementary.

3.8 Measurement of the intensity of global solar radiation on a horizontal surface — using a bimetallic actinograph Mk 3

The bimetallic actinograph Mk 3 (Figure 19) is designed to record the irradiance of the global solar radiation, but should only be used when the use of the more accurate thermopile pyranometers is impracticable.

The instrument broadly follows the general description given on page 6–26. A plain glass hemisphere, A in Figure 19, covers the sensitive element and is supported by the outer cover. A hinged inspection panel, inserted into the top of the outer cover, provides access to the clock and drum. Either weekly or daily clocks and drums can be used, but the daily versions are to be preferred.

A circular spirit-level B is fitted to the instrument base and a silica-gel drier is used to keep the air inside the case dry, thus minimizing the risk of condensation on the inside of the glass dome.

The instruments should give reliable daily radiation totals with an uncertainty of about 10 per cent, provided it is calibrated at frequent intervals. The time-constant of the sensor alone is about 4 minutes but in practice, taking pen friction into account, this figure increases to about 7 minutes.

Installation. The recommendations regarding exposure (see page 6–33) should be followed as closely as possible. The instrument should stand freely on a firm support, except in exposed positions where some form of fixing may be required. The glass window opposite the drum should face north in the northern hemisphere; the bimetallic strips will thus be aligned east–west.

Once installed, the instrument should be carefully levelled by using the levelling screws and observing the spirit-level on the case.

Method of use. The chart should be changed after sunset to avoid disturbing the record unnecessarily during the daytime. For the same reason it is better to note the difference between the chart time and the standard time once a day rather than to make a time mark in the normal manner.

The instrument should indicate zero in the absence of radiation, for example at night. However, the pen deflexion is dependent to some extent on the difference in temperature between the glass dome and the instrument body. This temperature difference is influenced by the long-wave radiation exchange with the atmosphere, both by day and by night, which in turn depends on the cloud cover. Consequently the zero trace during the night may not be constant. The accuracy of the instrument does not, however, justify any attempt to distinguish between different cloud conditions. The daytime trace, therefore, may be referred to a zero obtained from the mean night-time trace.

Care should be exercised when removing or replacing the outer case as the clearance between the rim of the glass dome and the bimetallic strips is very small. The guide rods must be in their sockets before the case is slid fully home.

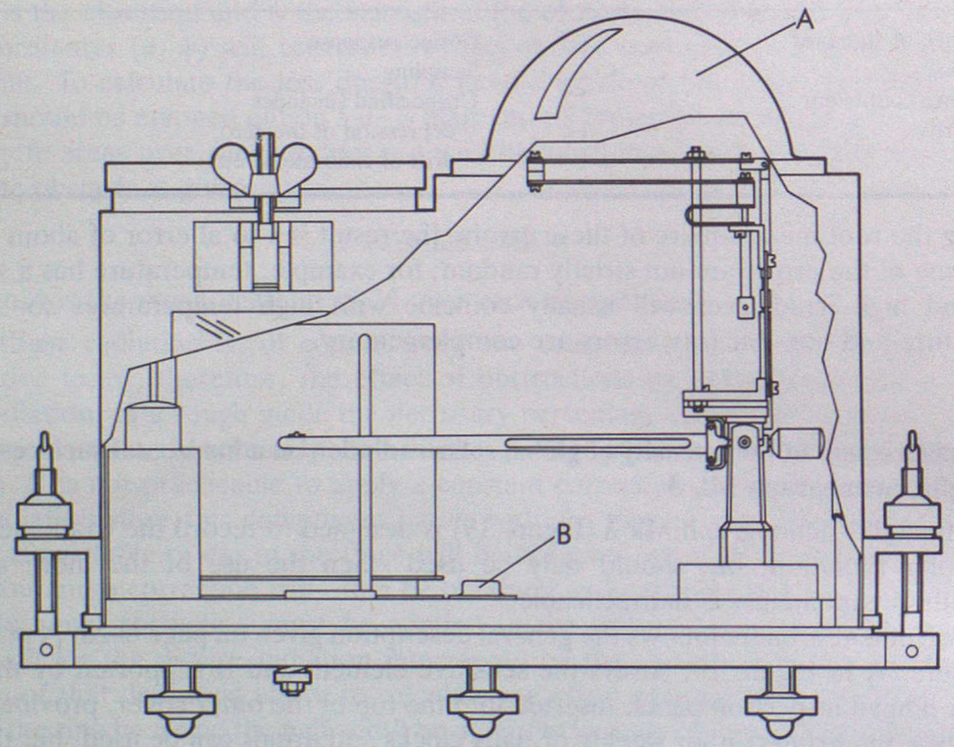


Figure 19. Bimetallic actinograph Mk 3.

Maintenance. The moving parts of the instrument should be kept clean and free of dust, and the pivots and linkage should be oiled sparingly with clock oil two or three times a year. The instrument case should be kept clean and the glass hemisphere should be cleaned daily, using a clean soft cloth or tissue.

The adjustment of the gate suspension should be checked regularly to ensure that the pressure of the pen on the chart is kept to a minimum.

The silica-gel drier will need regular reviving by heating. When dry the indicator is coloured blue and when damp it is coloured pink.

3.9 Measurement of the net flux of incoming and outgoing total radiation using the net pyrradiometer Mk 8

The net pyrradiometer Mk 8 (Plate X) is described on page 6–31. In selecting a site for the instrument the recommendations made on page 6–33 should be followed as closely as possible.

The instrument should be mounted on a support with the sensor plates horizontal and at a height of 1 metre above the ground. The sensor plates should also face south, so that the shadow cast by the support does not fall directly beneath the downward-facing sensor plate at any time. Though the support should be substantial enough to withstand the strongest winds likely to be experienced at the site, it should also have as small a cross-section as possible so as not to interfere unduly with the exposure of the downward-facing sensor plate.

The pyrradiometer is used with the same equipment, i.e. a potentiometric chart recorder in parallel with a MODLE, being used to record global and diffuse radiation data (page 6–34).

3.10 Measurement of solar radiation at normal incidence

Measurements of solar radiation at normal incidence may be in the form of either spot readings or a continuous recording, depending on the type of pyrheliometer used. The Ångström and silver-disc pyrheliometers are only suitable for spot readings whereas the Kendall, Eppley normal incidence and Linke-Feussner pyrheliometers can be used in either mode.

For continuous recording an equatorial mounting is necessary. The mounting, which is motor driven, rotates the pyrheliometer about an axis parallel to the axis of the earth's rotation so that the receiving surfaces of the pyrheliometer are at all times perpendicular to the line joining the sun to the receiver. Two examples of an equatorial mounting are shown in Plates VI and VIII. The mounting has to be adjusted daily to take account of changes in the sun's declination.

3.11 Standard instruments and calibration of sensors

Within the United Kingdom the primary standard for solar radiation is a cavity-type radiometer (see page 6–26) held at the National Radiation Centre. In addition to the primary standard, two Ångström pyrheliometers are held as secondary standards. The primary standard is submitted to periodic international comparisons so that its calibration can be checked. The comparisons, organized by the World Meteorological Organization, are held at the World Radiation Centre at Davos where the primary standard is a series of cavity-type radiometers from which a mean reference reading is obtained.

Calibration of pyrheliometers. Pyrheliometers are calibrated by direct comparison with the primary standard. The calibration is made in the open, under conditions of reasonably steady solar radiation.

Calibration of transfer standard pyranometers. These calibrations are only carried out between March and October, weather conditions permitting: the solar elevation is too low at other times of the year. The two transfer standard instruments, Kipp CM2 pyranometers, are mounted in the open on a calibration stand and can be shaded by an occulting disc (Plate XIII). The solid angle subtended by the disc at the centre of the thermopile is identical to the effective aperture (5°) of the standard pyrheliometer. The outputs from the pyranometers are logged on a potentiometric recorder at the rate of one reading of each output every 20 seconds, the recorder being periodically calibrated against an accurate voltage source to determine the linearity of the scale readings. A record is obtained with one pyranometer shaded and the other unshaded, simultaneous pyrheliometer measurements being taken manually. For comparison, a period of steady outputs for at least 5 minutes is chosen. The shaded pyranometer is then unshaded, and vice versa, and the process repeated. The irradiances for the two sequences may differ and so, as a final step, both instruments are shaded and a ratio of their outputs for diffuse irradiance obtained. The output from the shaded pyranometer in either of the first two sequences may then be corrected to give the expected value of the output for diffuse irradiance for the unshaded pyranometer under similar conditions.

The sensitivity of each pyranometer with respect to the vertical component of the direct solar radiation is then obtained from

$$k = \frac{T - D}{E\sin\theta}$$

where E = the irradiance at normal incidence due to the observed direct solar radiation, as measured by the pyrheliometer,
θ = the mean solar elevation,
T = the pyranometer output in the unshaded condition,
D = the pyranometer output in the shaded condition, and
k = the sensitivity of the pyranometer.

Calibration of network pyranometers. The calibration of pyranometers intended for operational use is performed in an integrating chamber. The chamber (Plate XIV) has a cylindrical base about 2 m in diameter and a hemispherical dome. The inner surface of the chamber is painted with a highly reflective diffuse paint. Six 600–watt tungsten–halogen lamps, A in Figure 20, are mounted equidistantly around the inside of the chamber at a height of 950 mm, providing an irradiance of about 40 mW cm^{-2} at the sensor surface. Situated in the centre of the chamber is a hollow column B on which the pyranometers are mounted; the height of the column is such that the surface of the sensor thermopiles will be in the plane of the base of the hemispherical dome.

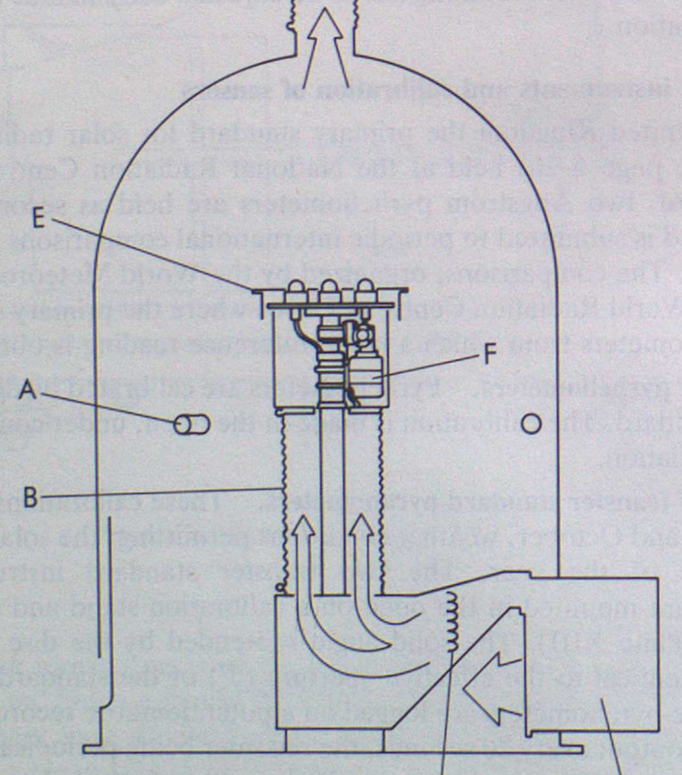


Figure 20. Interior of the integrating chamber.

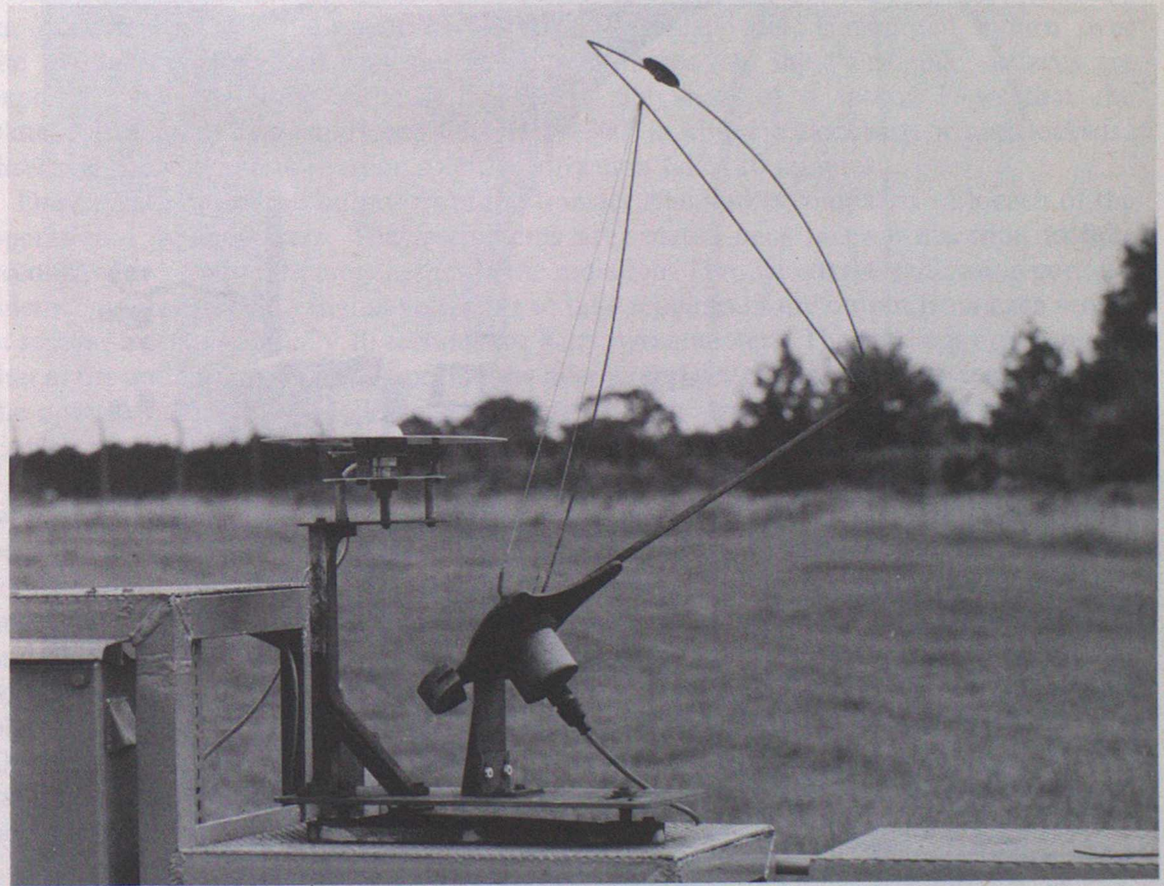


Plate XIII. Occulting disc apparatus.

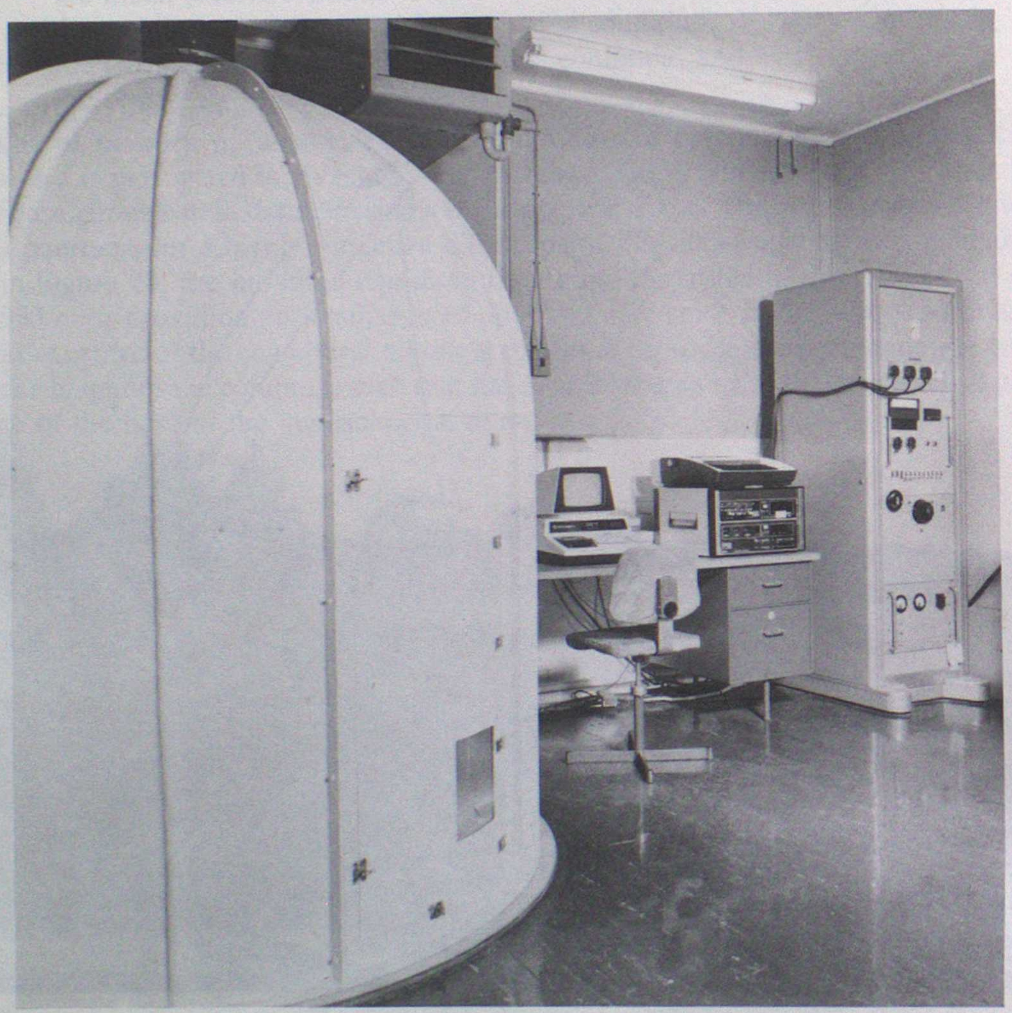


Plate XIV. Integrating chamber and ancillary equipment.

Fitted into the side of the chamber are an air-conditioner C and an electrical heater D. The air emerging from the air-conditioner is directed in part to the main body of the chamber and in part over the thermostatically controlled heater and thence, via trunking, up the inside of the central column to the base of the pyranometers. A thermistor, mounted inside the column below the pyranometer mounting plate, is used to control the heater output. The pyranometers are thus maintained at a temperature of about 22 °C, whilst the temperature of the air in the main body of the chamber varies between about 22 and 25 °C. Air is extracted from the chamber by a fan mounted over a vent in the top of the dome.

Electrical resistance thermometers (ERTs), mounted centrally at the top and bottom of the chamber, are used to monitor the vertical temperature gradient within the chamber. Another ERT, mounted inside the column adjacent to the thermistor, is used to monitor the temperature of the air reaching the pyranometers.

The transfer standard pyranometer and either one or two operational pyranometers are mounted on a plate at the top of the column, with a shade plate E mounted, in turn, over the pyranometers so that only the glass hemispheres and the thermopile surfaces are exposed. The mounting plate is linked to the shaft of a motor F so that the plate–pyranometers assembly can be rotated 360° in either a clockwise or anticlockwise direction; one complete rotation in either direction takes 10 minutes.

During calibration the output from the transfer standard is compared with each of the operational pyranometers. The instruments are rotated once in each direction to take account of any slight inhomogeneities in the radiation. Throughout the calibration period a microcomputer directs a digital voltmeter to take readings of the output from each sensor at regular intervals, usually 10 seconds for Kipp pyranometers. The readings are stored so that at the end of the calibration period the microcomputer can calculate the sensitivities of the operational instruments, using the sensitivity of the transfer standard for comparison. Eppley precision spectral pyranometers are also calibrated by the above method.

Outdoor calibrations are also carried out using a six-channel voltage integrator system with automatic printing of the integrated totals at pre-selected time intervals. The counting period is usually set at 30 minutes, which is a compromise figure based on the conflicting requirements of a long period to reduce counting errors when evaluating the signal ratios and a short period to permit selection of suitable intervals during the day based on weather and sky conditions and solar elevation and to detect any variation in instrument sensitivity related to these variables. With a clear sky or one with well-broken cloud, emphasis is placed on observations near solar noon to reduce the effect of cosine response error. Overcast skies with near-isotropic conditions are probably the best for this type of calibration but a variety of conditions are aimed at to assess overall instrument performance.

The Kipp pyranometer exhibits a departure from an exact cosine response at low solar elevations, particularly in the direction of the line of its thermo-junctions. This is compensated for by 'radiometrically levelling' the instrument prior to calibration. The pyranometer is mounted horizontally on a stand fitted with levelling screws and exposed to a lamp, angled at 15° to the horizontal, within a dark-room. The levelling screws are adjusted until the output from the pyranometer at two points 180° apart on the axes, along and perpendicular to the line of the thermo-junctions, is similar. The spirit-level on the pyranometer is then adjusted so that the bubble is central, and then sealed in position. Thus, when the pyranometer is installed operationally, the surface of the thermopile will not necessarily be geometrically level.

Eppley pyranometers are also 'radiometrically levelled', though the above symptom is not quite so marked as with the Kipp pyranometer.

Accuracy of the calibration. The use of an integrating chamber for calibration purposes ensures a constant radiation source and an independence of weather conditions. However, the spectral distribution of the energy of the lamps is different from that of the sun, though this is unimportant if the transmission characteristics of the glass domes of all the instruments are similar. Also, the radiance of the inner surface of the chamber is reasonably uniform whereas, in normal use, the major part of the global radiation incident on a pyranometer may be the direct component.

The sensitivity determined by the outdoor method does not always agree with that obtained by indoor calibration, differences of 1 to 2 per cent being common with the indoor figure being the higher. Where there is a consistent difference for a particular pyranometer the figure used is biased towards that obtained outdoors.

Calibration of net pyrradiometers. The calibration of net pyrradiometers for short-wave radiation is carried out in a dark-room with the sensor mounted 1.5 m vertically below a 600-watt tungsten–halogen lamp. The radiant flux of the lamp is amplified, by incorporating two silvered prisms in the lamp house, to give an irradiance of approximately 5 mW cm^{-2} at the sensor surface. Prior to any calibration this irradiance is determined accurately by placing a Linke-Fuessner pyrheliometer in the position to be occupied by the net pyrradiometer; the pyrheliometer is a transfer standard previously calibrated by comparison with the primary standard.

The net pyrradiometer is mounted and levelled in a precise position beneath the lamp. At regular intervals a shade plate is automatically interposed midway between the lamp and the sensor, each mode — 'shaded' and 'unshaded' — being maintained for 5 minutes. In this way the sensor is alternately exposed to and shielded from the short-wave radiation emitted by the lamp. The long-wave radiation reaching the sensor is essentially the same for both positions of the shade plate. Any difference in the output of the sensor measured in consecutive shaded and unshaded modes is therefore representative of the irradiance due to the lamp.

During calibration the output of the sensor is monitored by a microcomputer programmed to distinguish between the shaded and unshaded modes and to compute the means of three shaded and four unshaded periods. Quality-control routines in the program ensure that the spurious readings encountered during the changeover from shaded to unshaded modes, and vice versa, are omitted from any calculations. The difference between the shaded and unshaded measurements is determined, and the sensitivity of the exposed side of the sensor plate derived, using the lamp factor previously measured. The sensor plate is then inverted and the calibration sequence repeated. At the completion of this second sequence the final sensitivity is computed as the mean of the sensitivities of both sides of the sensor plate.

Net pyrradiometers intended for operational use must have symmetrical sensor plates, i.e. the sensitivities of both sides of the sensor plate must not differ by more than 2 per cent.

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APPENDIX 1

METEOROLOGICAL RECORDING INSTRUMENTS — GENERAL CONSIDERATIONS CONCERNING CONSTRUCTION, MAINTENANCE AND OPERATION

CONTENTS

LIST OF DIAGRAMS

LIST OF PLATES

APPENDIX 1

A.1 RECORDING METHODS

A.1.1 Introduction

The effect of friction on the accuracy of a recording instrument is generally larger and more serious than in a comparable indicating instrument, especially when a pen, writing continuously on paper, is used to record the results. The friction between the pen and the paper is usually much larger than the total amount of friction in the bearings of the instrument; the concept of adequate control thus arises.

The effect of friction is to impose a certain force on the indicating mechanism in the opposite direction to that in which the variable element is causing the mechanism to move. This force causes the reading of the instrument to be in error by a certain amount. The 'control' of the instrument may be defined as the force which must be applied to the indicating mechanism at the point where it is recording (e.g. at the pen) to keep the indication constant when the value of the element which is being recorded changes by one unit. This is equal to the force required to move the indicating mechanism over one unit of the scale provided the measured element remains constant. The greater the control the less will be the effect of friction and the more detailed will be the record. In any case the control should be such that the maximum effect of the friction on the reading should be less than the least change it is desired to record. If this is not so, the errors will be markedly different for rising and falling values of the element recorded and there will be 'lost motion' when the variable element reaches a maximum or minimum value.

A.1.2 Recording charts

There are several methods by which the indication of an instrument can be made to give a permanent record. In the majority of these the record is in the form of a line on a sheet of paper, and is measured by reference to the position of the line on the paper. The properties of the paper are thus of some importance.

Good chart paper is manufactured so that its fibres lie largely in one direction ('downboard'). These fibres are hygroscopic and swell slightly in a lateral direction when they absorb water. Thus it is found that an instrument chart changes its dimensions when it is soaked in water, or to a somewhat lesser extent when the humidity changes, and the magnitude of the change in any direction depends on the direction of the fibres. All Meteorological Office charts are cut with the time-scale 'downboard', and it is found that the change in length in this direction when the chart is immersed in water after being in a normal room atmosphere is about 0.2–0.3 per cent. On the other hand the change in length in a direction perpendicular to this is 2.5–3.0 per cent, i.e. 10 times as much. The chart will not of course become soaked in normal use, but experiments have shown that the changes in dimensions are very nearly as much when the charts are exposed in a humidity chamber and the relative humidity is altered from about 50 per cent to about 100 per cent. The change in length 'downboard' is 0.1–0.2 per cent, and the change in length in a perpendicular direction is 1.5–2 per cent.

In very accurate work it is thus necessary to have two datum lines drawn on the chart at fixed positions; these can be used as base lines to enable zero errors (due to chart slipping or being inserted wrongly) and changes in scale value (due to the chart altering in size before the record was made) to be measured and allowed for.

A.1.3 Pen recorders

In most meteorological instruments using pen recording the pen rests lightly on a chart wrapped around a vertical cylindrical drum. The drum is rotated at a constant speed, and as the element to be recorded varies the pen moves up and down the chart. To reduce friction, it is necessary to adjust the pressure of the pen on the chart to the minimum consistent with a clear record. This is achieved in many Meteorological Office instruments by means of the gate suspension (Figure A1). The pen arm is suspended in a small gate, A, so that it can rotate freely about the gate axis. The gate itself is fixed to a collar, B, and can be rotated about an axis parallel to the pen arm, i.e. its inclination to the vertical plane containing the pen arm can be varied. When the axis of the gate is in this vertical plane there is no tendency for the pen arm to move in one direction or the other, but when the gate is inclined to the vertical plane there is a component of the weight of the pen arm which exerts a moment about the gate axis and causes the pen either to press on the chart or to fall away from it. The pressure between the pen and the paper can thus be adjusted to a suitable value which remains practically independent of the position of the pen on the chart provided the pen arm is perpendicular to the pen-arm spindle. It is normally found that an inclination of the gate axis of about 10° to the vertical is quite sufficient.

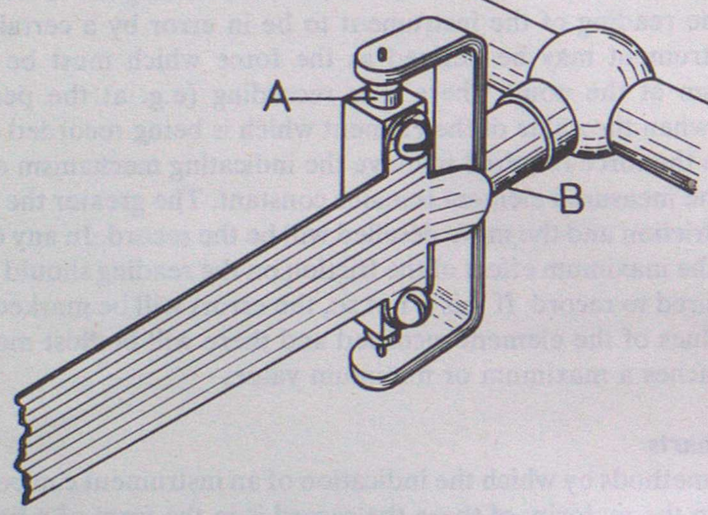

Figure A1. Gate suspension for pen arm.

There are two main ways in which the changes in the variable element being recorded are converted into changes of the position of the pen. In the first, the point of support of the pen arm is moved in a direction perpendicular to the time axis on the chart; the hour lines on the chart are straight lines and the length of the pen arm is immaterial. In the second, the changes in the variable element are converted into angular movements of a spindle on which the pen arm is mounted; the hour lines are approximately arcs of circles, with radii equal to the length of the pen arm (measured from the axis of the pen-arm spindle to the point of the pen) and with their centres on the plane through the pen-arm spindle parallel to the time axis. The true hour lines are not exactly arcs of circles because the pen writes on a cylinder and not on a plane surface.

It is necessary to ensure that the chart is printed for the correct pen-arm length and for the correct position of the pen-arm spindle. When replacing the pen on the pen arm, or fitting a new pen arm, every care must be taken to ensure that the effective pen-arm length is correct. The displacement of the pen at the end of the pen arm for a given angular movement is proportional to the length of the pen arm, so that an error of 8 mm in the length of a pen arm which should be 160 mm long will give an error of 5 per cent in the deflexion of the pen, and in the scale value on the chart at that point. The correct charts for all standard Meteorological Office instruments have identifying numbers, and these should always be quoted when requesting stocks. If a non-standard chart has to be supplied specially, the data given should include the length of the pen arm and the position of the pen-arm axis, if the hour lines are not straight.

Pens. Various types of pen are used on the standard Meteorological Office instruments; the chief ones are illustrated in Figure A2. The type in normal use on the commoner instruments is shown at (a); it consists of a simple triangular reservoir attached to a short holder which can be slid over the end of the pen arm; it can hold more than sufficient ink for at least a normal week's record on any standard sized drum. Preferred alternatives for use on certain instruments are shown in (b) for the tilting-siphon rain-gauge, and in (c) for the thermograph and barograph. Both (b) and (c) are disposable items consisting of an ink reservoir fitted with a fibre nib; either pen will provide at least a year's normal record.

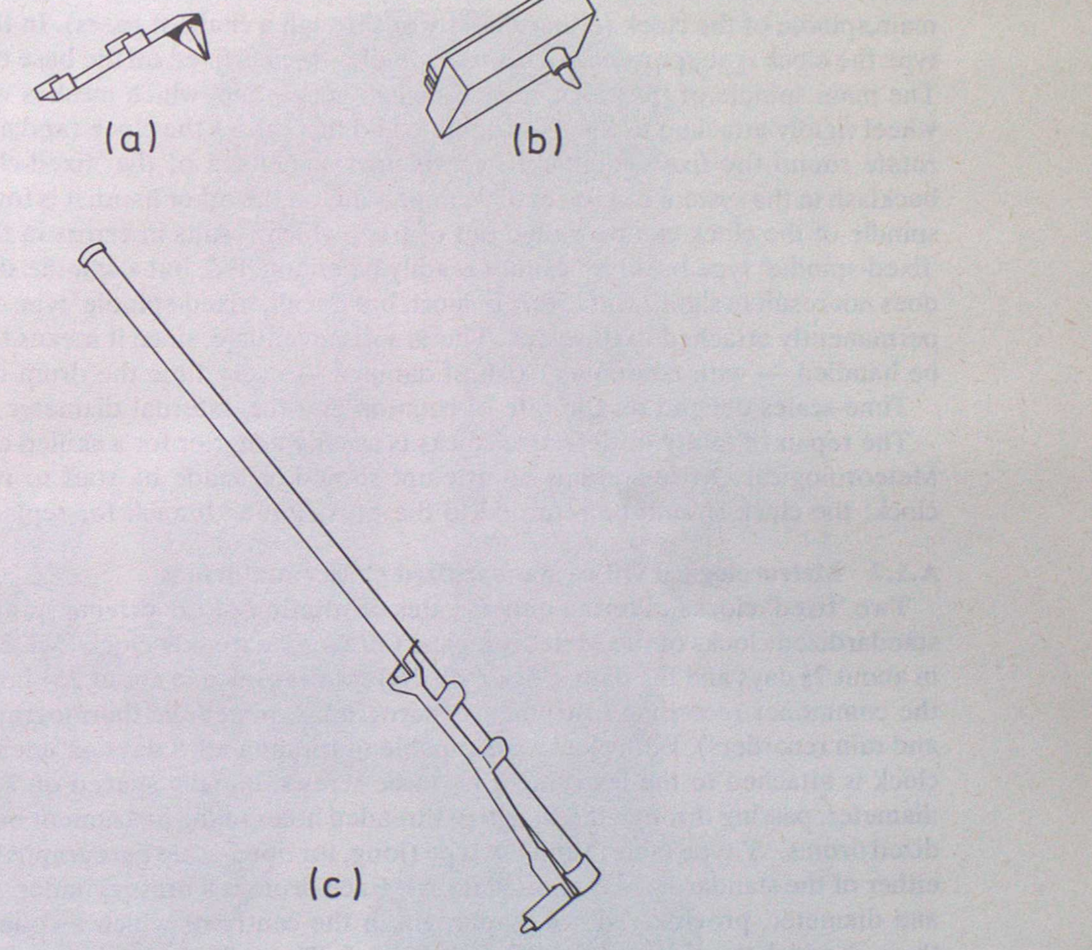

Figure A2. Instrument pens.

A.1.4 Electrosensitive paper

Recorders using various types of electrosensitive paper are also used. Paper is coated with zinc oxide so that when a small current passes from a stylus to the paper the zinc oxide coating is reduced to free zinc and a marking results. This process produces a fine, clean and dry trace resistant to smudging.

A.1.5 Electrical recorders

Devices for balancing potentiometric or bridge recorders have various forms, some manual, some self-balancing. Whatever the method used the principle is the same. A galvanometer, or an electronic circuit, is arranged to detect when the system is out of balance. Where a galvanometer is used, the position of the galvanometer pointer is detected either manually or electrically, and the slide-wire contact moved to the point of balance. Where an electronic circuit is used to detect the out-of-balance it is usual for the output of the detecting circuit to control the direction of rotation of a reversible motor which moves the slide-wire contact and positions the pen arm or pointer.

A.1.6 Clocks, drums and time-scales

Most meteorological recording instruments are fitted with 'daily' or 'weekly' clocks, i.e. clocks which cause the drum to rotate once in about $25\frac{1}{2}$ hours and once in about $7\frac{1}{3}$ days respectively. The overlap is necessary to allow some margin for the time of changing the chart, and to prevent the trace from crossing the join when the pen is near the top or bottom of the chart (on those instruments in which the hour lines are curved).

There are two possible ways of using the clock to drive the drum. In the 'fixed-clock' type the clock is screwed to the base of the recording instrument and the drum attached to the main spindle of the clock (either directly or through a chain of gears). In the 'fixed-spindle' type the clock is supported on a central spindle which is fixed on the base of the instrument. The main spindle of the clock carries a small gear wheel which meshes with another gear wheel rigidly attached to the fixed spindle and this causes the clock (and attached drum) to rotate round the fixed spindle. The principal advantage of the 'fixed-clock' type is that backlash in the system can be readily eliminated; on the other hand, it is found that the main spindle of the clock can be pulled out of true, which results in errors in the record. In the 'fixed-spindle' type backlash cannot readily be eliminated, but a spindle slightly out of true does not result in significant error. In most, but not all, 'fixed-spindle' type clocks the drum is permanently attached to the clock. This is a disadvantage, since it means that the clock will be handled — with consequent risk of damage — every time the drum is removed.

Time-scales depend on the rate of rotation and the external diameter of the drum.

The repair of faulty or defective clocks is usually a matter for a skilled clock repairer. At Meteorological Office stations no attempt should be made by staff to repair a defective clock; the clock should be returned to the provisioning branch for replacement.

A.1.7 Meteorological Office standardized clocks and drums

Two 'fixed' clocks differing only in rates of rotation of the driving spindles, serve as the standardized clocks of the Meteorological Office. The weekly clock (Mk 2A) rotating once in about $7\frac{1}{3}$ days and the daily clock (Mk 2B) rotating once in about $25\frac{1}{2}$ hours are used with the commoner recording instruments (barographs, bimetallic thermographs, hygrographs and rain recorders). Both clocks are capable of running for 8 days on one full winding. The clock is attached to the instrument by three screws, equally spaced on a circle of 89 mm diameter, passing through the flange to threaded holes in the instrument base. Two standardized drums, 'S' type (short) and 'O' type (long, for open-scale barographs), are for use with either of the standardized clocks (Plate A). Each drum is a brass cylinder, of defined height and diameter, provided with a diaphragm in the centre of which a collar is screwed and through which the clock's driving spindle passes. The collar has radial teeth on its underside which engage with similar teeth on a collar attached to a clutch drive on the driving spindle of the clock; a knurled nut secures the drum to the driving spindle of the clock. The object of the clutch drive is to facilitate the setting of the drum to its correct position when fitted to the clock. The drum is flanged around its base and the chart is held in position by two clips. In addition to the chart clips the 'O' type drum has two small pins screwed into its side, lying in the same line as the chart clips. These pins help to keep the chart in position where the two ends overlap. The 'S' type is 93 mm in diameter, so that it gives a time-scale of 11.4 mm h^{-1} with a daily clock. When used with a weekly clock Mk 2A the clock is adjusted to rotate once in 7 days 7.2 hours, giving a time-scale of 1.67 mm h^{-1}. The 'O' type drum is not normally used with a daily clock, but if it were the time-scale would be 17.2 mm h^{-1}. Used with a weekly clock Mk 2A, the clock is adjusted to rotate once in 7 days 8 hours, giving a time-scale of 2.5 mm h^{-1}. (The difference between a time of rotation of 7 days 8 hours and 7 days 7.2 hours is negligible for most purposes.) The standardized clocks and drums are completely

Plate A. Standard Meteorological Office clocks and drums.

interchangeable, i.e. any clock can be used with any drum. The weekly clocks can be regulated over a range of 2¼ hours in the 7 days and the daily clock over a range of 20 minutes in the 24 hours.

A.2 CORRECTION OF RECORDING INSTRUMENTS

It is important to ensure correct timing of any part of the recorded trace, and to be able to make an estimate of any errors in the record itself. There are three main causes of error that can affect the timing of the record:

(a) Backlash between the drum and the spindle on which it is mounted. This defect is not serious with clocks of the standard Meteorological Office pattern or similar types. It delays the starting of the record and causes a constant error once the record has started.

(b) An error in the clock rate (or the use of an unsuitable time-scale on the chart). If the difference is small the rate of revolution of the drum can be adjusted to the correct value (given by the time-scale on the chart) by means of the clock regulator. Small errors may occur, however, owing to the variability of the clock rate, e.g. with temperature changes.

(c) Errors due to the change in length of the chart with humidity variations (see page A–3). These are small in charts which are cut from the paper in the correct direction, but are serious if the chart is cut in the wrong direction.

In order that errors of this kind may be recognized it is essential to make accurate time marks on the records themselves. Although it is preferable that the time marks be made at about the same time each day, it is not essential provided the exact time at which the mark is made is known. The actual time (it suffices for most records if it is correct to the nearest minute) should be entered in the register. On weekly charts one time mark a day would suffice. On daily charts it is preferable to have more than one, the first being made at least half an hour but not more than 2 hours after starting the record, and another after about a further 8–12 hours. It is often convenient to make a time mark coincide with an hour mark and to note the timing error.

On most instruments a time mark may be made by depressing the pen between 3 mm and 6 mm and then releasing it. These limits should not be exceeded, as the careless depression of the pen can often disturb the calibration of the instrument or even strain some of the parts beyond their elastic limits.

On some instruments, e.g. barographs, a simple mechanical device is provided which enables time marks to be made without opening the case of the instrument. If a reading of the record has to be obtained at the same time as the time mark it should be made just before the time mark and not after it.

Recording instruments are generally less accurate than the comparable indicating instruments, and they cannot often be made absolute. It is therefore usual to compare their readings with those of an indicating instrument at several of the main observation hours throughout the day. In some recording instruments, e.g. the barograph, this will give immediately the error of the record or the necessary correction to the record, assuming that the indicating instrument is correct. It should be noted that the error is equal, but opposite in sign, to the correction. The mean correction for the day can therefore be ascertained and applied to any tabulated readings taken from the record.

No instrument responds immediately to changes in the element that is being measured, and different instruments respond at different rates. Comparisons should therefore be made only when the measured element is constant or changing very slowly, or mean values should be taken over a period in which any errors due to the different time-constants may be expected to cancel out.

Another possible procedure is to plot the readings of the recording and indicating instruments against one another; the points obtained should lie on or about a line at 45° to each axis passing through the origin. If the best-fitting straight line does not pass through the origin a zero error is indicated, and if the slope is not 45° there is an error in the scale value of one instrument, usually the recording instrument.

A.3. OPERATIONAL PROCEDURE

Some general instructions on the method of handling recording instruments are given below. These are supplementary to the more particular instructions given for each individual instrument.

A.3.1 Changing the chart

Remove the pen from the old chart, noting the correct time to the nearest minute (this serves as an extra time mark). Clean the pen if necessary and top with ink. See that the ink is flowing sufficiently freely to give a legible trace, but not so freely as to give a thick trace. It is rarely advisable to fill the reservoir completely. Remove the old chart and wrap the new chart round the drum so that it fulfils the following conditions (these are absolutely necessary if good and reliable records are to be obtained):

(a) The chart should fit tightly round the drum.
(b) The lines of equal scale value should be parallel to the flange at the bottom of the drum, i.e. corresponding lines on the beginning and end of the chart in the overlap portion should coincide.
(c) The bottom of the chart should be as close to the flange as possible and touching it in at least one place (if the chart is not cut quite correctly it may not be possible for it to touch the flange in all places and still comply with the other conditions cited).
(d) The end of the chart should overlap the beginning and not vice versa.

When the chart is fitted properly the spring clips should hold it in place. The clock can then be wound and the new record started. When setting the pen to the correct time the final adjustment should be made by moving the drum in the opposite direction to its normal motion to take up any backlash in the gear train, i.e. the drum should be moved from a time on the chart in advance of the actual time back to its correct position. Once they have been correctly set most recording instruments should not require readjustment more often than three or four times a year. If careful examination, extending over a period, shows that readjustment is necessary this may be done at the time a chart is changed, and a note should be made on the chart and in the register.

A.3.2 Writing up the chart

Before being filed away, the record should have inserted on it the following particulars: date (including the year), name of the station, its position, its height above mean sea level, actual time of each of the time marks, readings of the control instruments when the time marks were made, and time at which the record began and ended. If a reliable estimate of the mean errors in the record has been made, covering the period of the chart, this should be indicated. The reasons for any abnormal features, e.g. failure to ink, clock stopping, etc., should also be recorded if known.

A.3.3 Care at each main observation hour

See that the instrument is recording properly and read it. If necessary, a time mark should be made.

A.3.4 General hints (including cleaning)

Special care should always be taken to keep instruments clean. This not only improves their performance (by reducing friction) but also lengthens their useful life (by preventing

corrosion) and improves their appearance. General methods of cleaning the different materials most often used in instruments are as follows:

(a) *Plain brass or copper parts*. Unlacquered brass or copper parts may be kept bright by the use of jeweller's rouge applied with an oily rag or by metal polish applied sparingly. The polish should not be allowed to reach any bearing surfaces. The inside of a rain-gauge funnel should however only be rubbed with a dry rag.
(b) *Lacquered brass or copper parts*. These should be cleaned with a soft chamois leather. No polish should be applied, but where there is exposure to damp a little petroleum jelly may be used with advantage.
(c) *Polished woodwork*. This should be cleaned with a soft chamois-leather. A little linseed oil may be rubbed in with a soft cloth if necessary.
(d) *Glass and porcelain*. The dirt should be cleaned off with a moist rag or chamois-leather.
(e) *Bearings, pinions and hinges of instrument cases*. These should be lubricated sparingly with a touch of clock oil. Refer also to the detailed instructions for the instrument.
(f) *Ball races*. These should be treated in accordance with the detailed instructions for each instrument.
(g) *Steel parts*. These should be cleaned with an oily rag and protected from rust with a trace of petroleum jelly. If, in spite of care, rust appears, the part should be carefully cleaned with a fine emery cloth or carborundum cloth.
(h) *Painted woodwork*. In dusty localities woodwork should be brushed periodically, and at stations affected by smoke or soot a thorough cleaning with soap and water should be carried out once a month.
(i) *Painted surfaces liable to inking*. The ink should be removed while wet with a damp cloth. Older stains should be removed by the application of a small quantity of whiting applied with a damp cloth. Methylated spirit may be used with the whiting if there is no risk of this getting on to lacquered brass or polished woodwork.
(j) Naphthalene balls are effective in keeping insects from the interior of instruments exposed out of doors, e.g. recording rain-gauges.

Special care must be given to keeping the end of the pen arm and the fitting which actually supports the pen free from ink, or else corrosion may set in. This may lead to the use of a pen arm which is too short and thus give rise to faulty records.

APPENDIX 2

The International Systems of units (SI)

The International System (SI) consists of seven 'base units' together with two 'supplementary units'. From these are formed others known as 'derived units'. The base and supplementary units, and some of the derived units, have been given names and symbols. The symbols are printed in lower case except where derived from the name of a person; for example m (metre), but A (ampere). Symbols are not pluralized (1 m, 10 m) nor do they take a full stop. The names of the units do not, however, take capitals (except of course at the beginning of a sentence), although they may be pluralized; for example, 1 kelvin, 10 kelvins.

The *base units* are:

metre (symbol m)	the unit of length
kilogram (symbol kg)	the unit of mass
second (symbol s)	the unit of time
ampere (symbol A)	the unit of electrical current
kelvin (symbol K)	the unit of thermodynamic temperature, defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.
candela (symbol cd)	the unit of luminous intensity
mole (symbol mol)	the unit of the amount of a substance which contains the same number of molecules as there are atoms in exactly 12 grams of pure carbon.

The two *supplementary units* are:

radian (symbol rad)	the measure of a plane angle
steradian (symbol sr)	the measure of a solid angle.

A few of the *derived units* are:

Quantity	*Name of unit*	*Symbol*	*Expressed in base units*
frequency	hertz	Hz	$1\ Hz = 1\ s^{-1}$
force	newton	N	$1\ N = 1\ kg\ m\ s^{-2}$
pressure	pascal	Pa	$1\ Pa = 1\ N\ m^{-2}$
work	joule	J	$1\ J = 1\ N\ m$
power	watt	W	$1\ W = 1\ J\ s^{-1}$

(1 newton = 10^5 dynes, 1 pascal = 10^{-2} millibars, 1 joule = 10^7 ergs.)

Multiplying prefixes

The multiples and sub-multiples of the units are not arbitrarily related to the units, as is usual in the British system,

e.g. 1 pound = 16 ounces = 7000 grains
1 yard = 3 feet = 36 inches,

but are formed by means of multiplying prefixes which are the same irrespective of the unit to which they are applied.

The names and values of the prefixes, and some examples of their use, are given below. Because the prefixes cover such an astronomical range it is not normally necessary to consider more than a selection of them applied to any one unit.

Prefix name	*Prefix symbol*	*Factor by which the unit is multiplied*	
tera	T	10^{12} =	1 000 000 000 000
giga	G	10^{9} =	1 000 000 000
mega	M	10^{6} =	1 000 000
kilo	k	10^{3} =	1000
hecto	h	10^{2} =	100
deca	da	10^{1} =	10
deci	d	10^{-1} =	0.1
centi	c	10^{-2} =	0.01
milli	m	10^{-3} =	0.001
micro	μ	10^{-6} =	0.000 001
nano	n	10^{-9} =	0.000 000 001
pico	p	10^{-12} =	0.000 000 000 001
femto	f	10^{-15} =	0.000 000 000 000 001
atto	a	10^{-18} =	0.000 000 000 000 000 001

Examples:
gigahertz (GHz), megawatt (MW), kilometre (km), centimetre (cm), milligram (mg), microsecond (μs), nanometre (nm), picofarad (pF).

NON-SI UNITS

The following non-SI units are in current use in the Meteorological Office and may be found in publications of the Office.

1. **Pressure**

The millibar is used as the unit of pressure in meteorology. Despite the recommended abbreviation mbar, the Meteorological Office will continue to use mb (1 mb = 1 hPa, where h = hecto = 10^2). The WMO preferred unit is the hPa, though it has yet to be promulgated.

2. **Temperature**

The unit degree Celsius (symbol °C) continues to be used.

Celsius temperature = temperature (in kelvins) minus 273.15 K (note that the sign ° is no longer used with K).

3. **Distance**

There is a continuing requirement for some distances to be measured in nautical miles (symbol n. mile).

Because the nautical mile varies with latitude, an internationally agreed International Nautical Mile is preferred. This has been in use in the United Kingdom since 1970.

The International Nautical Mile is defined as 1852 m (6076.12 feet).

4. **Height**

Heights other than cloud heights are expressed in metres. Because of the requirements of aviation the heights of cloud will continue for the time being to be expressed in feet (1 foot = 0.3048 m).

5. **Speed**

The derived SI unit is the metre per second ($m\ s^{-1}$). However, the World Meteorological Organization recommends the use of the knot for horizontal wind speed for the time being (1 knot = 1 nautical mile per hour ≈ 0.5 $m\ s^{-1}$). The symbol kn for knot is recommended to avoid confusion with the symbol for kilotonne and will be used in Meteorological Office publications.

6. **Time**

Units other than SI, such as day, week, month and year, are in common use.

7. **Direction**

Direction is measured in degrees clockwise from north and refers to the true compass.

8. **Cloud amounts**

The use of 'okta' (one eighth of the area of the sky) for the measurement of cloud amount is authorized by the World Meteorological Organization.

APPENDIX 3

Terminology

In metrology (the field of knowledge concerned with measurement) confusion often arises in the usage of terms. These differences may range from subtle changes of meaning of common terms to the misuse of everyday terms, extracted from dictionaries, by ascribing to them specific meanings applicable only in certain areas of use.

Whilst by no means comprehensive, the following list represents terms occurring most frequently in this volume. For a more complete glossary of terms reference should be made to British Standards Institution publication BS 5233 from which these definitions are extracted.

Accuracy (of a measuring instrument). The quality which characterizes the ability of a measuring instrument to give indications equivalent to the true value of the quantity measured. The quantitative expression of this concept should be in terms of uncertainty.

Analogue (measuring) instrument. Measuring instrument in which the indication is a continuous function of the corresponding value of the quantity to be measured, e.g. mercury-in-glass thermometer.

Calibration. All the operations for the purpose of determining the values of the errors of a measuring instrument.

Conventional true value (of a quantity). A value approximating to the true value of a quantity such that, for the purpose for which that value is used, the difference between these two values can be neglected.

Correction. A value which must be added algebraically to the indicated value (uncorrected result) of a measurement to obtain the measured value (corrected result).

Detector. A device or substance which responds to the presence of a particular quantity without necessarily measuring the value of that quantity.

Digital (measuring) instrument. Measurement instrument in which the quantity to be measured is accepted as, or is converted into, coded discrete signals and provides an output and/or display in digital form.

Discrimination (of a measuring instrument). The property which characterizes the ability of a measuring instrument to respond to small changes of the quantity measured. *Note.* In some fields of measurement the term 'resolution' is used as synonymous with 'discrimination', but attention is drawn to 'sensitivity'.

Error (of indication, or of response) *of a measuring instrument.* The difference $v_i - v_c$ between the value indicated by (or the response of) the measuring instrument v_i and the conventional true value of the measured quantity v_c.

Hysteresis (of a measuring instrument). That property of a measuring instrument whereby it gives different indications, or responses, for the same value of the measured quantity, according to whether that value has been reached by a continuously increasing change or by a continuously decreasing change of that quantity.

Index. A fixed or movable part of the indicating device (e.g. recording pen, a pointer) whose position with reference to the scale marks enables the indicated value to be observed.

Indicating instrument. Measuring instrument which is intended to give, by means of a single unique observation, the value of a measured quantity at the time of that observation. An indicating instrument may have either continuous or discontinuous variation of indication.

Indication (or *response*) *of a measuring instrument.* The value of the quantity measured, as indicated or otherwise provided by a measuring instrument.

Maximum permissible error (of a measuring instrument). The extreme values of the error (positive or negative) permitted by specifications, regulations etc., for a measuring instrument.

Quantity (measurable). An attribute of a phenomenon or a body which may be distinguished qualitatively and determined quantitatively.

Range (of a measuring instrument). The interval between the lower and upper range-limits, e.g. a thermometer may have a range −40 °C to +60 °C.

Repeatability (of measurement). A quantitative expression of the closeness of successive measurements of the same value of the same quantity carried out by the same method, by the same observer, with the same measuring instruments, at the same location at appropriately short intervals of time.

Repeatability (of a measuring instrument). The quality which characterizes the ability of a measuring instrument to give identical indications, or responses, for repeated applications of the same value of the measured quantity under stated conditions of use.

Reproducibility (of measurement). The quantitative expression of the closeness of the agreement between the results of measurements of the same value of the same quantity, where the individual measurements are made under different defined conditions, e.g. by different methods, with different measuring instruments.

Resolution. See *Discrimination.*

Response. See *Indication.*

Response time (of a measuring instrument).* The time which elapses after a step change in the quantity measured, up to the point at which the measuring instrument gives an indication equal to the expected indication corresponding to the new value of the quantity, or not differing from this by more than a specified amount.

Scale. The array of indicating marks, together with any associated figuring, in relation to which the position of an index is observed. The term is frequently extended to include the surface which carries the marks or figuring.

Sensitivity (of a measuring instrument). (a) The relationship of the change of the response to the corresponding change of the stimulus (it is normally expressed as a quotient), or (b) the value of the stimulus required to produce a response exceeding, by a specified amount, the response already present due to other causes, e.g. noise.

Sensor. The part of a measuring instrument which responds directly to the measured quantity.

Span. The algebraic difference between the upper and lower values specified as limiting the range of operation of a measuring instrument, e.g. a thermometer intended to measure over the range −40 °C to +60 °C has a span of 100 °C.

Standard. A measuring instrument, or measuring apparatus, which defines, represents physically, conserves or reproduces the unit of measurement of a quantity (or a multiple or sub-multiple of that unit) in order to transmit it to other measuring instruments by comparison.

Primary standard. A standard of a particular quantity which has the highest class of metrological qualities in a given field.

Secondary standard. A standard the value of which is determined by direct or indirect comparison with a primary standard.

Reference standard. A standard, generally the best available at a location, from which the measurements made at the location are derived.

Working standard. A measurement standard, not specifically reserved as a reference standard, which is intended to verify measuring instruments of lower accuracy.

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*For the purposes of this handbook, where a response time is quoted it refers to the time necessary for a measuring instrument to register 90 per cent of a step change in the quantity being measured. The time taken to register 63.2 per cent of a change is given the preferred title 'time-constant'.

Transfer standard. A measuring device used to compare measurement standards, or to compare a measuring instrument with a measurement standard by sequential comparison.

Travelling standard. A measuring device, sometimes of special construction, used for the comparison of values of a measured quantity at different locations.

Systematic error. An error which, in the course of a number of measurements of the same value of a given quantity, remains constant when measurements are made under the same conditions and remains constant or varies according to a definite law when the conditions change.

Transducer (measuring). A device which serves to transform, in accordance with an established relationship, the measured quantity (or a quantity already transformed therefrom) into another quantity or into another value of the same quantity, with a specified accuracy, and which may be used separately as a complete unit.

Uncertainty of measurement. That part of the expression of the result of a measurement which states the range of values within which the true value or, if appropriate, the conventional true value is estimated to lie.

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