WORLD METEOROLOGICAL ORGANIZATION

WMO INTERNATIONAL RADIOSONDE COMPARISON
PHASE I
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by
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Simultaneous data, for 300, 100, 30 and 10 hPa
Pressure data - all hours combined
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Geopotential data - 00 GMT

Simultaneous Humidity data - all hours combined
975 to 700 hPa - 10 to 25% and 85 to 100%
700 to 500 hPa - 10 to 25% and 85 to 100%

Simultaneous Wind data - all hours combined
0-20km range, 0-20 degrees elevation
0-20km range, 20-40 degrees elevation
40-60km range, 0-20 degrees elevation
40-60km range, 20-40 degrees elevation

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Geopotential - 00, 04, 08, 12, 16 and 20 GMT
Temperature - 00 and 12 GMT
1. GENERAL MATTERS

1.1 Introduction

CIMO-VIII identified a need for further international comparisons of radiosondes with regard to both PTU and wind data. As a result, the first meeting of the CIMO Working Group on Upper-Air Technology, held in November 1982, considered the design of such intercomparisons, bearing in mind the considerable number of radiosonde designs in operational use, the difficulties of flying several radiosondes together in a single assembly and the constraints of time and funding. The task of detailed planning was accepted by two participants in the meeting — Mr A H Hooper (U.K.) and Mr F Schmidlin (U.S.).

In May 1983, considerable attention was given by Congress (Cg-IX) to the need to promote the standardization of meteorological observations. The steps to be taken were recorded in Resolution 11 and included the organization of a WMO International Radiosonde Comparison. Venues for the work were offered by the Permanent Representatives of the U.K. and the U.S.A. The Executive Council (EC-XXXV) subsequently approved specific arrangements; the WMO International Radiosonde Comparison should be carried out in two phases.

Experience of previous radiosonde intercomparisons indicated that it was indispensible for such work to be very carefully planned. Accordingly, an International Organizing Committee was set up in agreement with the President of CIMO which held its first meeting in the WMO Secretariat in November 1983, chaired by the President of CIMO. It considered aspects of participation, detailed planning of data processing and of the benefit of linking the results obtained at the two venues. The second session of the Committee was held in Bracknell during the intercomparison.

This Report is concerned with Phase I of the Intercomparison which was held at Bracknell, UK, in 1984. It is based upon data kindly provided by the Project Leader and his team, both at the time and in subsequent discussions. Most of the Tables and Figures given here are computer products provided by the U.K. Meteorological Office and form a small part of the full set supplied to the WMO Secretariat to serve as an archive for reference by interested persons. Copies of these data (Nash et al., 1984) are also held as seven volumes in the Library of the U.K. Meteorological Office, Bracknell.
When flying several radiosondes together it can be difficult to operate them within the available radio-frequency bands without suffering from mutual radio interference and a resulting loss of data. For this reason no more than five radiosondes could be flown together at Bracknell even when making full use of the three radio-frequency bands available for radiosonde work. With more than five designs participating, cyclic flight grouping would be necessary with less flights being made by each design in the limited time available. At the planning stage it was hoped that the designs would be representative of different WMO Regions so that comparative data would be obtained to link operational results in different continents.

However, this proved to be impossible for various reasons and in the event two places were occupied by operational radiosondes (UK and Finland) in extensive use in Region VI and one other place by a radiosonde (USA) in extensive use in Region IV. In the absence of operational radiosondes from other Regions, a place was taken by a new design from the Federal Republic of Germany (FRG) expected to enter operational service in Region VI in 1985. Finally, the USSR withdrew from participation at a very late stage and rather than suffer a limitation upon the value of the intercomparison, the fifth place was filled at short notice, at the invitation of the UK Meteorological Office after consultation with the other participants, by a system (Beukers Microsonde) in limited use in Region II and which may see oceanic use in the ASAP Programme.

1.3 The opening ceremony

The WMO International Radiosonde Comparison was undertaken at Beaufort Park, Bracknell, UK, over the period 18 June to 27 July 1984. The five teams taking part attended an inaugural meeting at 1430 on 18 June. The meeting was chaired by Mr J M Nicholls of the UK Meteorological Office, Assistant Director in charge of Observational Requirements and Practices. Mr Nicholls welcomed the visiting teams and explained that because of his responsibility for upper-air observations (amongst others) and for observing practices he had a direct interest in the outcome of the intercomparison. He went on to assure the teams of any help that they might need and expressed the hope that their stay would be memorable.

Dr R E W Pettifer, in charge of instrumental development in the UK Meteorological Office and the Vice-President of CIMO, warmly welcomed the team members, reminding them that the intercomparison is the latest in a succession of such activities which began with that undertaken at Payerne, Switzerland, in 1950. He explained that the present intercomparison arises from
a need formally expressed at CIMO-VIII, and that the full response will entail both the work of Phase I at Bracknell and a Phase II due to begin in February 1985 at Wallops Island, USA. He remarked that radiosonde intercomparisons are complex and difficult to conduct successfully. He went on to explain that the results of such work are of considerable importance, for numerical analysis schemes, for the purposes of general forecasting, and for the calibration of satellite-borne sounding instruments. For all these applications it is necessary to have a clear knowledge of the systematic differences between the data provided by radiosonde systems. Such differences can only be estimated by means of direct intercomparisons of radiosondes representative of operational performance. Thus for the next few weeks the work of the participating teams will be of high, perhaps of the highest, significance to the meteorological community of the world.

Dr Pettifer, speaking on behalf of both the Director-General of the UK Meteorological Office and the President of CIMO, concluded by formally declaring the WMO International Radiosonde Comparison open.

Dr J Nash, the Project Leader of Phase I of the Intercomparison, then spoke and explained the underlying reasons for the flight programme adopted. The flights to be undertaken at 00GMT and 12GMT would provide links with the operational soundings obtained over Region VI while those flights planned for 08GMT and 20GMT would represent sounding conditions in some other Regions and would also provide comparative data for the NOAA 8 satellite when passing over Bracknell.* These latter flights would also enable the results to be obtained at Wallops Island during Phase II to be combined with those secured during the present phase. Dr Nash then proceeded to describe the scientific and domestic arrangements in detail, and after clarification of several matters closed the inaugural meeting.

* However, the NOAA 8 satellite ceased to operate just before the intercomparison flights began. In this situation, and after consultation between the President of CIMO and the Project Leader, additional flights at 04GMT and 16GMT were undertaken in the later stages of the intercomparison to provide comparison data at the time of the overpass of the NOAA 7 satellite and to provide more detail upon the effect of the solar tide in the latitude of Bracknell.
1.4 Preparations

Following the inaugural meeting, the next one and a half days were occupied first in setting up the ground stations and then in undertaking proving flights. It was established that the stations and the airborne radiosondes could generally operate successfully in the close proximity necessary for the intercomparison. The main body of flights then began at mid-day on 20 June.

1.5 Composition of the teams

Due to the duration of the intercomparison, there were several changes to the composition of the participating teams. More extensive staff changes occurred in the much larger home team which had also to support the very considerable tasks of data collection and processing and to provide flight managers and teams to assemble rigs ready to lift the radiosondes.

1.6 Second session of the International Organizing Committee

The International Organizing Committee chaired by the President of CIMO held its second session at Beaufort Park, Bracknell, from 25 to 30 June 1984. Those present included the Project Leaders of both phases, the Site Manager for Phase II and Mr. S. Klemm of the WMO Secretariat. The Committee reviewed the procedures and facilities used at the intercomparison site. It came to the conclusion, in agreement with all team leaders of the participating Members, that all the procedures, facilities and accommodation provided, were excellent and worked very well. It also noted that the high altitude balloons (TOTEX) used at the intercomparison, which were provided by WMO, were of high quality and very suitable for the purpose. The opportunity was taken to attend the daily briefing and review meeting of the participating teams.

1.7 Visitors

A considerable number of visitors, with a scientific interest in the work, came during the intercomparison to appraise the quality of the results being achieved.
2. THE SOUNDING SYSTEMS

2.1 Basic information

Some information upon the five systems is given in Table 1, along with model numbers of the radiosondes themselves. Four of the five systems are automatic and need an Operator solely to guide them through the natural stages of sounding preparation and to monitor progress during flight. The fifth system is semi-automatic and uses a skilled Operator for in-flight data selection as well. In the computer-derived tabulation of results provided in later sections of this report labels have been used for convenience in identifying the systems. These labels are given in the Table, and will be used hereafter.

2.2 The sensors used

Details of the sensors used appear in Table 2. It will be seen that all five radiosonde designs employ a single aneroid capsule, the deflections of which are sensed in different ways. In two designs (FIN and FRG) a capacitor is fitted within the capsule, while the remainder all use external devices. Thus the UK capsule drives a ferrite probe which moves without friction along the axis of a ferrite inductor, while the USA and OCAN systems, both use the same design of baroswitch which drives a contact over a commutator. However, those flown by the USA were "premium" devices while those used by OCAN were standard devices of lower expected performance and were possibly less well aged. For temperature, the same design of thermistor rod is used in two systems (USA and OCAN) and a thermistor bead in the FRG system. A thin tungsten wire is used by the UK and a ceramic capacitor by FIN. No corrections are applied for lag in response of the sensors, although in the troposphere a time constant of, for example, 5 seconds would cause an overall average temperature error typically of 0.2K.

Humidity sensing is undertaken by the same design of carbon film hygristor in the FRG, USA and OCAN systems (but each with a different exposure), while an organic polymer film is used by FIN and gold-beater's skin by the UK.

The use of the same sensor design in different designs of radiosonde offers the possibility of studying the effect of differences in exposure, telemetry and processing. This applies to the humidity data provided by FRG, USA and OCAN and to the temperature and pressure data provided by the USA and OCAN systems.

*Abbreviation of radiosonde 1524-511 (Beukers)*

see Table 4.
2.3 Photographs of radiosondes

Various photographs of the radiosondes themselves are provided. Photograph P1 provides a general view of the RS80 with a strut extending upward and outward to carry first the humidity sensor beneath a thimble-shaped shield and then the thermometer. In P2 is seen the interior of the G 78 C radiosonde. The thermistor can be seen above the strut extending into the duct to the right. However, neither the humidity sensor (which is suspended beneath the strut) nor divergent funnels forming extensions to the duct appear (the duct extensions can be seen in P7 - the uppermost sonde of the photograph). The 1524-511 radiosonde appears in P3, with its thermistor extended on wire supports (the humidity sensor is exposed in a duct within the case). Photograph P4 shows the RS3 radiosonde. The humidity sensor is located within the shield just above the main body of the instrument while the wire thermometer is supported on pins extending upward from a plastic moulding encircling the rod leading upward from the top of the radiosonde to the suspension. The 1392-510 radiosonde is shown in P5, with the thermistor mounted within a light plastic frame extending upwards from the body, the humidity sensor lying in a duct within the body and the transmitter mounted in an extension beneath the sonde. Finally, photograph P6 is included to show the baroswitch assembly within the same radiosonde (for reference in later discussion).

2.4 Telemetry

Telemetry characteristics are provided in Table 3. With earlier designs in mind, a trend is seen towards electronic switching between variables, with a consequential saving in size and weight. Sampling intervals in the range 1.2 to 5 seconds are provided for temperature and humidity data in various signal patterns. The patterns include pressure and up to three reference signals of various kinds. Also, greater radio-frequency stability than has been usual in the past has been provided in two systems by means of crystal control.

The telemetry arrangements make use of analogue representation in four of the systems and, for the first time, digital representation in one of them.

Three systems (FIN, FRG and OCAN) make use of the 403 MHz band, with the USA operating at 1680 MHz and the UK still at 28 MHz.
Four wind-finding systems participated in the intercomparison, between them representing most techniques in present day use. Two of them (FIN and OCAN) employed the navaid (Omega) technique, the former using signals from up to six stations at all times and the latter using just the best three signals (selected prior to each sounding). The USA employed a radio-theodolite (1680MHz) while the UK employed a primary radar (10cm). Averaging of data over time intervals of up to 4 minutes for the navaid systems and up to six minutes for the radio-theodolite data in the stratosphere was undertaken. The radar winds were averages over an interval of one minute obtained by least-squares fitting to five successive sets of radar observations taken every fifteen seconds.

2.5 The ground stations

Four ground stations were fully automatic, using a computer-controlled system for signal reception, quality-control, data evaluation and TEMP message selection. The USA system (GMD Ia) was semi-automatic, using manual selection and extraction of data from a strip chart record, followed by manual entry into a computer facility for data processing and TEMP message selection.

The minute-data required for the intercomparison is, of course not an operational requirement and the systems were extended to provide these data.

2.6 Pre-flight check

Initial correction before flight of the radiosonde data at the surface (usually indoors) was undertaken so as to agree with independent information (controls, base-line check) by FIN and UK. The FRG carried out an acceptance check before flight and if within tolerance used the radiosonde without correction or else rejected it. Both USA and OCAN used the same design of precision temperature and humidity sensors without check or correction, while the baroswitches were used in different ways. USA undertook mechanical adjustment of the contact strip (disposed in an arc at the base of the radiosonde - see photograph P6) to place it in a specified position in relation to the contact arm and so establish on all occasions the same relationship between the contact sequence and the surface pressure. OCAN determined the relationship as it existed on each occasion as part of the in-flight processing, by means of automatic examination of the first few in-flight contact signals with regard to the calibration data, the rate of ascent and the surface pressure.
3. SUPPORT ARRANGEMENTS

3.1 Flight Rigs

With but a few exceptions, the radiosondes were flown five designs at a time. The main rig to do this comprised a lightweight spreader in the form of a cross of thin bamboo canes, the limbs of which extended for 2 metres from the centre. The radiosondes were suspended, one from each extremity and one from the centre. Cords were used to transfer the load from these five points to a common point about 6 metres above the cross and thence to the radar target (provided for tracking) and finally on to the balloon. The distance from the cross to the radar target was 30 metres and from the target to the balloon about 5 metres. The rig is depicted in Figure 1A and shown in photograph P7.

A second rig was also used on occasions to fly just two radiosondes at the level already described and the remaining three a further 20 metres below the first two. This was to gain evidence concerning the possibility of radio-interaction between the various radiosondes and possible excess air temperature in the balloon wake. This rig is depicted in Figure 1B.

These assemblies were handled at launch by team members, one to each radiosonde, who rapidly learned how to run and launch in unison. Their skills proved very valuable in avoiding crashes at launch on the few occasions that occurred of strong surface wind.

3.2 Synchronization

To determine the systematic difference between radiosonde designs simultaneous observations have to be made. To achieve this, a central timing system was built by the UK to provide a synchronizing pulse at launch and at each minute thereafter. The system is able to provide time offsets at individual outlets so that allowance can be made (through an assumed rate of ascent) for any vertical separation between particular radiosondes.

The USA system made use of the pulses to place time marks automatically on their strip-chart records so that data could be easily read off at the times required, rather than be obtained by interpolation between data chosen at other times. The UK ground station was able to accept the pulses and generate data automatically for the times concerned. The three remaining systems used just the launch pulse, one system automatically (FIN) and the others manually (FRG and OCN), to initiate flight processing and then generated their own in-flight minute times.
Corrections for any timing errors at launch were derived by subsequent examination of the fine-structure profiles that all these systems provided.

Concerning minute-times in flight, use was made of the central timing system to monitor the internal clock of the UK ground station (which is dependent upon the frequency of the public power supply) and so establish timing corrections for any system that was power-supply frequency dependent. It was found that the error did not accumulate at a steady rate and could attain ±15 seconds over a two-hour period. The data were used to correct the FRG system which like the UK system made direct use of the frequency of the public power supply. However, the remaining systems (FIN and OCAN) proved to be satisfactory in maintaining timing in-flight, the FIN time data, for example, being found always within ±1 second of the central timing system.

As a further precaution, use was made of the fine-structure profiles available to ensure that any residual effect due to in-flight timing errors was negligible. Noting that for typical tropospheric lapse rates a timing error of 2 second would cause a temperature error of about 0.07K, it is believed that the correction procedures overcame the effect of timing errors well enough for the purpose.

4. DATA GATHERING AND QUALITY CONTROL

4.1 Initial presentation and input format

The results of each flight were provided both in the detail necessary for intercomparison and in the form of a regular TEMP message. The detailed format included values of pressure, temperature, relative humidity and geopotential for each minute of flight. Also included were temperature, relative humidity and geopotential data for a set of fixed pressure values. These detailed results were normally required by the Data Management Centre within two hours of flight termination. Except on occasions of equipment failure, the four visiting teams provided their data via punched paper tape backed up with a print-out. The detailed results of the UK system were supplied in manuscript upon Forms specially designed for use by any participating team. The TEMP messages were normally required to be handed to the Data Management Centre nominally within a half hour of flight termination. Punched paper tape was used by three teams and manuscript on special forms by the remainder. Working on a twice-daily basis, the detailed data tapes were machine-read and the manuscripts hand-keyed into the computing system of the UK Meteorological Office to compile an initial data set.
4.2 Data verification

Copies of data received into the computer were provided (generally on the following day) in the form of a print-out and plot to the originating teams for verification. Tentative corrections were then entered for manual errors in processing, transcription and other mistakes, along with adjustments for any timing discrepancies. Revised plots were supplied to the Project Leader and, subject to his approval, the corrections were embodied as providing the most reliable representation of system performance.

4.3 Data editing

The special circumstances of an intercomparison may occasion results that are not indicative of general operational performance. Examples include signal reception problems arising from the close proximity of signals from other radiosondes and mistakes made by operators. Events of this kind are usually self-evident. Because of such possibilities, frequent meetings were held at which the team leaders reviewed the results with this in mind and raised any queries that they wished. It was occasionally decided to flag quite limited bursts of data as unrepresentative.

Finally, the flagging of much broader sweeps of data was occasionally decided upon by the Project Leader. This was done whenever the results were clearly anomalous by comparison with those of other participants, since such data are best excluded from statistical analysis and noted separately. In addition, sweeps of relative humidity data were flagged when the time-rate-of-change was so large that differences in simultaneous data would be dominated by the effect of differences in the response times of the sensors and could thus mislead the study of other observational problems.

Following these actions, revised plots of unflagged data were scrutinised by the Project Leader who then gave final approval for embodiment into the Intercomparison Data Set.
5. DATA ANALYSIS SCHEME

5.1 Direct differences

Taking each flight separately, each possible pair of the radiosondes flown was considered by differencing the available simultaneous values. For any one pair, the differences were then grouped according to the (pre-set) pressure interval within which they were observed and a mean found for each group. This mean was taken as a single value indicative of the difference between the two radiosondes concerned within the pressure interval. Corresponding means obtained for other flights at a like time of day were later combined to obtain an overall mean (the Direct Difference) and standard deviation for the two radiosonde designs, pressure interval and time of day concerned.

5.2 Consistent differences

Because of data losses, the Direct Differences described in section 5.1 are not necessarily consistent, with the result for example that the Direct Difference for design A with design C may not agree with that implied by the Direct Differences for A with B and B with C. Accordingly the computations were extended by means of a standard statistical procedure to provide a set of Consistent Differences for each pressure interval. Full details of the procedure are provided as Annex I to the WMO Report of the First Session of the International Organizing Committee for Radiosonde Intercomparison 1984. For the intercomparison reported herein, corresponding Direct Differences and Consistent Differences agree closely except at the highest altitudes where the effect of data losses upon the Direct Differences became appreciable. Sample tabulations of Direct and Consistent Differences are provided in the Appendix.

5.3 Standard errors

The population of each design of radiosonde participating in the intercomparison was represented by a sample of about 100 radiosondes. There is always the risk that a sample does not reproduce the population performance closely, particularly for designs of greater variability. Thus another intercomparison might give a significantly different result. Accordingly the Intercomparison Data Set achieved was modelled one hundred times assuming zero population mean differences with standard deviations for individual data chosen in the light of evidence gained in the intercomparison and in other studies. The method is discussed in the second part of the Annex I referred to in section 5.2 and will not be further discussed here. The standard errors obtained by the procedure are given in the statistical tables of results.
6. THE RESULTS

6.1 The weather experienced

It cannot be expected that in any intercomparison of practical duration the full range of factors which can influence radiosonde performance will be represented in the results. For example, heavy precipitation with attendant risk of icing may not occur, or a cloudy spell may dominate so that solar radiation at low levels in the atmosphere are not fully represented. Thus it is necessary to provide a summary of the weather experienced during the intercomparison.

Synoptic conditions during the intercomparison (20 June to 25 July 1984) were generally anticyclonic, with a surface high-pressure centre to the south-west of the UK in mid-June gradually moving north before turning east across the country during the first week in July. Conditions at the intercomparison site were dry with periods of low cloud cover. During the second week in July low pressure became established to the west and associated fronts advanced eastwards across the UK accompanied by rain. By 17 July however, high pressure was again firmly established over the country and temperatures rose steadily. A small thundery low developed to the south-west on 23 July and there was a severe hail storm at the intercomparison site with 43mm of rain falling in 44 minutes.

The mean sea level pressure over the south of England during the intercomparison was about 1020 hPa. Conditions were warmer than usual for June/July and aside from the storm very much drier than normal. Some 45% of ascents passed through a layer of low cloud but it was precipitating at launch time on less than 3% of occasions. Shallow radiation fog was observed at 4% of launches. Maximum windspeeds of more than 60 knots were recorded on 26% of ascents.

6.2 The flight programme achieved

In all, 100 flights were used to compile the statistics, each being made generally with all five, but occasionally with four, of the radiosonde designs. The number of flights undertaken at each of the six nominal sounding times is given in Table 5.
6.3 Selected segments of flight profiles

In addition to securing the data already mentioned, the opportunity was taken to obtain a considerable amount of fine structure detail so that instrumental phenomena such as lag could be studied. It is not the intention to consider these results here but merely to illustrate the information available.

Figure 2A compares the detailed temperature structure observed through a ground-based radiation inversion. The profile which is cooler than the general trend was provided by the OCAN system. The offset exists from the first given observation aloft and could, it is believed, have been avoided by application of a control correction. Figure 2B provides alternative temperature profiles through the tropopause. The greater detail and extreme values provided by the UK thermometer can be readily seen.

Figure 2C presents relative humidity plots from surface up through clear air. The base of a temperature inversion layer as defined by the very fast response of the UK thermometer is marked. Although a considerable spread of humidity values is seen beneath the inversion layer, all the humidity sensors respond to the onset of the marked hydro-lapse occurring at the base of the layer. It is also seen that the UK sensor subsequently reacts less quickly than do the other sensors within the inversion layer.

Figure 2D shows similar profiles observed on an occasion when cloud was present. Again there is a considerable spread of humidity values at the lowest levels followed by a quick response at the onset of a marked hydro-lapse. However two of the humidity sensors fail in varying extent to approach saturation within the cloud layer.

Turning to wind data, Figures 2E and F show wind speed and direction profiles for winds deduced at one minute intervals on an occasion of light winds and stronger winds respectively. The effect of the different smoothing interval (one minute for radar, more than two minutes for navaid) is readily seen. Thus although all systems follow the same trend, the radar data provide greater detail and better observe wind maxima and minima. Noting that oscillations are present from minute to minute, in both wind speed and direction data, especially in the stratosphere, it might be wondered whether the radar antenna assembly is hunting about the true position rather than tracking real events. Because of this possibility, Figures 2G and 2H have been included. These show, again for light and for stronger winds, data from two radars tracking the same flight. One radar is that used at the intercomparison site while the other is that used at an operational sounding station about 50 kilometres distant. It is seen that oscillations of wind speed and direction occur and are nearly always matched by both radars despite their considerable separation. Thus it is concluded that the oscillations are real variations in the wind profile.
6.4 Summary of comparative data

The complete set of tables and other computer products is very large indeed and occupies seven volumes. For example, fourteen different height bands were used for radiosonde data rather than just the four given here while for wind data evaluation of differences was undertaken for every five kilometres of slant range. The tables appended to this report are intended only to illustrate the types of statistical summary available, the full set has been compiled by Nash et al (1984).
7. DISCUSSION OF MAIN RESULTS

7.1 Pressure Differences

The mean and variability of the pressure differences over all flights are represented, pressure interval by pressure interval, in Figure 3. Three sonde designs (FIN, UK and USA) provided pressure data during the intercomparison within, on average, one hPa of each other in the troposphere, reducing to within 0.1 hPa of each other at the 10 hPa level. The FIN and UK radiosondes agreed especially closely up through the stratosphere. The pressure data of the FRG and OCAN designs differed substantially from that of the first three designs, even though gross differences in excess of 10 hPa were removed during quality control as being non-representative.

The systematic pressure differences of the FRG data have since been attributed to gas leaking into the pressure capsules at their seals between calibration and use. Most, but not all, of the OCAN differences are thought to be due to use of in-flight software-derived corrections rather than pre-flight manual adjustment to allow for calibration shift (see section 2.6) and to an occasional excess contact count by the in-sonde electronics.

The pressure variability from sonde to sonde, expressed as a standard deviation - the Sonde Error - for both the FIN and UK designs was less than ± 0.75 hPa in the lower troposphere, reducing up through the stratosphere to within ± 0.35 hPa. The USA variability was about twice as great. The considerably greater Sonde Errors of the FRG and OCAN designs may have arisen from the system problems already mentioned and so no statement can be made upon the intrinsic design variability.

7.2 Temperature differences in darkness

From Fig. 4A it is seen that in darkness the five designs of radiosonde provided mean temperatures, layer by layer up through the troposphere, within one half-degree Celsius of each other. Because of the very fast response of the UK thermometer, the other designs can be expected to be warmer by about 0.07 deg C at the surface, increasing to about 0.2 deg C at the 300 hPa level, where a typical lapse rate of 2.5 deg C per minute was experienced during the intercomparison. With the exception of the OCAN data, a considerable part of the observed tropospheric differences can be explained by this.

In the stratosphere, cooling due to long-wave radiation is to be expected for the thermistors of the FRG, USA and OCAN designs.
since the coating used to reflect short-wave radiation is unavoidably dark to infra-red radiation. The FIN sensor, however, has an aluminised coating of high reflectivity and its temperature can be expected to be less sensitive to long-wave radiation effects. In addition, empirical corrections are applied. The extent to which the difference between the FIN and UK temperature data is due to residual long-wave radiation errors is not known and cannot be ascertained from the intercomparison results.

The closely similar trend with altitude of the USA and OCAN temperatures is to be expected in view of the use of identical sensors. The systematic offset between them may arise in several ways such as the different arrangements for mounting and for exposure or, perhaps, from differences in production batches.

The standard deviation from sonde to sonde of any one design - the Sonde Error - is seen to be typically ± 0.15 deg C in the troposphere, increasing to about ±0.25 deg C at the 10 hPa level. The OCAN Sonde Error is somewhat greater; about ±0.25 deg C at all levels.

7.3 Temperature differences in sunlight

Figures similar to that for darkness are provided for each of the five other nominal flight-times, all of which were in daylight (except for the lowest altitudes at 04GMT).

It is convenient first to consider Fig. 4D for 12 GMT (local noon), when the solar altitude is at its greatest. The systematic difference between the FIN and UK data in the troposphere is closely similar to that in darkness and in the stratosphere is negligible.

The mid-day data for USA and OCAN are again in close agreement, and unlike in darkness are warmer than are the data of the remaining designs. No corrections are applied for solar radiation. Thus the change in offset from darkness to midday represents the response to solar radiation, provided that there is no change on average between the 00GMT and 12GMT data sets for the FIN and UK designs. Subject to the same assumption, it also appears that there is very little difference between the FRG temperature data for 00GMT and 12GMT.

The estimate of Sonde Error at 12GMT is hardly different from that for darkness except at the highest altitudes. However, the differences at high altitudes may not be real since the estimates are more uncertain at 12GMT because of the reduced number of sondes providing data. An additional variability is present in the FRG temperature data. This arises from the effect of fluctuating pressure errors of the order of 10hPa upon the solar radiation correction (which varies rapidly with pressure).
Individual consideration of the Figures 4 for other solar altitudes will not be given here except to remark that the Systematic Differences and Sonde Errors are similar to those already discussed. Instead, an over-view is given by reference to Figures 5A and 5B. These use the mean temperature differences at the several flight times, for four of the pressure intervals. The differences given are with respect to the USA data which, being uncorrected for solar radiation, can be expected to vary in a regular way with changes of solar altitude.

The variation with solar radiation of USA data can be deduced from studies of day-night differences observed in reports from the USA radiosonde network. When combined with the intercomparison data, solar radiation corrections can be developed for use at the USA sounding stations along with adjustments to reduce the Systematic Differences between the sounding systems participating in the intercomparison. It is understood that this will be attempted once the additional data secured from Phase II of the Intercomparison are available.

7.4 Relative humidity differences

Fig 6A shows mean relative humidity departures from the average of FIN and USA for six bands of relative humidity for data observed in the pressure range 975 to 700 hPa. These average data for FRG, OCAN and USA agree closely at high and low relative humidities with a maximum average spread of six per cent at mid relative humidities. The three designs of radiosonde use the same sensor (an Acculok Hygristor), each with a different exposure. The differences are small in relation to the Sonde Errors concerned. The three designs provide closest agreement and consistency at high relative humidities.

Compared with the three foregoing designs, the UK humidity data (which depend upon a Gold-Beater's skin sensor) show a relative under-read of 11 per cent relative humidity at high humidities, and a similar over-read at low relative humidities. While this may to some extent arise from the larger lag of the UK sensor, for which no correction is made, this sensor is known to under-read upon entering cloud from substantially drier air beneath. From the same Figure it is seen that by comparison with the Hygristors, the FIN humidity results tend to under-read at high relative humidities.

The same relationships can be seen in Fig 6B for higher altitudes (and colder temperatures).

At all levels, Sonde Errors are least at high relative humidities where the standard deviation for all five designs is typically ±2.5 per cent relative humidity, increasing to ±6 per cent for humidities below about 50 per cent relative humidity.

A more detailed account of humidity effects observed during the intercomparison has been given by Nash et. al. (1985)
7.5 The geopotential of significant levels

The tropopause is the only significant level for which the geopotential is regularly reported. However, meteorological services may need the heights of other significant features from time to time, either in course of special investigations of their own, or to allow radiosonde data to be related to observations of atmospheric phenomena made by other agencies.

Fig 7 shows the mean difference of simultaneous geopotential data for the OOGMT soundings, using the same format as for temperature data. The data combine the errors of all three variables, (pressure, temperature and relative humidity). It is seen that heights of particular atmospheric features derived from the FIN, UK and USA data agree within about thirty geopotential metres close to the ground, within about fifty geopotential metres at an altitude of 16 kilometres and within about 230 geopotential metres at an altitude of 30 kilometres. The FRG and OCAN data run out from these data. Corresponding values for the mid-day soundings include the additional effect of differences in temperature, pressure and, to some extent, humidity errors between OOGMT and 12GMT.

Equally important is the variability which at an altitude of 16 kilometres, for example, ranges from a standard deviation of about ±20 metres to ±140 metres according to the design considered.

Overall, the heights of significant atmospheric features provided by a radiosonde depend considerably upon both the design of the sonde concerned and upon the particular instrument used. They are often insufficiently precise for non-meteorological purposes.

7.6 The temperature at a standard isobaric surface

The differences between the intercomparison temperatures reported by two radiosondes for a standard isobaric surface generally arise in part from the differences between simultaneous temperature data (sections 7.2 and 7.3) and in part from differences between simultaneous pressure data (section 7.1). This is because the temperatures assigned to an isobaric surface by two radiosondes flown together will be taken at different flight times when there are simultaneous pressure differences between the radiosondes. In daytime erroneous pressures introduce a further error by causing the use of wrong solar radiation corrections. Because the error terms change in a regular way with altitude and because they are independent, it is, of course, possible for the temperature and pressure error contributions to augment or partly cancel each other or to change between these two states in course of ascent.
Figure 8 shows mean temperature differences for standard isobaric surfaces at 00GMT and 12GMT. The differences reflect the differences and interactions just described. It is seen, for example, that with the exception of FRG and, in daytime also OCAN, the mean temperatures are within one half-degree of each other in the troposphere. The smallest differences arise between the FIN and UK systems. The various remarks made in sections 7.1 to 7.3 also apply to these data. As is to be expected, the standard deviations are generally somewhat greater than those for simultaneous temperatures.

7.7 The geopotential of standard isobaric surfaces

Average differences of the geopotentials of standard isobaric surfaces are plotted in the usual format in Figs 9A to 9F. Pressure errors make only a secondary contribution and so the differences are much smaller than those of significant levels (section 7.5). In darkness (Fig 9A), the difference between the average geopotentials of the FIN and UK designs increases almost linearly from zero at the surface to 56 metres at the 10 hPa level. Since the differences between standard isobaric level geopotentials depend almost entirely upon the temperature differences, the average differences of the three other designs vary in a non-linear way in close accord with the temperature differences of Figure 4A. For the same reason, the average differences between the standard isobaric level geopotentials at other flight-times reflect the temperature results of Figures 4B to 4F.

Concerning variability, the Sonde Errors of FIN, UK and USA in darkness are about ±8 metres at the 100 hPa level with FRG and OCAN being about ±14 metres. In darkness at the 10 hPa level, Sonde Errors are generally between ±20 and ±25 metres (±30 metres for OCAN).

7.8 Differences between wind data

The quality of navaid wind data depends considerably upon the geographical locations of the navaid transmitters in relation to the sounding site. Both the quality of the signals received and the geometry of the position lines implicit in the signal analysis may be affected. Thus it is first noted that any conclusions drawn from data gathered at an intercomparison cannot be applied to other locations without allowance for these factors.
The data obtained during the present intercomparison comprise winds at intervals of one minute for 97 flights. The winds provided by the four systems are not exactly comparable. Thus the radar winds are calculated from data gathered over one minute, the navaid winds make use of at least two minutes of data, and the radio-theodolite winds are averages over two minutes in the troposphere increasing to four minutes or more in the stratosphere.

The wind data have been divided not only into height bands but also into categories which reflect the sensitivity of the radar and radio-theodolite systems to distance and elevation angle and the sensitivity of the navaid systems to propagation variations with time of day. A further elaboration is necessary to allow for wind being a variable which has two-parameters. Examples of the tables comprising the full data set appear in the Appendix. A simplified treatment is presented here.

It is to be expected that the primary radar used in the intercomparison will be more accurate than the other systems—certainly at short ranges. Thus it is sensible to choose the radar data as the system against which the other systems can be compared. Since the intercomparison was completed, it has been possible to quantify the variability of the radar used for the intercomparison. This was done by tracking a series of sounding rigs with a second radar of identical design at an operational sounding station located some 50 kilometres away. With this additional information it is possible to apportion the overall variability of the differences between the radar and each other system concerned.

Figure 10A shows the variation with range of r.m.s. vector differences (see footnote) for four bands of radar elevation angle. The vector differences relate the intercomparison radar data with that of the three other intercomparison systems. Also shown are the r.m.s. vector differences of the intercomparison and operational station radars. Mean heights associated with the ranges and elevation angles for the intercomparison data are indicated.

**NOTE.** The r.m.s. vector difference between sets of alternative winds was calculated using the following instructions.

For each pair of alternative winds:

- Obtain the vector difference and resolve into Northerly and Easterly components, $\Delta N$ and $\Delta E$.
- Sum the squares of all such components (Northerly and Easterly all together) and divide by the number of vector differences.
- Take the square root of the foregoing sum as the r.m.s. vector difference.
It is seen that of the two navaid systems, closer agreement with the radar data was provided by the FIN system in all circumstances. A significant difference between the two navaid systems is that the FIN system made use of as many Omega signals as possible and varied the selection automatically during processing, while the OCAN system used just three signals selected on each occasion before launch and used without change throughout the sounding that followed. For both navaid systems, the difference with the radar data was a minimum for slant ranges of between 5 and 10 kilometres. At greater ranges there is an overall increase of difference with height. This is in part due to the smoothing of the navaid systems which serves to reduce the real variability of the winds more than does one-minute smoothing of the radar. For example, the mean difference between maximum wind-speeds reported by the radar and by the navaid systems was 2 metres per second for the FIN system and 3 metres per second for the OCAN system, with the radar wind being greater on average than the navaid winds.

The r.m.s. errors of the primary radar are about 0.5 metres per second ranges up to 20 kilometres, increasing to about 2 metres per second at a slant range of 110 kilometres. When allowance is made for this performance, the r.m.s. errors of the FIN system, taken over all times of day in the circumstances of the intercomparison, were about 2.4 metres per second at both short and long ranges reducing to about 1.3 metres per second in favourable conditions in the troposphere. The r.m.s. errors of the OCAN system were about 3 metres per second generally, reducing to about 2 metres per second in the troposphere. The r.m.s. errors of the radio-theodolite as operated at the intercomparison were about 3.2 metres per second for all ranges with low elevation angles, generally about 2.7 metres per second and decreasing to about 1 metre per second for ranges within 10 kilometres and with elevation angles between 20 and 70 degrees.

As already mentioned, there can be a diurnal variation in navaid signal quality. Figure 10B shows in the same format as Figure 10A the r.m.s. vector differences for different times of day. It is seen that at the intercomparison site the navaid wind variability was greatest for the 16GMT and 20GMT soundings. It can be seen that the degradation at such times was greater for the OCAN system, no doubt because of the use of just three signals.

An aspect not brought out by consideration of r.m.s. vector errors is the spatial error distribution. This is shown for one sub-set of data (at ranges for which the radar error distribution is indistinguishable from circular) for FIN-UK in Figure 10C and for OCAN-UK in Figure 10D. The ellipticity of the OCAN-UK vector differences can be explained by the use of just three Omega signals in the OCAN system and their origin in relation to the intercomparison site. The circularity of the FIN-UK vector differences is thought to arise from the use of up to six Omega signals which although of considerably varying signal strength at the intercomparison site may have combined in their
effect to even out the error distribution.

Of course, an elliptical error distribution can also occur with radar winds, at ranges where the effect of angular errors overwhelms that of range errors. However, the alignment of the major error component is essentially radial and so varies with the direction of the rig being tracked, while any ellipticity of the navaid error distribution is in a fixed direction for any one location and selection of signals. The author is unaware of any view expressed by users of sounding data upon whether systems with elliptical error distributions should be compared by means of their major error components or by some overall index such as the standard vector deviation, or the r.m.s. vector difference used here.

The reality of the radar and navaid r.m.s. results can readily be seen by reference to the wind profiles already referred to. Thus Figures 2E and 2F compare the profiles provided by the radar and (amongst others) the FIN navaid systems on one intercomparison flight. Considerable differences between the two sets of data exist, and the effect of smoothing in the navaid system can also be seen. Figure 2G and 2H provide similar profiles obtained on one of the calibration flights using the intercomparison radar and an operational radar located some 50 kilometres away. While there are fluctuations from minute to minute about which some doubt might have been felt had they been obtained by just the intercomparison one radar, it is seen that the second radar provides the same features at almost every altitude of the sounding.

It is helpful to relate the quasi-uniformity of navaid performance with range with the range-dependent performance of a wind-finding radar. For example, it appears from the intercomparison results that for southern England, the "break-even" slant range for comparable performance of navaid-Omega and primary radar winds is about 100 kilometres. However, it should be remarked that the navaid winds are averages over at least two minutes of data. If this is acceptable for a wind-finding system then such averaging can be applied also to the radar data with a consequential extension of the "break-even" range. Having regard for the wind regime over southern England, it appears that for most of the time winds there are better determined by radar than by a navaid-Omega system. The navaid-Omega winds are better only in those circumstances when the sounding rig is at ranges such as occur in the stratosphere from time to time in the winter half of the year. In order to draw a corresponding conclusion for other locations it would be to allow for the performance of the primary radar concerned and for the particular reception conditions of the Omega signals.
7.9 **Effect of the solar tide**

Differences between radiosondes flown together provide information upon their relative performance in the conditions concerned, no matter what time of day the flight is made. However, data obtained by radiosondes that have to be flown operationally at times other than local midnight and local noon include not only the effect of any different instrumental response to the radiation conditions of the two times of day concerned but also a substantial effect due to the solar tide. In such circumstances it is insufficient to estimate radiation corrections from the average difference between the data gathered at the two sounding times. Because of this the Project Leader of the intercomparison took the opportunity provided by the use of six flight times to undertake a study of the solar tide at the intercomparison site.

The procedure for each radiosonde design was to use successive 00GMT data to estimate 100 hPa geopotentials for intermediate flight times by linear interpolation. When a 00GMT value was missing for a particular radiosonde design then a value was estimated using all possible information, including data from the nearby regular sounding station when necessary and estimates of the systematic difference between the radiosonde designs concerned. Differences were then formed with the geopotentials actually observed at the intermediate flight-times. The average of each such difference is given in Figure 11A, where values made at different times of day but exposed to about the same solar altitude are linked by dotted lines. The difference between linked data pairs is attributed to the effect of the solar tide. The data are re-plotted in Figure 11B with the mean bias of each linked data pair with respect to 00GMT removed so as to allow for the systematic errors between different radiosonde designs. The effect is to display estimates to a common base by all designs of radiosonde of the average diurnal change in the solar tide at the period and location of the intercomparison. Figures 11C and 11D present similar data for the 100-30 hPa geopotential increment.
8. CONCLUSION

8.1 Concerning radiosondes

The results of a radiosonde intercomparison should benefit both the radiosonde designers and the users of operational sounding data. However, the number of radiosondes flown in course of an intercomparison of typical duration (about six weeks) is unavoidably limited by the cost of consumables and labour, and by the time needed for reduction of the sounding data. Because of these factors, together with the instrumental variabilities then attainable, the significance for operational users of radiosonde data of some intercomparisons undertaken in the past has been limited (although the system designers themselves have always gained much useful information for further instrumental development).

Technological advances in recent years have enabled intercomparison results to be considerably improved. Thus some recent radiosonde designs have shown a marked increase in consistency from sonde to sonde, so that results can be statistically significant when compared with the likely uncertainties imposed upon synoptic analysis by the small-scale variability of the atmosphere itself. For these improved radiosonde designs a test programme of about thirty midnight and thirty midday flights can be sufficient to ascertain the performance of the radiosondes used in an intercomparison.

Technological advances have also enabled automatic data-reduction to be used for radiosonde ground stations with a considerable reduction in the labour and time required for sounding results to be obtained. This, in turn, has allowed additional intercomparison flights to be undertaken between the standard sounding times of 00GMT and 12GMT. Two advantages stem from this. One is that many more sondes of each design can be flown, thus reducing the risk that the intercomparison results are not representative of the whole population of a particular radiosonde design. The second is that flights made at intermediate times provide data upon radiosonde performance at additional solar altitudes. This is especially helpful for those radiosonde designs flown operationally in many longitudes.

Each of the three operational systems reported upon here shows a consistency from radiosonde to radiosonde which is markedly improved over earlier performance. Taking the variability of the 100 hPa geopotential from flight to flight as an index of consistency, the intercomparison results show that a standard deviation of ±8 metres can be attained. This is equivalent to a consistency in mean temperature from surface to the 100 hPa level of ±0.12 degrees Celsius and represents a very high standard when the constraints placed upon radiosonde design are considered. The standard deviation of ±14 metres obtained for
the two remaining designs is also a considerable improvement over the performance of earlier designs of radiosonde.

With regard to the effect of solar radiation, the intercomparison results are well established and serious consideration should be given to their use as station corrections for the USA and OCAN radiosondes, and also at stations flying the FRG sonde when introduced into service. This would be a worthwhile step towards uniformity of upper-air data. The same view applies to corrections for long-wave radiation.

A more difficult matter is that of the Systematic Differences that arise between the data of the various designs of radiosonde when flown at night-time. There is of course no independent measure that enables the Systematic Error of each design to be determined and corrected for as part of the station procedure. However, the second phase of the Intercomparison will include data from a high-precision height-finding radar. These will be of help if the variabilities of two radiosonde designs are considerably different and cannot be separated by use of other data. A further possible benefit may arise if it can be assumed that errors in the radar height data are small by comparison with those of the radiosondes. In this circumstance, then for any one assumed temperature error distribution with altitude there will be a corresponding pressure error distribution and it may be possible to establish an envelope of paired temperature/pressure error distributions. By study of the whole set of intercomparison data, it may then be possible to set limits for the probable uncertainty with respect to truth of the radiosonde data obtained.

Whether or not this can be done, it is expected that empirical adjustments can be devised to bring the radiosonde data to a common standard close to the truth. With the technique established, it will then be possible to use a similar precision radar at later intercomparisons to provide a link between the results.

It is remarked that adjustments for Systematic Differences are essentially different from the application of corrections for scientifically estimated sounding system errors, and are not appropriate for application at the sounding stations. They should, instead, be applied at analysis centres. There is evident advantage in evaluating the relative performance of all radiosonde designs in operational use with view to referring radiosonde data to the same standard at all analysis centres, rather than for each centre to use its own set of adjustments.

8.2 Concerning wind-finding

This phase of the intercomparison has provided useful data upon three alternative methods of wind-finding. At the intercomparison site the systems displayed a very considerable
spread in accuracy and resolution, the r.m.s. errors extending from 0.5 to 2.0 metres per second (radar) and from 1.3 to 2.0 metres per second for the eight-station Omega system. Errors for the three-station Omega system were significantly greater and for the radio-theodolite greater still or else subjected to smoothing of up to six minutes at greater ranges.

It has often been advanced that a navaid system has the advantage of uniform resolution with range while a radar wind-finder suffers a loss of resolution with range. A relevant aspect of this reasonable qualitative view is the range beyond which the navaid system has a better resolution and the altitudes and frequency with which such ranges are experienced in course of soundings. A second relevant aspect is that a navaid system suffers a diurnal variation of accuracy because of signal propagation changes while a radar does not. Thus consideration of these very different wind-finding systems has to include their quantitative performance. For the Omega navaid signal regime at the location of the intercomparison, radar wind-finding provides greater accuracy and resolution except at ranges such as are experienced when ascending up through the stratosphere from time to time in the Winter half of the year. It is also seen that a wind-finding radar can provide more definition of the vertical wind-structure such as wind speed maxima. Although not a new factor emerging at the intercomparison, the opportunity is taken to note that both systems fail to provide wind structure in the boundary layer. This is because of the need for a large averaging time (navaid) or because of a minimum observable range (radar).

8.3 Concerning intercomparisons themselves

The work reported here secured data from 100 flights, nearly all with five radiosondes. The amount of data is very great and this report can be concerned only with the broad results. There is material available for several detailed studies. In the writer's view the intercomparison has been very successful and sets a pattern of data gathering and analysis that later intercomparisons can build upon. In particular, the benefit of flying radiosondes at several times of day is apparent, both with regard to solar radiation corrections and with achieving a better representation of operational quality.

It has to be said that there have been insufficient such intercomparisons in the past - no doubt because of the effort and cost entailed. With many more sounding systems in operational service than can be compared together, the benefits of a regular programme of intercomparisons phased into the CIMO 4-year cycle should be considered. Of the radiosonde designs flown in any one intercomparison there should be two designs that participated in the preceding intercomparison and two that will participate in the next intercomparison. These linking designs should not have changed their meteorological performance intermediately except in
ways that are clearly known. With improving performance, the need for intercomparisons will reduce, but this stage has not yet been reached.

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REFERENCES


### TABLE 1
THE RADIOSOUNDING SYSTEMS

<table>
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<tr>
<th>Radiosonde model no.</th>
<th>Weight (gm)</th>
<th>Wind technique</th>
<th>Level of automation</th>
<th>Usage in this Report</th>
<th>Label in this Report</th>
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<td>RS 80-15N&lt;sup&gt;4&lt;/sup&gt;</td>
<td>190 (8-station Omega&lt;sup&gt;^&lt;/sup&gt;)</td>
<td>navaid primary radar</td>
<td>full increasing</td>
<td>FIN</td>
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**NOTES:**

"full" means automatic reception and processing of received transmissions to produce results in WMO TEMP Message format either as a punched tape or as a print.

"semi" means automatic recording of received signals on a strip-chart recorder, with manual selection and extraction of data and subsequent computer-processing to produce the results in WMO TEMP Message format either as a punched tape or as a print.

* The primary radar was not deployed at the intercomparison.

^ Of the 8 possible stations, one (Hawaii) was unheard while another (Australia) was excluded owing to ambiguity arising from multiple path propagation.

<sup>4</sup> The mounting of the temperature and humidity sensors used during the intercomparison and the corrections for radiation effects differed from those in operational use in 1984.
TABLE 2

SOME PROPERTIES OF THE SENSORS USED

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<tr>
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<th>FIN</th>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short-wave</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Long-wave</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Correction applied at 10hPa, solar elevation 60 degrees</td>
<td>2.1K</td>
<td>2.0K</td>
<td>7.2K</td>
<td>7.2K</td>
<td>7.2K</td>
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<tr>
<td>HUMIDITY SENSOR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material and exposure</td>
<td></td>
<td></td>
<td></td>
<td>USA</td>
<td>FLG</td>
</tr>
<tr>
<td>Thin-film carbon dispersion on sub-strate in duct (ACCU-LOK Hygroist, 1368-163)</td>
<td></td>
<td></td>
<td></td>
<td>USA</td>
<td>FLG</td>
</tr>
<tr>
<td>Thin-film organic polymer on sub-strate (Humicap), with precipitation shield</td>
<td>FIN</td>
<td></td>
<td></td>
<td></td>
<td>OCAN</td>
</tr>
<tr>
<td>Gold-beater's skin in duct</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time constant (secs), 1000hPa &amp; 25°C</td>
<td>1 6</td>
<td>&lt;2</td>
<td>&lt;2</td>
<td>&lt;2</td>
<td>&lt;2</td>
</tr>
</tbody>
</table>

* Negligible

△ Same device

+ Premium Baroswitch

© Premium Baroswitch used on some flights, regular baroswitch used for remainder of flights.
### TABLE 3

**SIGNAL CHARACTERISTICS**

<table>
<thead>
<tr>
<th>TABLE 3</th>
<th>FIN</th>
<th>UK</th>
<th>USA</th>
<th>FRG</th>
<th>OCAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>DATA SAMPLING RATE</td>
<td>level (hPa)</td>
<td>1000</td>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>1.2</td>
<td>8</td>
<td>15 to 40</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>T</td>
<td>1.2</td>
<td>2</td>
<td>1.5 to 4</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>U</td>
<td>1.2</td>
<td>4</td>
<td>3 to 8</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Nominal time interval (seconds) between successive observations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>R1</td>
<td>1.2</td>
<td>24</td>
<td>15 to 80</td>
<td>?</td>
<td>4</td>
</tr>
<tr>
<td>R2</td>
<td>1.2</td>
<td>24</td>
<td>75 to 400</td>
<td>?</td>
<td>-</td>
</tr>
<tr>
<td>R3</td>
<td>1.2</td>
<td>24</td>
<td>--</td>
<td>--</td>
<td>?</td>
</tr>
<tr>
<td>internal Temp</td>
<td>1.2</td>
<td>*</td>
<td>--</td>
<td>--</td>
<td>?</td>
</tr>
<tr>
<td>RADIO-FREQUENCY BAND (MHz)</td>
<td></td>
<td>403</td>
<td>28</td>
<td>1680</td>
<td>403</td>
</tr>
<tr>
<td>CRYSTAL CONTROL</td>
<td></td>
<td>UK</td>
<td></td>
<td>FRG</td>
<td></td>
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<tr>
<td>POWER (mW)</td>
<td></td>
<td>250</td>
<td>400</td>
<td>300</td>
<td>350</td>
</tr>
<tr>
<td>FORM OF MODULATION</td>
<td></td>
<td>FM</td>
<td>AM</td>
<td>AM</td>
<td>FM</td>
</tr>
<tr>
<td>BANDWIDTH (kHz)</td>
<td></td>
<td>400</td>
<td>45</td>
<td>1000</td>
<td>30</td>
</tr>
<tr>
<td>MODULATING SIGNAL</td>
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<tr>
<td>audio lowest (Hz)</td>
<td></td>
<td>3500</td>
<td>10</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>square-wave highest (Hz)</td>
<td>9500</td>
<td>7500</td>
<td>190</td>
<td>2200</td>
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<tr>
<td>Digital (baud)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**NOTES:**

* The interval is determined by the baroswitch and increases with decreasing pressure.

* The internal temperature is estimated as a function of the external temperature and elapsed time, the function being based upon flight and laboratory experiment.

* Includes retransmission of OMEGA Navaid signals received by the radiosonde.

* The bandwidth for PTU data alone is 52 kHz.

* Although not used at the intercomparison, a few stations include a 75 kHz signal to provide range data for wind-finding.
TABLE 4
SOURCES OF THE RADIOSONDES

<table>
<thead>
<tr>
<th></th>
<th>Source</th>
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</thead>
<tbody>
<tr>
<td>RS 80-15 N</td>
<td>Vaisala Oy, Finland</td>
</tr>
<tr>
<td>RS 3</td>
<td>UK Meteorological Office</td>
</tr>
<tr>
<td>V 1392-510</td>
<td>VIZ Manufacturing Co, USA</td>
</tr>
<tr>
<td>G 78 C</td>
<td>Graw Messgerate GmbH, FRG</td>
</tr>
<tr>
<td>1524-511</td>
<td>Beukers Laboratories Inc, USA</td>
</tr>
<tr>
<td></td>
<td>(subsequently VIZ Manufacturing Co, USA)</td>
</tr>
</tbody>
</table>

TABLE 5
FLIGHTS ACHIEVED

<table>
<thead>
<tr>
<th>Nominal Time (GMT)</th>
<th>00</th>
<th>04</th>
<th>08</th>
<th>12</th>
<th>16</th>
<th>20</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Flights</td>
<td>26</td>
<td>10</td>
<td>12</td>
<td>28</td>
<td>10</td>
<td>14</td>
<td>100</td>
</tr>
</tbody>
</table>