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SECOND EVALUATION OF VAISALA GPS RADIOSONDE SYSTEM, CAMBORNE. (28 October to 6 November 1996)

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(Meteorological Office ,Bracknell,Berks,RG12 2SZ)

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1. INTRODUCTION

The network of world-wide Omega navigation transmissions is due to cease in September 1997. This will necessitate replacement of the windfinding systems at some of the overseas radiosonde stations deployed by the UK. In the short term the need to replace the obsolete groundstation in the Falklands has become the first priority. Of the alternative windfinding systems, Loran-C Navaid is unavailable in the required areas (Falklands, St Helena, Gibraltar). Use of radiotheodolite systems has been precluded because of poor wind measurement accuracy at low elevation angles , the costs of on site maintenance and the additional capital expenditure necessary to buy the radiotheodolite.

Vaisala and AIR GPS windfinding systems were originally tested by Met. Office staff during the week 15 to 19 January 1996, (Elms [1]). Following that test, various improvements have been made to the Vaisala GPS windfinding system. The purpose of this second test was to re-evaluate the windfinding accuracy and operational reliability of the Vaisala GPS radiosonde system. This was to be evaluated against the specification placed in the European Journal for application for the contract to replace existing UK controlled Omega windfinding upper air systems. The test was arranged between Vaisala Oy, and the UK Met Office. The company provided the groundstation and 22 GPS radiosondes. Vaisala representatives operated the system during the test. 21 GPS radiosondes were flown and one was kept by the Met Office for later reference. This report summarises the results of all 21 soundings, the majority of which were made in comparison with simultaneous radar and Loran measurements.

The weather during the trial week was ideal for testing the radiosonde system in a wide range of conditions. These included land gales on the first day when surface winds gusted to 70 knots during the passage of ex hurricane "Lilly". The winds moderated by mid-week as a ridge of high pressure built prior to the return of frontal systems on the last 2 days. There was little precipitation apart from some drizzle on Day 4. (Various surface analyses made during the week are shown in Annexe 2 and launch time WMO weather codes for each ascent are given in column 11, Annexe 3)

2. THE VAISALA GPS SYSTEM

2.1. Vaisala GPS Radiosonde RS80-15G.

The Vaisala GPS radiosonde is an RS80 radiosonde attached to a GPS 111 receiver module. This increases the size of the standard RS80 radiosonde by about 30 per cent, but would not be expected to adversely affect its ease of handling, if used in the Falklands. Measurements of pressure, temperature and humidity are obtained from sensors similar to those used in the operational RS80L Loran radiosonde . The Vaisala GPS radiosonde still incorporates a pressure element and does not attempt to report height from the GPS signals. These GPS transmissions are digitally modulated spread spectrum signals on 2 carrier frequencies (1.226 GHz and 1.575 GHz). The 1.575 GHz carrier is modulated by a satellite-specific pseudo random noise (PRN) code which effectively spreads the spectrum to 2 MHz.

The Vaisala system determines the differential velocity between the radiosonde and the ground system using the Doppler frequency shift between the GPS signals received by the radiosonde and those received at the ground. The GPS signals received by the radiosonde are detected by a Digital Signal Detector in the GPS 111 which removes the BPSK modulation of the satellite signal using a codeless technique. The Doppler frequency of received signal is extracted and then transmitted to the groundstation as a digital signal with the carrier frequency of the radiosonde modulated with 1200 baud FSK signals .

A minimum of four satellites are required for three dimensional velocity determination of the radiosonde and consequently for windfinding. However more than four satellites will be necessary if several of the satellite signals are received from similar directions. (The restriction on location accuracy imposed by the direction of reception of the signals is known as the Geometrical Dilution of Precision (GDOP)).

2.2 Vaisala GPS Groundstation.

The groundstation used at Camborne consisted of a standard Vaisala MW15 unit comprising receiver and computer. The GPS module within the MW15 computed the instantaneous wind values from the data received from the radiosonde. The operator interface to this module was provided by touch pads on the front of the MW15 as in previous "Digicora" systems. Displays of wind and PTU profiles were obtained from a PC linked to the MW15 using "MetGraph" software. A schematic diagram of the Vaisala GPS system is shown in Annexe 1.

3. TRIAL PROGRAM AND DATA ACQUISITION

3.1 The Trial Program

The GPS radiosonde was flown in 3 different configurations:-

(I) 6 ascents were made with the radiosonde suspended from a Totex parachute underneath a 350 g balloon (this configuration being similar to that used in the Falklands). 60 m of suspension was provided by a Vaisala unwinder. These tests were used to check the system under normal conditions of operation.

(ii) 4 ascents were made using larger balloons to lift a radar target as well as the GPS radiosonde. An unwinder was fixed to the bottom of the target to deploy the 60 m suspension to the GPS radiosonde. This configuration was used when conditions were too severe to launch 2 radiosondes.

(iii) In the remaining 11 ascents an RS80 Loran radiosonde was suspended 30 m below the radar target. On these ascents the GPS radiosonde unwinder provided a further (30m only) suspension underneath the Loran radiosonde .

Thus the GPS radiosonde was always suspended 60m below the balloon as recommended by the manufacturer for this test.

Annexe 3 is the ascent log for the test flights , including burst pressures, flight duration , delay between radiosonde preparation and launch , plus the availability of other measurements for comparison with the GPS measurements.

3.2 Data Synchronisation.

Radar and Loran winds were derived from 2 independent Vaisala PC-CORA groundstation systems .These two systems were synchronised from a pulse initiated by a remote button press on launch. The PC-CORA system interfaced with the radar was used in "Pilot" mode to record the raw radar data . (Radar winds evaluated by the PC-CORA system were not used in the analyses). The MW15 system timing was synchronised with PC-CORA using its own start switch. Timing corrections to adjust for differences in height of the radiosondes were not applied for wind comparisons as both radiosondes suspended below the balloon were assumed to be following the balloon movement. However, timing corrections for winds were required on 2 occasions when the MW15 timing switch was depressed a few seconds later than the remote start button.

Timing corrections to the pressure, temperature and humidity data were applied on all Loran v GPS comparison ascents to compensate for the 30m suspension difference between the GPS and Loran radiosondes (see column 19 of Annexe 3).

3.3 Wind Data Acquisition and Quality Control.

Vaisala RS80 radiosondes sample pressure, temperature and relative humidity approximately every 1.3 seconds. GPS raw wind data were recorded every 0.5 seconds and Loran phase derivatives were recorded every 10 seconds. The Cossor radar slant range, azimuth and elevation were recorded every 1 second by the PC-CORA groundstation.

In order to compare fine structure in the measurements the Vaisala data were interpolated to 2 second intervals from launch time and archived in a 2 Second Database. "RSKOMP" software devised by Kurnosenko [2] for use in WMO Radiosonde Comparisons was used to display and analyse the archived data. The amount of data excluded from statistical analyses of the results was kept to a minimum. Reasons for all excluded data are given in the Remarks column of Annexe 3. Where GPS winds were interpolated due to gaps in the received satellite data these were noted, but not excluded from the statistics unless it was clear that the operator would have diagnosed faulty data from a single sounding.

3.3.1 Radar Winds

Unlike the previous Vaisala GPS tests when the EHT was switched off until 5 minutes into flight, the radar was powered for tracking from launch time. 3.4 per cent of the radar data were excluded or missing. During the first afternoon of the Trial, the land gales caused a power outage during Flight 2. 18 minutes of radar data were missed whilst the EHT was reset ,the target was reacquired and the PC-CORA quality checks allowed the raw radar data to resume. A Data Processing Unit (DPU) fault (or possible bearing servo fault) affected small sections (11 minutes total) of Flights 7 and 9 causing an indeterminate shift in the bearing data recorded. These bearing errors produced erroneous winds which were subsequently erased from the archive.

Reference winds were computed independently from the PC-CORA raw radar archive using a Met Office program , UAWNDS. UAWNDS evaluates winds in a similar way to the PC-CORA software , except where winds are interpolated through gaps in the radar data. Both PC-CORA and UAWNDS programs fit 60 second least squares straight lines to the raw radar data, but the

PC-CORA system also fits a cubic spline to the resultant winds. This cubic spline can produce anomalies when interpolating through missing data.
Anomalies often occur during the first minutes of an ascent. Thus UAWNDS output was also preferred as a reference for the lowest level winds. The algorithms used by UAWNDS do not permit wind calculations until at least 15 seconds of optical tracking/radar data are available. Thus radar wind data were unavailable in the first 20 seconds of the ascents on most occasions.

3.3.2. Loran Winds

No Loran wind measurements were excluded, although about 3.5 per cent of the total Loran winds measured were labelled as "interpolated" by the PC-CORA system. In one extreme situation during Flight 16, 2.5 minutes of Loran winds were interpolated in a region of strong wind shear. This deficiency in Vaisala Loran processing has been observed on many occasions in previous UK flights.

3.3.3. GPS Winds

Only 1 per cent of the wind data has been excluded (the last 9 minutes of flight 20 and the last 7 minutes of flight 21) from the 20 GPS ascents in the statistical analyses. Large amounts of interpolation of the GPS winds at levels above 10 hPa and ranges greater than 150 km on these two ascents indicated to the operator that these data should not be reported in the message. All other interpolated GPS winds (2 per cent of total data), including the low level interpolations, have been used in the statistics.

Of the 21 GPS flights, only one (Flight 12), could be considered as a "failure". Winds on this ascent were not available until 6 minutes 40 seconds into flight. This time gap exceeds the limit set for interpolated data used in operational practice in the UK. Winds were then obtained until about 13 minutes before burst, as shown in the comparison profiles in Figure 7. The computed GPS winds also showed an uncharacteristic mean bias of about 0.5 $m.s^{-1}$ in the E-W component when compared with either radar or Loran winds. This ascent would have required repeating due to the loss of low level wind data and, because of the anomalies, has been entirely excluded from the wind statistics. It is possible that the GPS radiosonde used in Flight 12 may have been more susceptible to radio frequency interference from the Cossor radar than the other radiosondes supplied.

4. WIND REFERENCE MEASUREMENTS

4.1 Quality of Radar Winds.

The Cossor radar used to provide the reference wind measurements at Camborne is one of the few remaining radars currently used in the UK for windfinding. Tests in 1984 of the windfinding performance of this type of radar showed that the RMS vector errors in the wind vary from about 0.4 $m.s^{-1}$ at 20km range to 1.5$m.s^{-1}$ at 80km, Edge et al.,[3] .These results were derived by tracking the same balloons with Cossor radars separated by 50 km at Bracknell and Crawley (West Sussex). Operational RS3 radiosonde software was used to compute winds and this used a lower sample rate for the raw radar data than the PC-CORA or UAWNDS software.

In the last 2 years winds from the Aberporth (West Wales) Cossor radar have been compared with winds from a high precision tracking radar at the same site. 4 comparison flights have been made.

The results showed that RMS errors in the Cossor winds computed using UAWNDS software were significantly smaller than those found in 1984. These results are presented in Figures 1(a) and (b) as the standard deviation of the differences between Cossor and high precision radar wind for wind components resolved parallel (along) and perpendicular (across) the radar beam. The errors in the Cossor winds across the radar beam are expected to be linearly related to slant range if errors in azimuth tracking are independent of elevation , see Nash [4]. The results in 1(b) would be produced by an effective random error of 0.2° in Cossor azimuth measurements. For winds measured along the radar beam , errors in Cossor elevation cause the wind errors to increase as the height of the target increases , see Nash [4] and the results in Figure 1(a) correspond to short term random errors in elevation of less than 0.1°.

The derivation of these errors is given in Annexe 4. These comparisons with the High Precision Radar show that the RMS vector errors can be reduced from their original 1984 estimates to about 0.2 $m.s^{-1}$ at 20km range to 0.8 $m.s^{-1}$ at 90km.

The Cossor radar at Camborne has been regularly checked and maintained and its tracking accuracy is therefore regarded as at least as good as the radars of the same type used in earlier tests. During the GPS test the mean flat range was about 75 km at 100 hPa increasing to about 110km at 10 hPa. Maximum flat ranges on individual flights varied between 45km and 230 km and minimum elevations varied between 7 and 23 degrees. Estimates of the radar error (1 sd) in each component are shown on the statistical analyses in Figures 14(a) and 14(b), given that on average the wind direction was within 25° of 270° for this trial.

4.2 Quality of Loran Winds.

The Loran windfinding used transmissions from the following 2 chains:-
FRENCH CHAIN GRI 8940
Lessay (Master) , Soustons (1st slave) , Sylt (2nd slave)
NORWEGIAN CHAIN GRI 9007
Ejde (Faeroes) (Master), Jan Mayen (1st slave),Bo (Norway) (2nd slave), Vaerlandet (Norway)(3rd slave).

The RS80-L Loran radiosondes (all from identical calibration batch 6321) performed very well throughout the Trial. Loran wind data were obtained to burst on all ascents. The Loran line fitting length was set to 60 seconds at all flight levels throughout the Trial.

Experience has shown that Loran radiosonde windfinding at Camborne degrades slightly when transmissions from Sylt are not received. This is especially true if there are few other transmissions available. During this Trial, timing signals from all 7 stations in the 2 chains were received for most of the ascents and transmissions from Sylt were received on all flights.

The RMS vector error in the Loran wind components would be expected to be in the range 0.5 $m.s^{-1}$ in the troposphere and up to 1 $m.s^{-1}$ at long ranges in the stratosphere. (Oakley and Nash[5]).

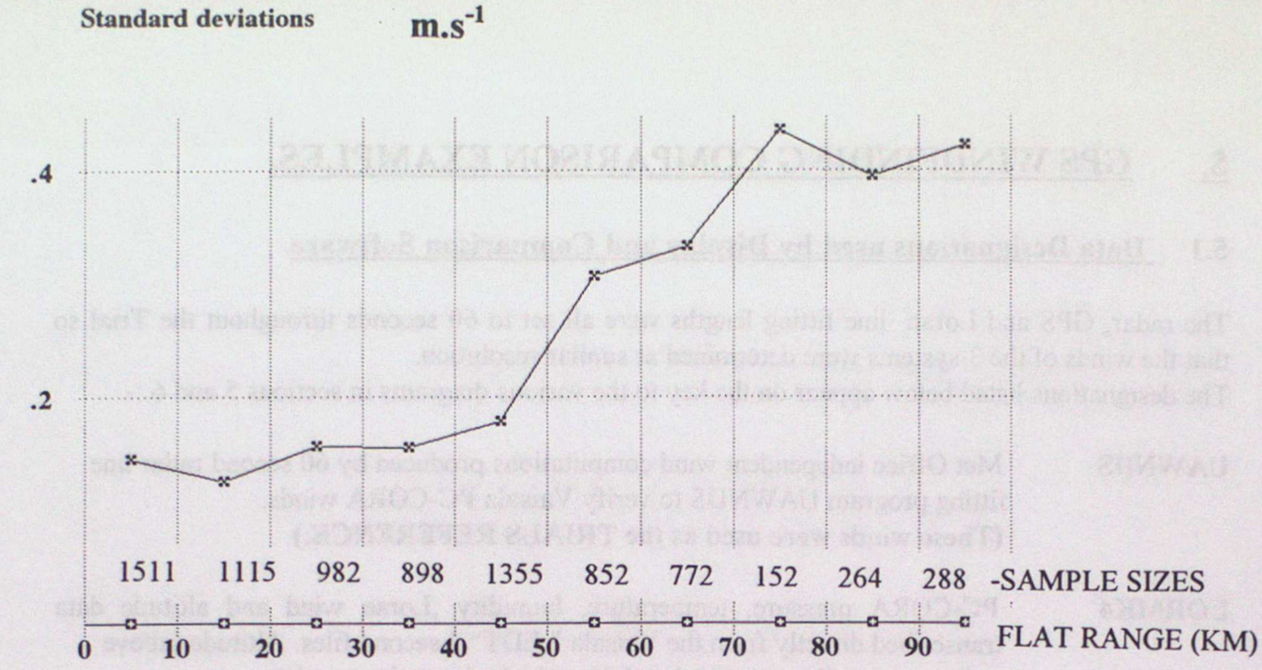


FIGURE 1(a)

HIGH PRECISION RADAR TRIAL -
STANDARD DEVIATION OF (COSSOR - HIGH PRECISION) RADAR WIND COMPONENTS MEASURED ALONG THE RADAR BEAM

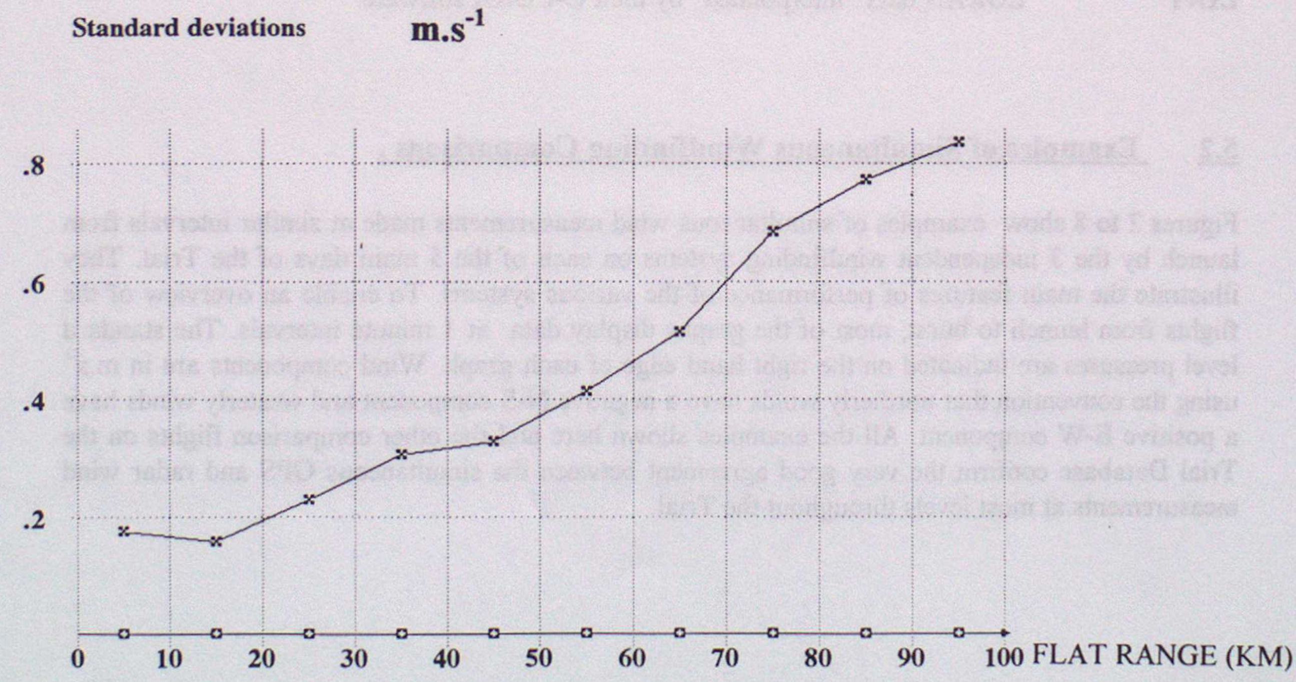


FIGURE 1(b)

HIGH PRECISION RADAR TRIAL -
STANDARD DEVIATION OF (COSSOR-HIGH PRECISION) RADAR WIND COMPONENTS MEASURED ACROSS THE RADAR BEAM

5. GPS WINDFINDING COMPARISON EXAMPLES.

5.1 Data Designations used by Display and Comparison Software

The radar, GPS and Loran line fitting lengths were all set to 60 seconds throughout the Trial so that the winds of the 3 systems were determined at similar resolution.
The designations listed below appear on the key to the various diagrams in sections 5 and 6 :-

UAWNDS Met Office independent wind computations produced by 60 second radar line fitting program UAWNDS to verify Vaisala PC-CORA winds. **(These winds were used as the TRIALS REFERENCE.)**

LORMK4 PC-CORA pressure, temperature, humidity ,Loran wind and altitude data transcribed directly from the Vaisala ".EDT" 2 second files. Altitude (above mean sea level) was calculated from the hydrostatic equation.

VAISGPS The Vaisala GPS radiosonde data transcribed directly from the Vaisala "EDT" 2 second files.

GPSRAW The Vaisala RAW GPS winds extracted every 2 seconds from launch from raw 0.5 second data provided by Vaisala Oy. (**These data not usually available in operational systems**).

OPT Independent winds obtained at 15 second intervals from optical theodolite.

VGINT GPS data "interpolated" by the MW15 software.

LINT LORAN data "interpolated" by the PC-CORA software.

5.2 Examples of Simultaneous Windfinding Comparisons .

Figures 2 to 8 show examples of simultaneous wind measurements made at similar intervals from launch by the 3 independent windfinding systems on each of the 5 main days of the Trial. They illustrate the main features of performance of the various systems. To enable an overview of the flights from launch to burst, most of the graphs display data at 1 minute intervals. The standard level pressures are indicated on the right hand edge of each graph. Wind components are in $m.s^{-1}$ using the convention that northerly winds have a negative N-S component and westerly winds have a positive E-W component. All the examples shown here and the other comparison flights on the Trial Database confirm the very good agreement between the simultaneous GPS and radar wind measurements at most levels throughout the Trial.

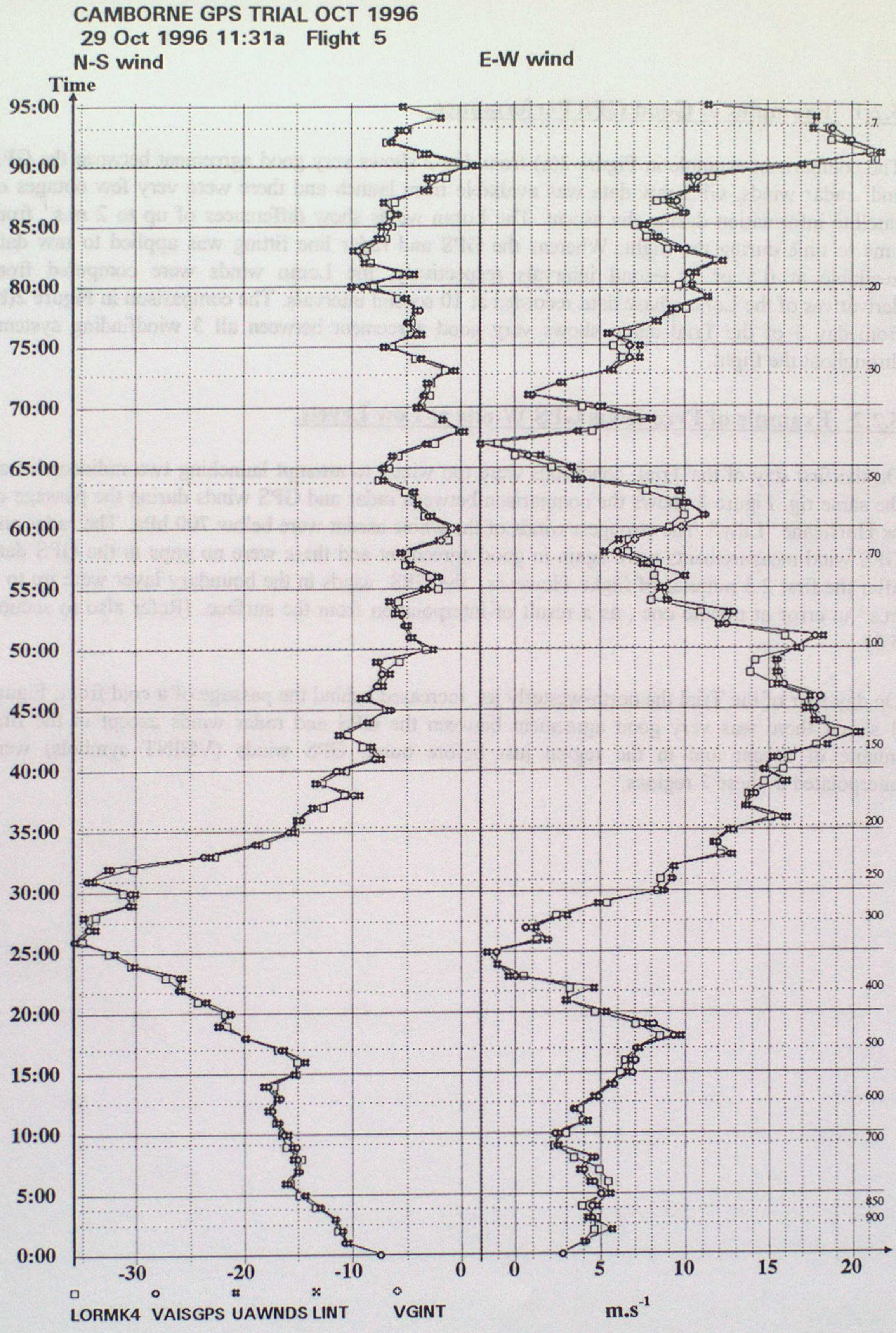
5.2.1 Examples of Good GPS Performance.

The comparison example in Figure 2(a) from day 2 shows very good agreement between the GPS and radar winds. GPS raw data was available from launch and there were very few outages of satellite information during the ascent. The Loran winds show differences of up to 2 $m.s^{-1}$ from time to time during the flight. Whereas the GPS and radar line fitting was applied to raw data available at 0.5 or 1 second intervals respectively, the Loran winds were computed from derivatives of the Loran phase data recorded at 10 second intervals. The comparison in Figure 2(b) from day 3 of the Trial again shows very good agreement between all 3 windfinding systems throughout the flight.

5.2.2 Example of Erroneous GPS Winds at Low Levels.

On the first day of the Trial, conditions were too windy to attempt launching two radiosondes on the same rig. Figure 3 shows the comparison between radar and GPS winds during the passage of ex Hurricane "Lilly". The strongest winds of the whole ascent were below 700 hPa. The radar and GPS wind measurements were again in good agreement and there were no gaps in the GPS data after the first 2.5 minutes of flight. However, the GPS winds in the boundary layer were up to 9 $m.s^{-1}$ in error at minute one , as a result of interpolation from the surface. (Refer also to section 5.3)

On day four of the Trial the north-westerly jet increased behind the passage of a cold front. Figure 4 shows there was very good agreement between the GPS and radar winds except in the first minute of ascent and in the region just before burst. GPS winds (VGINT symbols) were interpolated in these 2 regions.



CAMBORNE GPS TRIAL OCT 1996
29 Oct 1996 11:31a Flight 5
N-S wind
E-W wind
Time
95:00
90:00
85:00
80:00
75:00
70:00
65:00
60:00
55:00
50:00
45:00
40:00
35:00
30:00
25:00
20:00
15:00
10:00
5:00
0:00
-30
-20
-10
0
0
5
10
15
20
7
10
20
30
50
70
100
150
200
250
300
400
500
600
700
850
900
LORMK4 VAISGPS UAWNDS LINT VGINT
m.s-1

FIGURE 2(a)

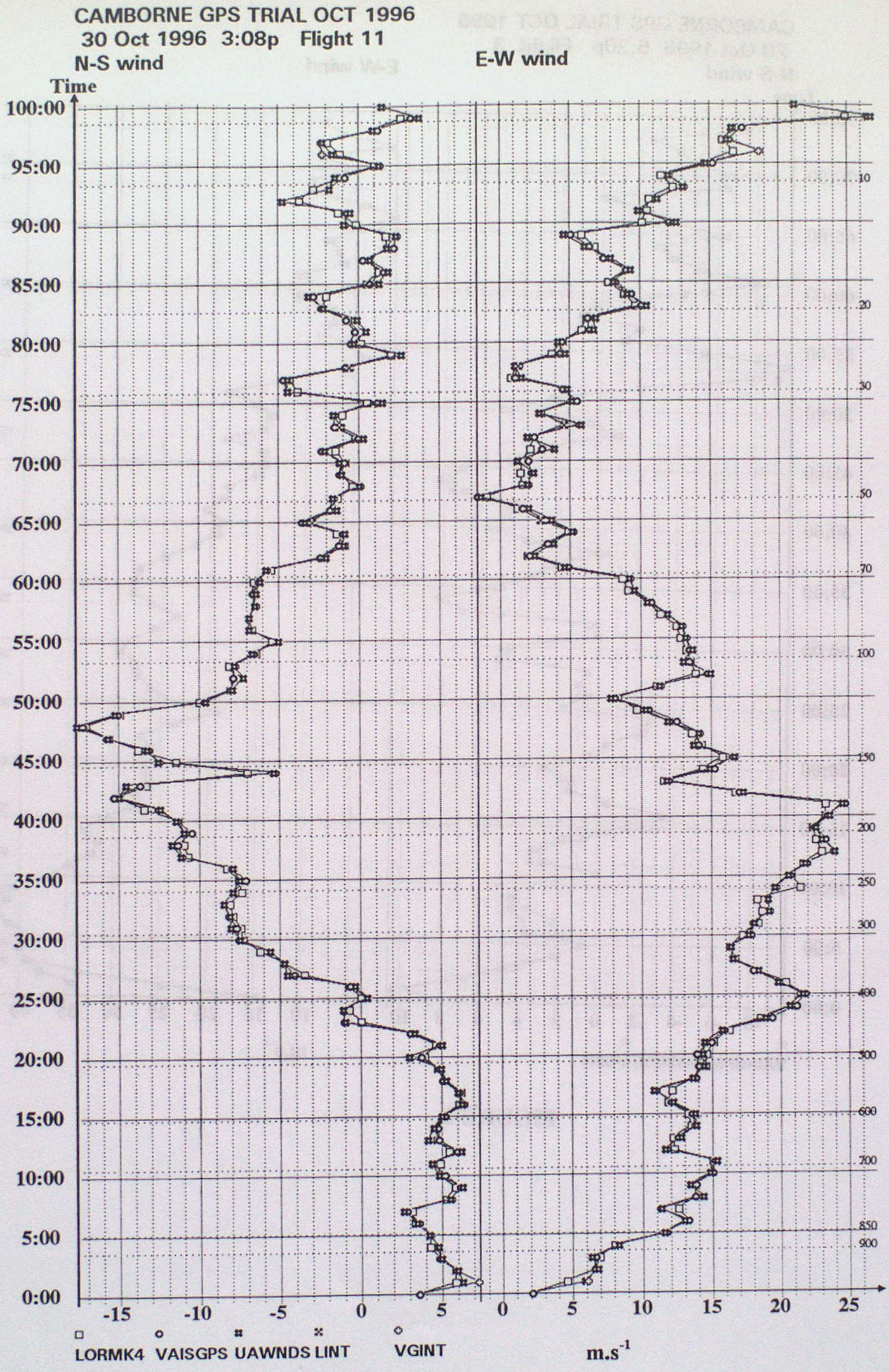
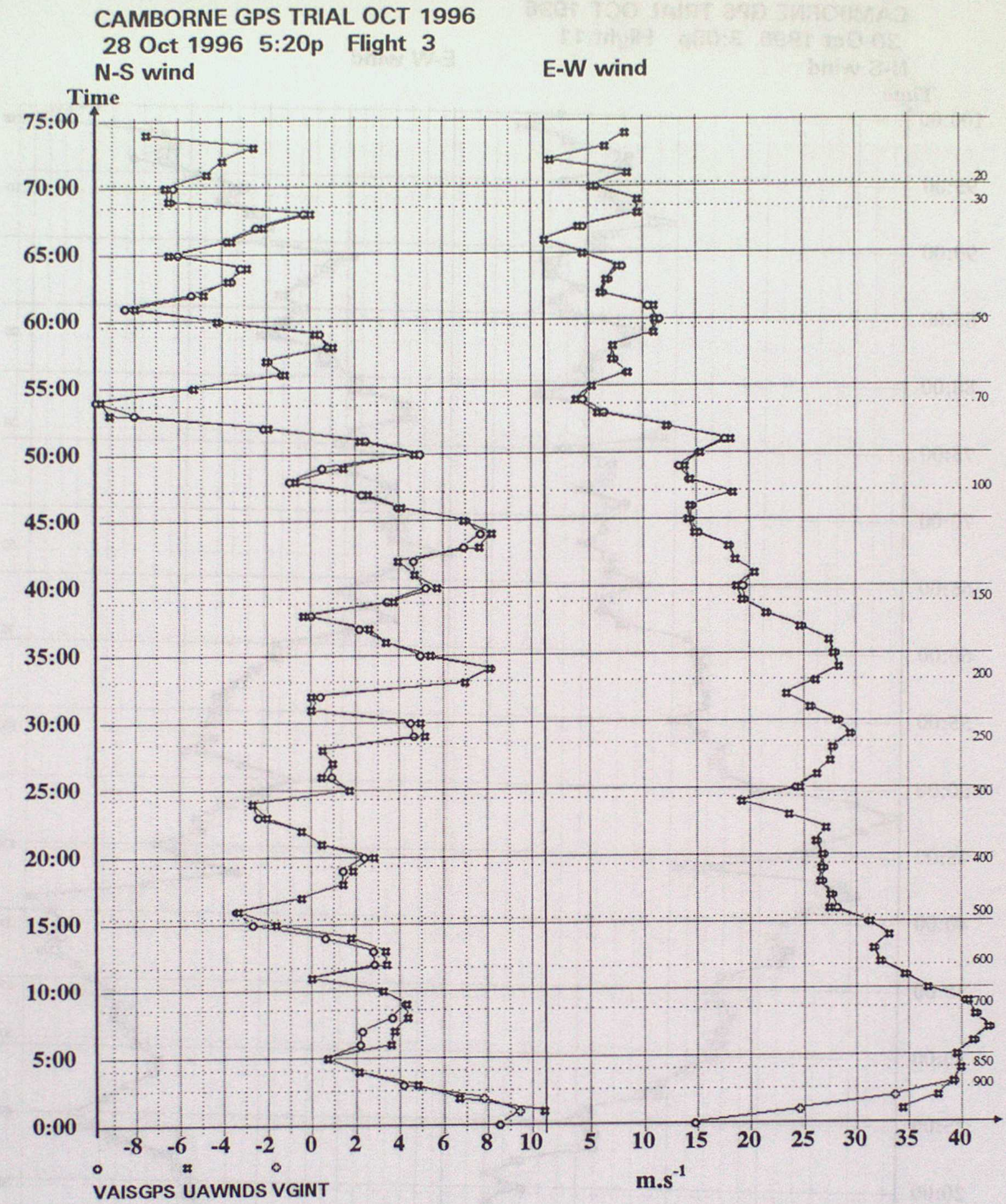

CAMBORNE GPS TRIAL OCT 1996
30 Oct 1996 3:08p Flight 11
N-S wind
E-W wind
Time
100:00
95:00
90:00
85:00
80:00
75:00
70:00
65:00
60:00
55:00
50:00
45:00
40:00
35:00
30:00
25:00
20:00
15:00
10:00
5:00
0:00
-15 -10 -5 0 5
0 5 10 15 20 25
10
20
30
50
70
100
150
200
250
300
400
500
600
700
850
900
LORMK4 VAISGPS UAWNDS LINT VGINT
m.s-1

FIGURE 2(b)



CAMBORNE GPS TRIAL OCT 1996
28 Oct 1996 5:20p Flight 3
N-S wind
E-W wind
Time
75:00
70:00
65:00
60:00
55:00
50:00
45:00
40:00
35:00
30:00
25:00
20:00
15:00
10:00
5:00
0:00
-8 -6 -4 -2 0 2 4 6 8 10
5 10 15 20 25 30 35 40
m.s-1
VAISGPS UAWNDS VGINT
20
30
50
70
100
150
200
250
300
400
500
600
700
850
900

FIGURE 3

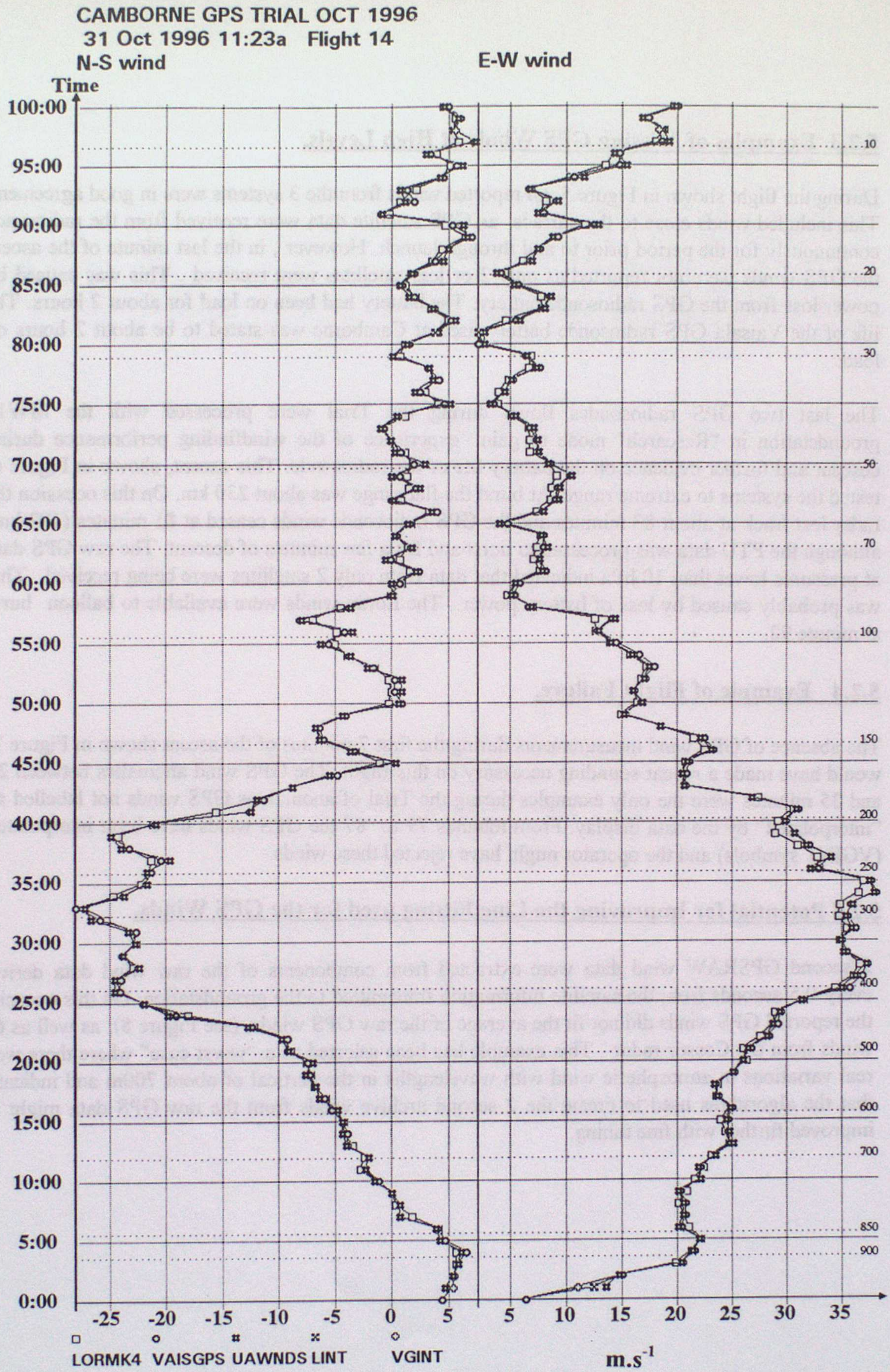

CAMBORNE GPS TRIAL OCT 1996
31 Oct 1996 11:23a Flight 14
N-S wind
E-W wind
Time
100:00
95:00
90:00
85:00
80:00
75:00
70:00
65:00
60:00
55:00
50:00
45:00
40:00
35:00
30:00
25:00
20:00
15:00
10:00
5:00
0:00
10
20
30
50
70
100
150
200
250
300
400
500
600
700
850
900
-25 -20 -15 -10 -5 0 5
5 10 15 20 25 30 35
LORMK4 VAISGPS UAWNDS LINT VGINT
m.s-1

FIGURE 4

5.2.3 Examples of Missing GPS Winds at High Levels.

During the flight shown in Figure 5, all reported winds from the 3 systems were in good agreement. This included winds close to the surface as GPS satellite data were received from the radiosonde continuously for the period prior to and through launch. However , in the last minute of the ascent the GPS winds were not reported as only 2 or less satellites were received . This was caused by power loss from the GPS radiosonde battery. The battery had been on load for about 2 hours. The life of the Vaisala GPS radiosonde battery used at Camborne was stated to be about 2 hours on load.

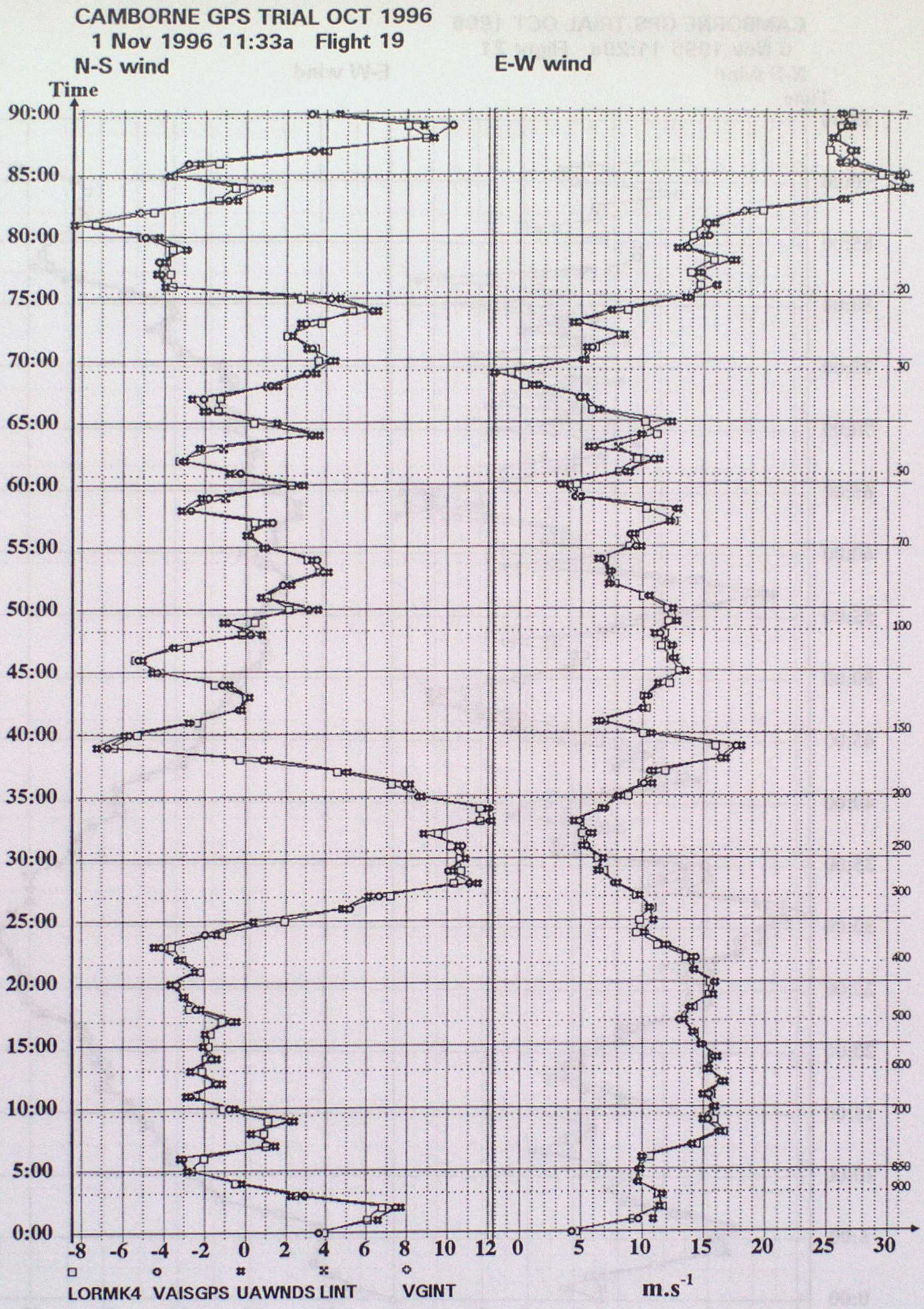
The last two GPS radiosondes flown during the Trial were processed with the MW15 groundstation in "Research" mode to gain experience of the windfinding performance during descent and further evidence on the battery life of the radiosonde. This ascent, shown in Figure 6, tested the systems to extreme range. At burst the flat range was about 230 km. On this occasion the radar lost track at about 83 minutes and the GPS radiosonde winds ceased at 81 minutes (193 km) although the PTU data was processed to burst and for a few minutes of descent. The raw GPS data at pressures lower than 10 hPa indicated that data from only 2 satellites were being received . This was probably caused by loss of battery power. The Loran winds were available to balloon burst at minute 92.

5.2.4 Example of Flight Failure.

The absence of GPS wind measurements during the first 7 minutes of the ascent shown in Figure 7, would have made a repeat sounding necessary on this flight. The GPS wind anomalies between 25 and 35 minutes were the only examples during the Trial of anomalous GPS winds not labelled as "interpolated" by the data display. From minutes 79 to 87 the GPS winds have been interpolated (VGINT symbols) and the operator might have rejected these winds.

5.2.5 Potential for Improving the Line Fitting used for the GPS Winds.

2 second GPSRAW wind data were extracted from components of the raw wind data derived every 0.5 seconds from the satellite information transmitted to the groundstation. On this occasion the reported GPS winds did not fit the average of the raw GPS winds, (see Figure 8), as well as the winds from the Cossor radar . This example has been selected as a "worst case" where there were real variations in atmospheric wind with wavelengths in the vertical of about 700m and indicates that the algorithms used to create the 2 second archive winds from the raw GPS data might be improved further with fine tuning.


CAMBORNE GPS TRIAL OCT 1996
1 Nov 1996 11:33a Flight 19
N-S wind
E-W wind
Time
90:00
85:00
80:00
75:00
70:00
65:00
60:00
55:00
50:00
45:00
40:00
35:00
30:00
25:00
20:00
15:00
10:00
5:00
0:00
-8 -6 -4 -2 0 2 4 6 8 10 12
0 5 10 15 20 25 30
LORMK4 VAISGPS UAWNDS LINT VGINT
m.s-1
7
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850
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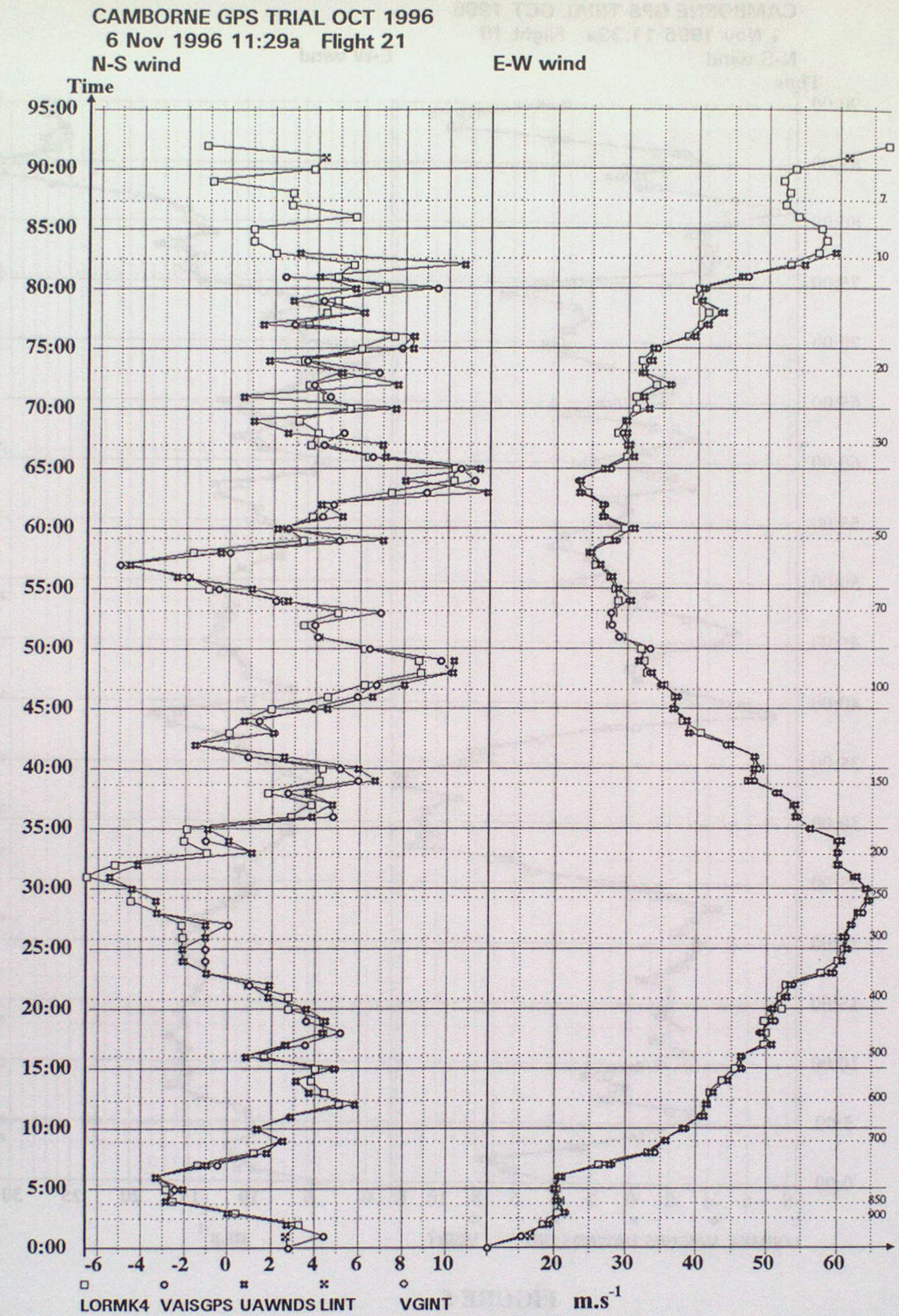
FIGURE 5


CAMBORNE GPS TRIAL OCT 1996
6 Nov 1996 11:29a Flight 21
N-S wind
E-W wind
Time
95:00
90:00
85:00
80:00
75:00
70:00
65:00
60:00
55:00
50:00
45:00
40:00
35:00
30:00
25:00
20:00
15:00
10:00
5:00
0:00
-6 -4 -2 0 2 4 6 8 10
20 30 40 50 60
LORMK4 VAISGPS UAWNDS LINT VGINT
m.s-1
7
10
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850
900

FIGURE 6

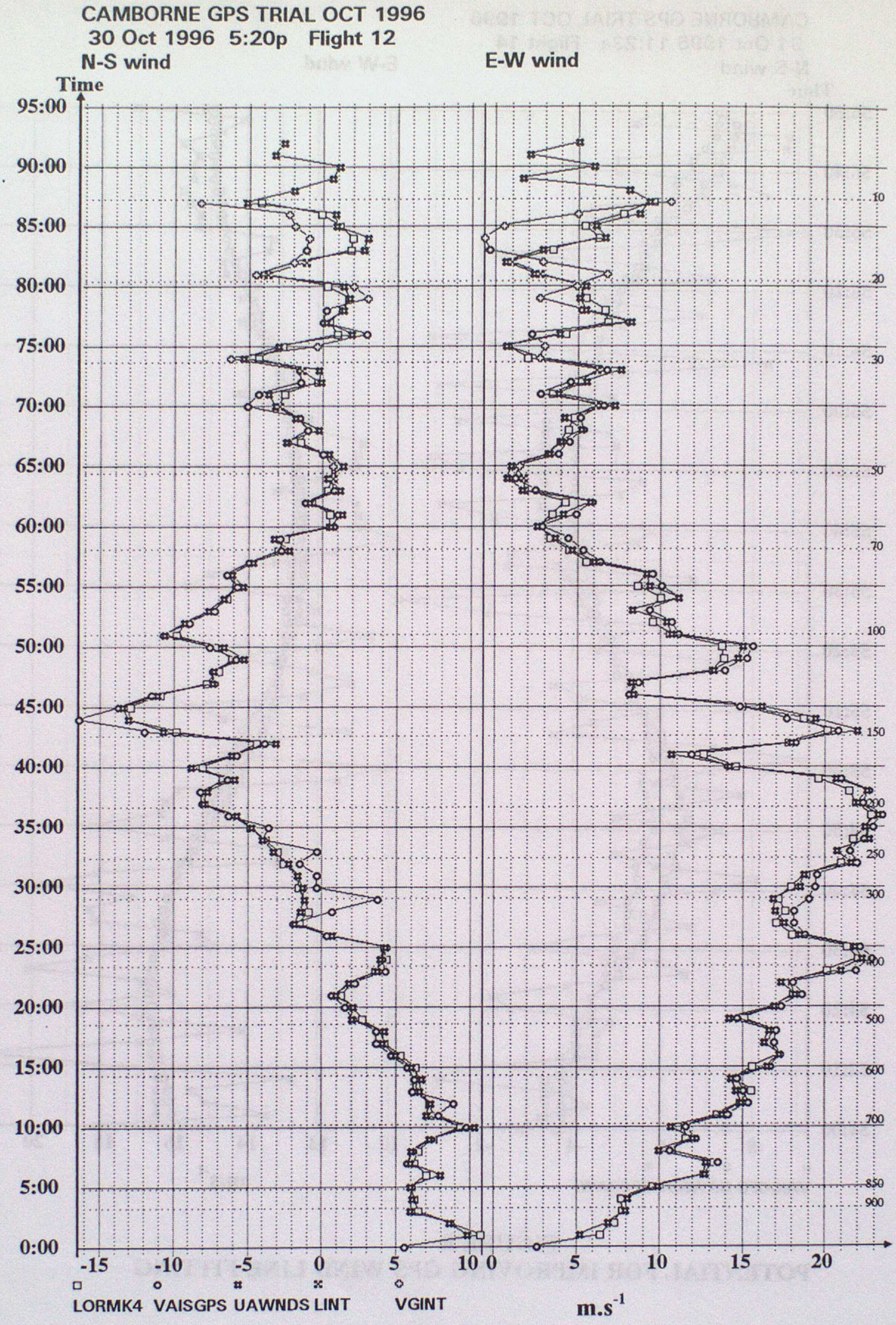

CAMBORNE GPS TRIAL OCT 1996
30 Oct 1996 5:20p Flight 12
N-S wind
E-W wind
Time
95:00
90:00
85:00
80:00
75:00
70:00
65:00
60:00
55:00
50:00
45:00
40:00
35:00
30:00
25:00
20:00
15:00
10:00
5:00
0:00
-15 -10 -5 0 5 10
0 5 10 15 20
LORMK4 VAISGPS UAWNDS LINT VGINT
m.s-1

FIGURE 7

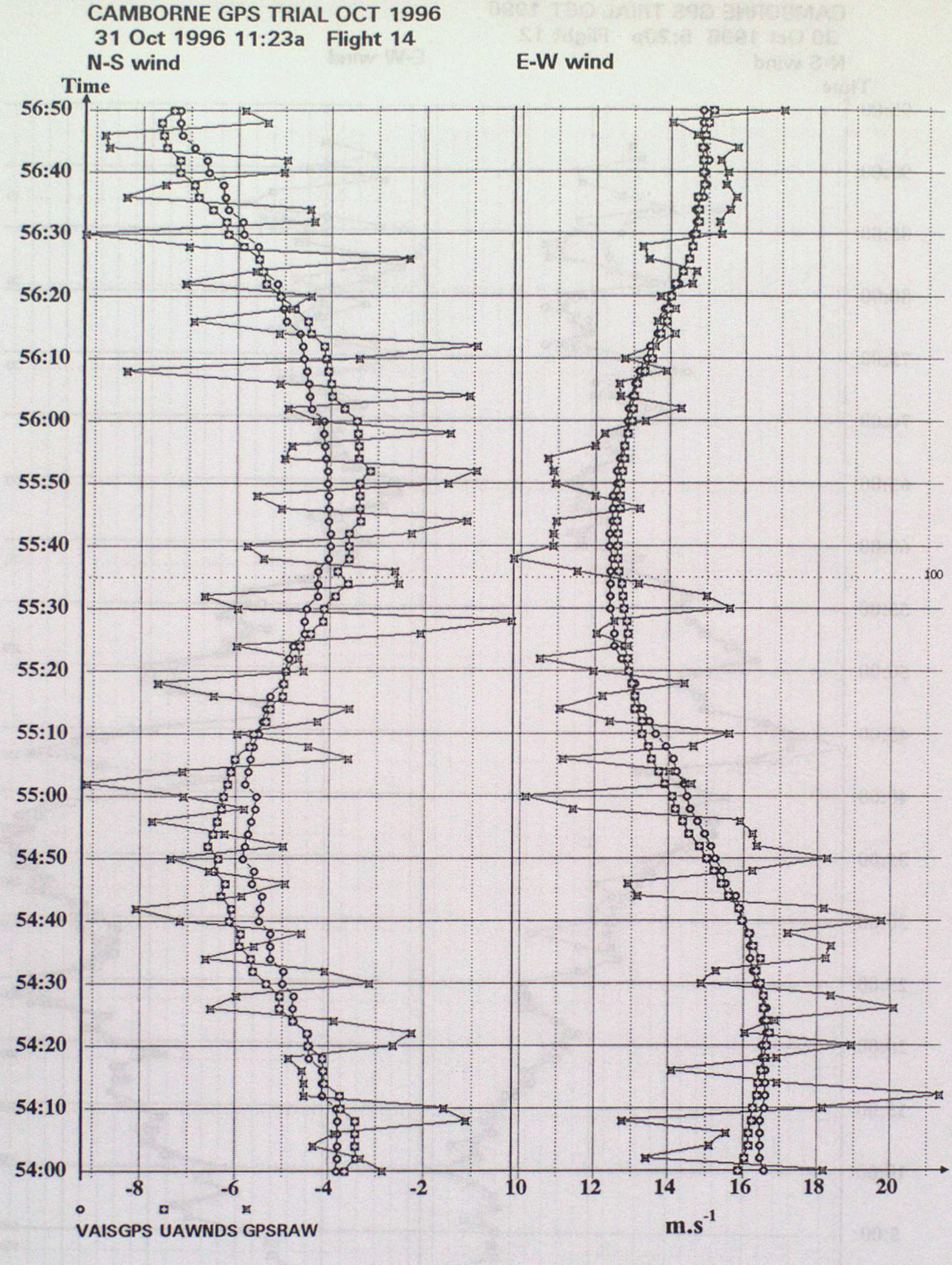


FIGURE 8
POTENTIAL FOR IMPROVING GPS WIND LINE FITTING

5.3 Low Level Windfinding.

Accurate determination of wind structure in the boundary layer is important for forecasting at some UK radiosonde stations and for Defence applications such as ballistics and acoustic forecasts. Cossor radar winds are not usually measured until about 90 seconds into flight. One minute on average is required for the radar to locate the target and a further 30 seconds to obtain sufficient positional data prior to the midpoint of a 60 second line fit to determine the balloon's movement. In order to supplement the low level radar windfinding information, an optical tracker is interfaced with the radar and groundstation computer at Camborne to provide balloon bearing and elevation data for the period from launch to radar target acquisition. Optical tracker data were used by the UAWNDS program to provide low level winds closer to the surface than with the standard PC-CORA software.

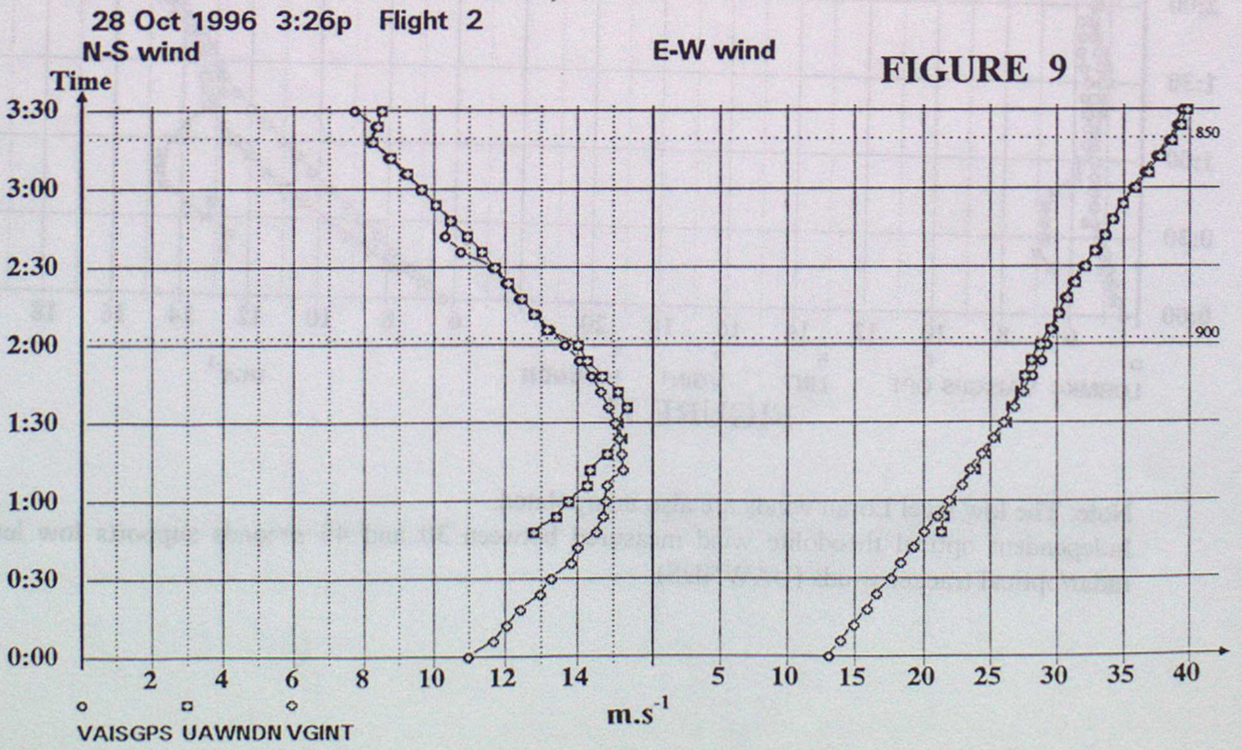
A completely independent optical theodolite was used to provide further confirmation of low level winds on 8 ascents (including flights 8 and 10 which were flown without radar or Loran reference data). The amount of additional data provided by both the optical tracker and the optical theodolite is given in columns 13 and 14 of Annexe 3. Unfortunately , optical theodolite observations could not usually be obtained earlier than 30 seconds into flight due to the large bearing and elevation changes occurring on launch. Low cloud or strong wind conditions also restricted the number of measurements. Optical theodolite measurements were calculated using plan positions computed every 15 seconds. The theodolite was also used to verify the optical tracker bearings and elevations. The theodolite and optical tracker were aligned with the sun and the elevations from the two instruments compared with each other and with astronomical values. As a result, a small correction of 1.4 degrees was added to all optical tracker elevations and 1.9 degrees was added to all optical tracker bearings.

5.3.1 Detailed Low Level Wind Profile Examples.

If GPS signal reception following launch was inadequate , the Vaisala GPS windfinding software interpolated between the surface wind input by the operator and the first valid GPS winds obtained. The first valid winds were often only available after one or two minutes of ascent. Column 16 of Annexe 3 summarises the duration of interpolation from launch.

Examples of detailed low level comparisons between UAWNDS and GPS measurements are shown in Figures 9 to 11. In Figure 9 , the radar measurements agree relatively well with the GPS , but in both Figures 10 and 11 the assumed interpolations between the ground and the first valid GPS wind led to large errors.

FIGURE 9



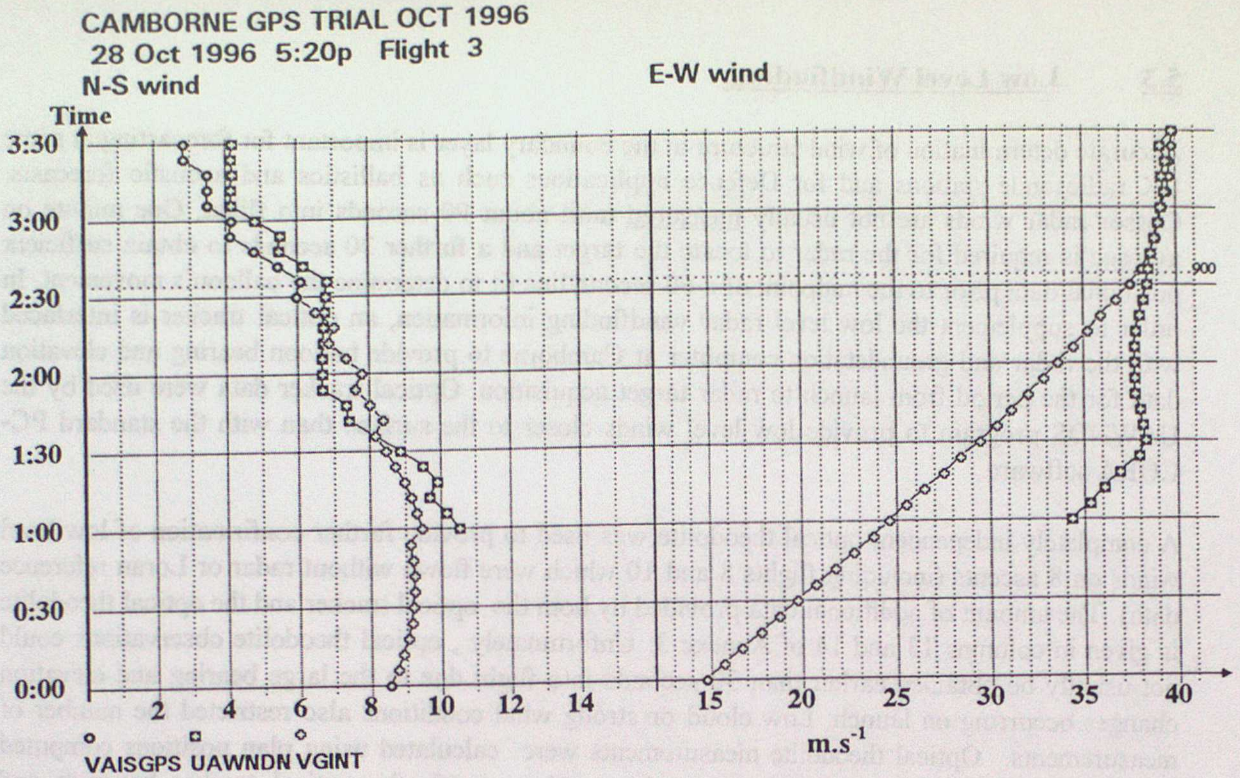


FIGURE 10

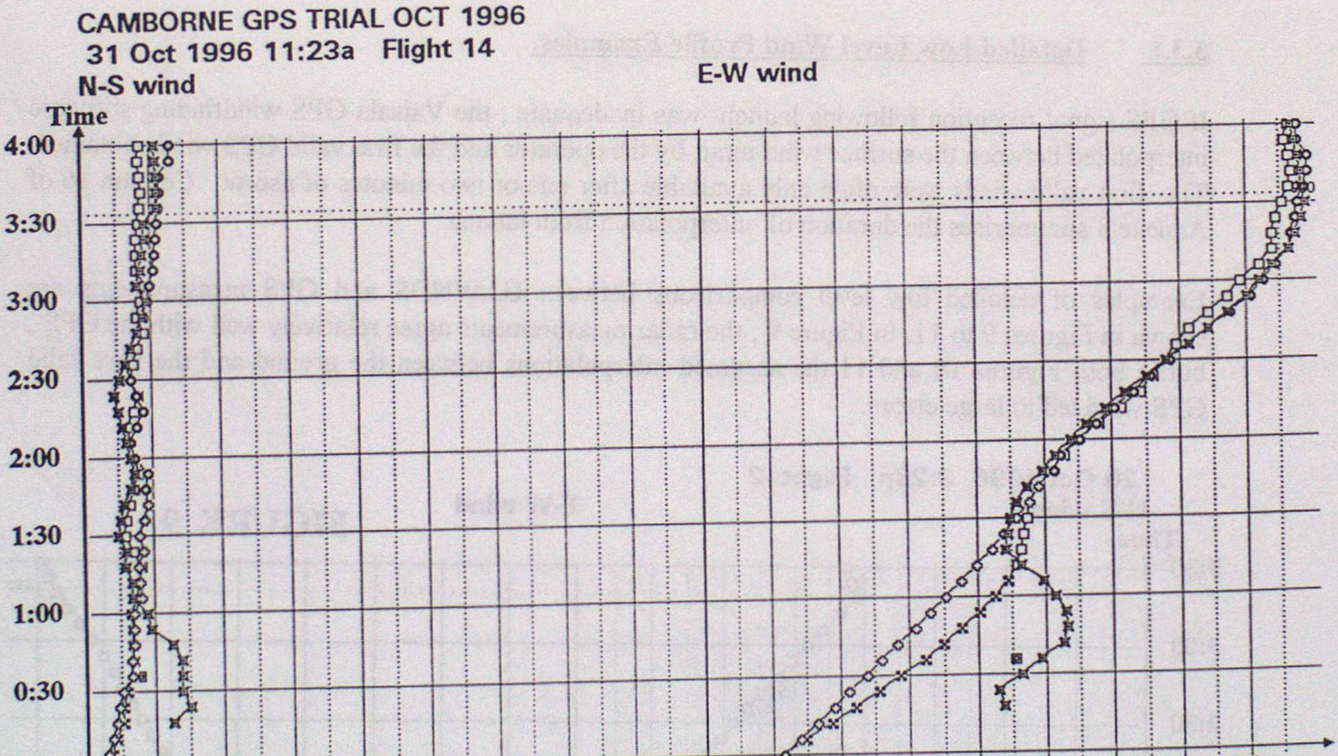


FIGURE 11

Note: The low level Loran winds are also interpolated.
Independent optical theodolite wind measured between 30 and 45 seconds supports low level radar/optical tracker winds (UAWNDS).

Figure 12 shows an example of the 0.5 second raw GPS data wind components extracted from the raw data (provided by Vaisala Oy) at 2 second intervals. This was an occasion when valid GPS data were being transmitted from the radiosonde to the groundstation prior to launch, at time 12 minutes 43 seconds. The reported GPS wind has been adjusted by the software to fit to the surface wind. This wind was obtained from a 10m anemometer mast located about 60m from the launch area and input by the operator. Thus the reported GPS data diverged significantly from the average raw GPS wind measurements by about 2 m.s^{-1} in the E-W component in the first 30 seconds of flight. Current UK practice is to input the 10 minute mean wind from the local anemometer. This may differ significantly from the instantaneous wind at launch.

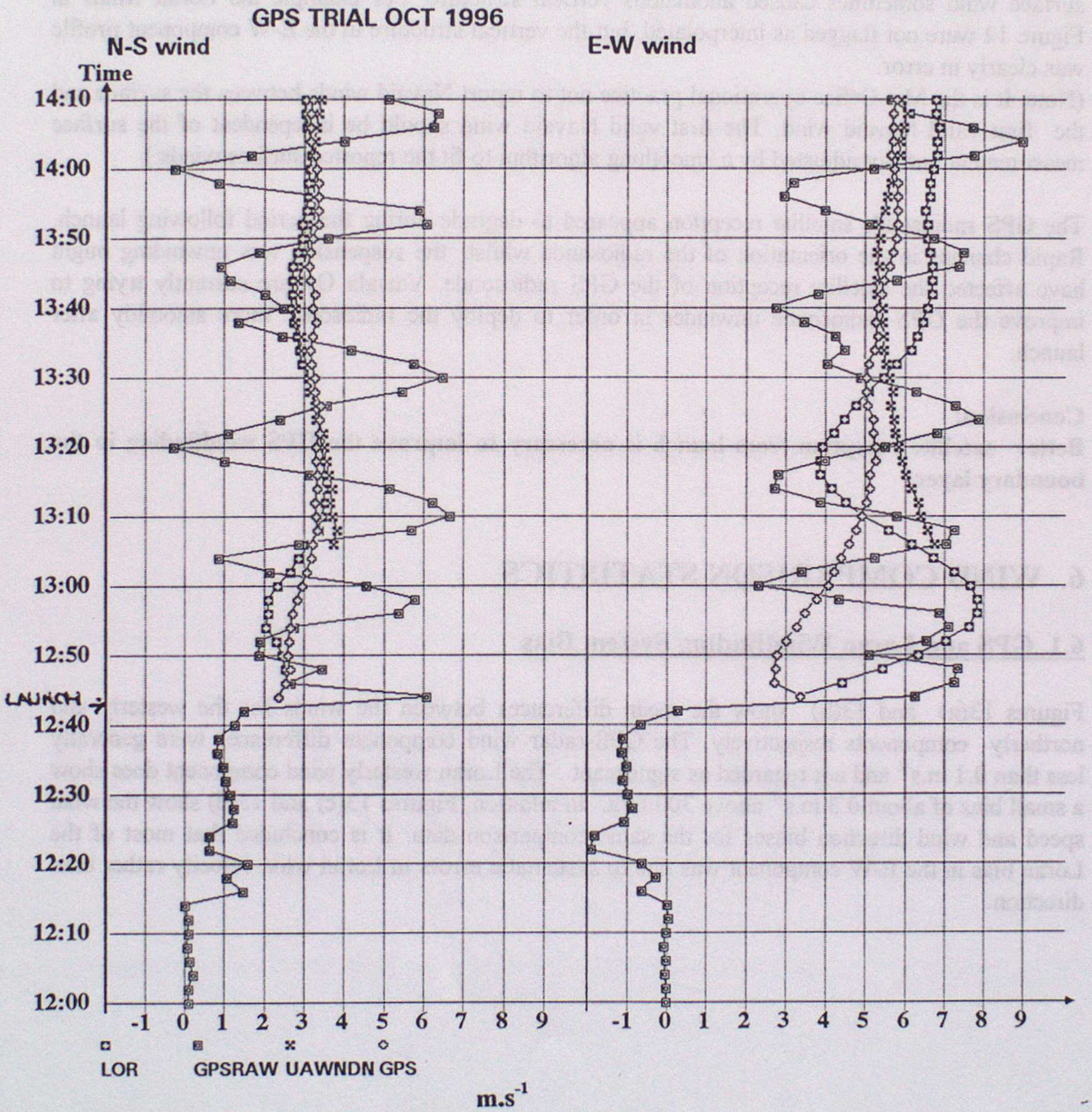


FIGURE 12

FLIGHT 9 - RAW GPS WIND (GPSRAW) THROUGH LAUNCH

5.3.2 Summary of Low Level Windfinding.

Less than 30 seconds of interpolated GPS winds were found in the first minute of ascent on only 4 out of 21 ascents. Flights 5,9,13 and 19 were the only flights where the RAWGPS data were received and retransmitted by the radiosonde through the period immediately before and after launch. All four flights were followed by radar from launch suggesting that **there was no strong correlation between missing GPS winds and interference from the Cossor radar**.

Loran measurements were available from the surface on 8 out of 11 ascents. (Refer to column 17 ,Annexe 3 , for the amount of interpolated low level Loran wind data during this Trial.). However , even when the Loran data was "measured" , the cubic spline algorithms fitting the profile to the surface wind sometimes caused anomalous vertical structure. For example the Loran winds in Figure 12 were not flagged as interpolated, but the vertical structure in the E-W component profile was clearly in error.
(Note: It is the Met Office operational practice not to report Navaid winds between the surface and the first valid Navaid wind. The first valid Navaid wind should be independent of the surface measurement and not adjusted by a smoothing algorithm to fit the reported surface winds.)

The GPS radiosonde satellite reception appeared to degrade during the period following launch. Rapid changes in the orientation of the radiosonde whilst the suspension was unwinding might have affected the satellite reception of the GPS radiosonde. Vaisala Oy are currently trying to improve the GPS radiosonde unwinder in order to deploy the radiosonde more smoothly after launch.

Conclusion:
Better satellite reception from launch is necessary to improve the GPS windfinding in the boundary layer.

6. WIND COMPARISON STATISTICS

6.1 GPS and Loran Windfinding System Bias

Figures 13(a) and 13(b) show the mean differences between the winds for the westerly and northerly components respectively. The GPS-radar wind component differences were generally less than 0.1 $m.s^{-1}$ and not regarded as significant . The Loran westerly wind component does show a small bias of about 0.3 $m.s^{-1}$ above 300 hPa. In addition, Figures 13(c) and 13(d) show the wind speed and wind direction biases for the same comparison data. It is concluded that most of the Loran bias in the E-W component was due to systematic errors in Loran wind velocity rather than direction.

Direct differences E-W wind
Reference: UAWNDS

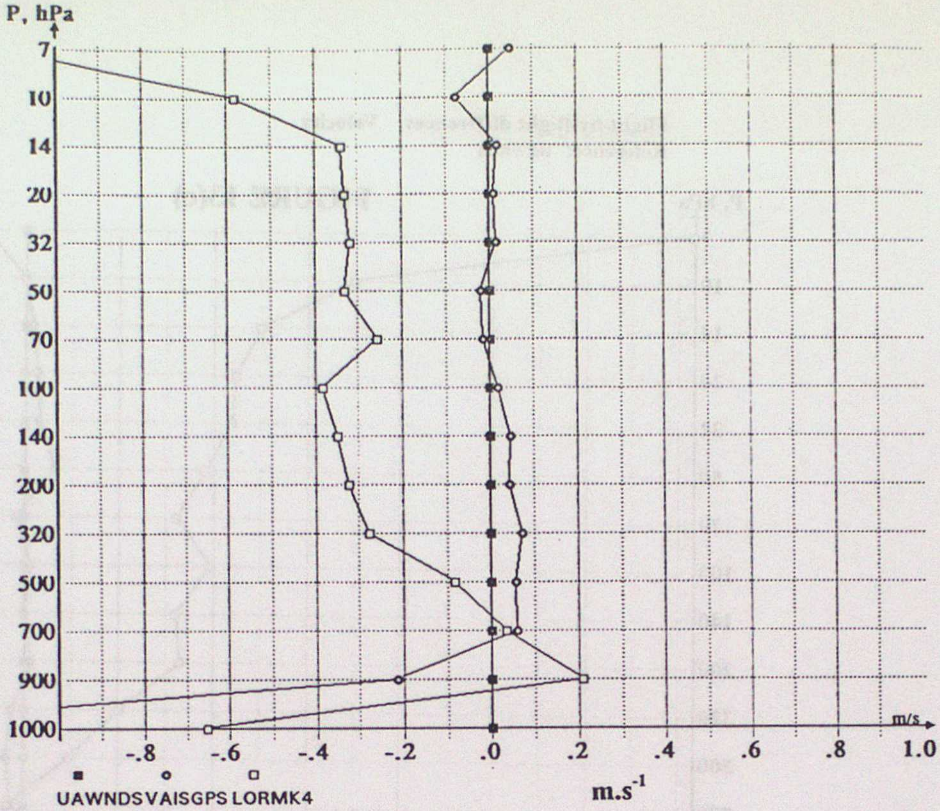


FIGURE 13(a)

Flights: 2 3 4 5 7 9 11 13 14 16 17 19 20 21

Direct differences N-S wind
Reference: uawnds

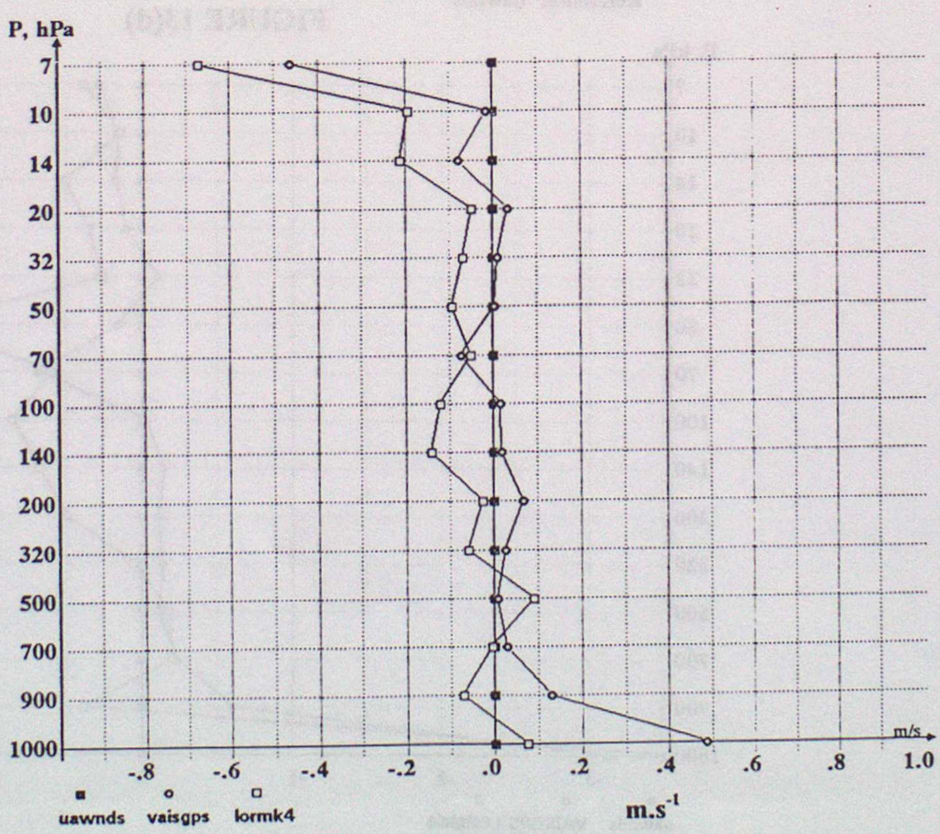
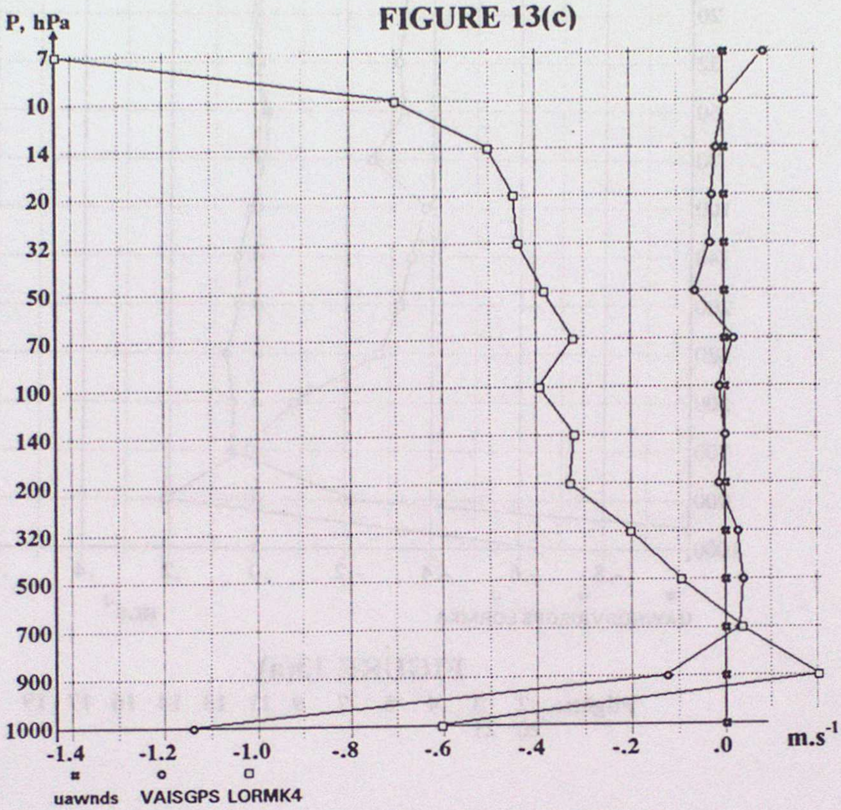


FIGURE 13(b)

Flights: 2 3 4 5 7 9 11 13 14 16 17 19 20 21

Flight-by-flight differences Velocity
Reference: uawnds

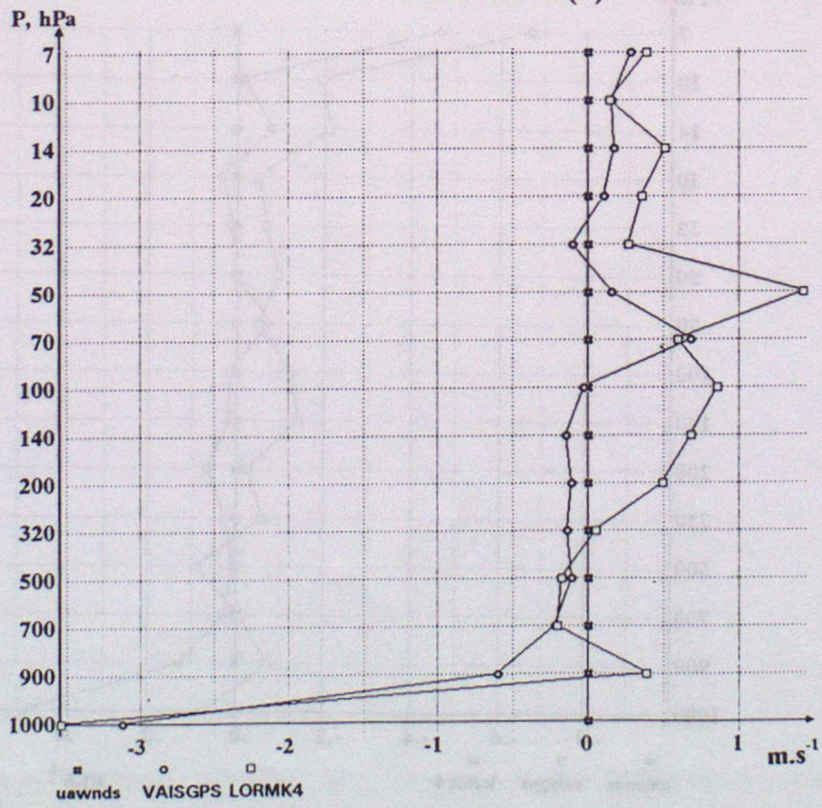
FIGURE 13(c)



Flights: 2 3 4 5 7 9 11 13 14 16 17 19
20 21

Flight-by-flight differences Direction
Reference: uawnds

FIGURE 13(d)



6.2 GPS and Loran Windfinding System Standard Deviations

Interpretation of the standard deviations between the various wind measurements must take into account that if there is no correlation between the errors of the two sets of winds being computed:-

$$(\text{s.d. of } \Delta u)^2 = Eu_1^2 + Eu_2^2$$

where E_{u1} and E_{u2} are the rms errors of wind components measured by systems 1 and 2 respectively.

6.2.1 Radar Error Assessment.

Estimates of the errors in the radar tracking for each wind component are shown as dashed lines in Figures 14(a) and 14(b). These were derived from simultaneous comparisons of wind measurements made between Cossor and High Precision radars at Aberporth in the past 3 years. The source of these error estimates is discussed in section 4.1.

6.2.2 Standard Deviation of the GPS-Radar Wind Component Differences.

Figures 14(a) and 14(b) display the standard deviations of the wind component differences for the westerly and northerly components respectively

The standard deviations of the Vaisala GPS wind differences in the E-W component were only about half those of the Loran wind differences in the E-W component and about .7 of the standard deviations in the N-S component at all levels up to 10hPa.

The standard deviations of the Loran winds compared with those from the radar were generally less than 1 $m.s^{-1}$ in each component. These results are consistent with Cossor radar/RS80-L wind comparison results obtained in various locations in the UK within the last 5 years, see Nash and Oakley [5].

There were significant anomalies in the standard deviation profiles in Figures 14(a) and 14(b). The larger variabilities in the lowest level nominally at 900 hPa were caused mainly by interpolated data .

6.2.3 GPS Error Assessment.

Estimates of the errors in the GPS measurements have been derived from the measurements in Figures 14(a) and (b) as detailed in Annexe 4.

The errors in the GPS windfinding measurements for both (E-W) and (N-S) components appear to have been between 0.2 and 0.4 $m.s^{-1}$ for all levels from 900 hPa to about 14 hPa (1 sd). These errors were only generally exceeded at heights less than about 500m above the surface and at pressures lower than 14 hPa where diminishing battery power probably caused the satellite reception to degrade in the high stratosphere.

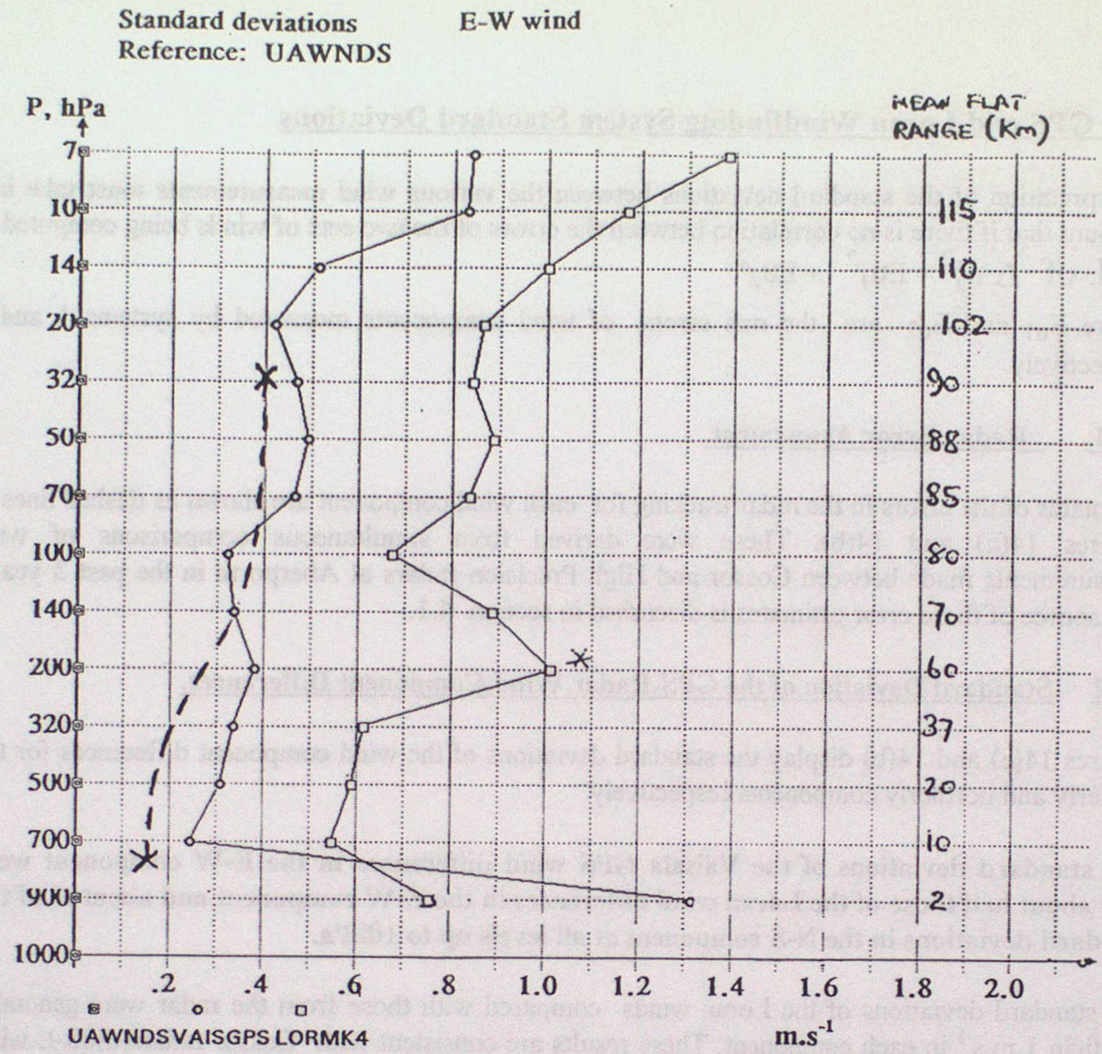


FIGURE 14(a)

STANDARD DEVIATIONS OF GPS and LORAN (E-W) WIND

Flights 2 3 4 5 7 9 11 13 14 16 17 19 20 21

* NB Loran anomaly at 200 hPa due to poor interpolation in strong vertical shear (Flight 16)

X -----------X Estimated Cossor Radar Error ,transposed from Figure 1(a)

Reference: uawnds

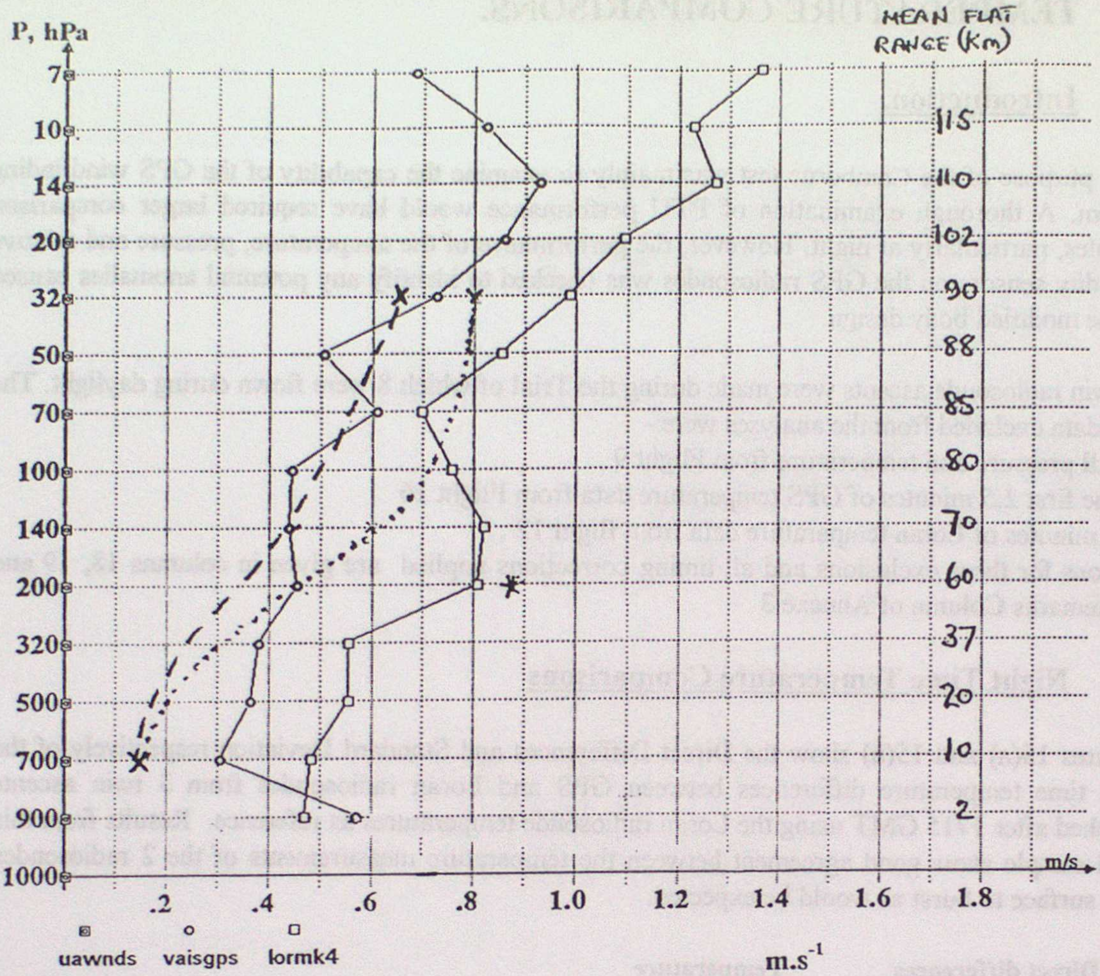


FIGURE 14(b)

STANDARD DEVIATIONS OF GPS and LORAN (N-S) WIND

Flights 2 3 4 5 7 9 11 13 14 16 17 19 20 21

* NB Loran anomaly at 200 hPa due to poor interpolation in strong vertical shear (Flight 16)

x . . . . x Original Cossor radar errors transposed from Figure 1(b)

X -----------X Best Estimate of Cossor Radar Error (adjusted for Camborne radar)

7. TEMPERATURE COMPARISONS.

7.1 Introduction.

The purpose of the Camborne test was mainly to examine the capability of the GPS windfinding system. A thorough examination of PTU performance would have required larger comparison samples, particularly at night. However, the performance of the temperature, pressure and relative humidity sensors on the GPS radiosondes was checked to identify any potential anomalies caused by the modified body design.

11 twin radiosonde ascents were made during the Trial of which 8 were flown during daylight. The only data excluded from the analyses were:-
(a) All pressure and temperature from Flight 9
(b) the first 2.5 minutes of GPS temperature data from Flight 16
(c) 4 minutes of Loran temperature data from flight 12 .
Reasons for these exclusions and all timing corrections applied are given in columns 18, 19 and the Remarks Column of Annexe 3 .

7.2 Night Time Temperature Comparisons

Figures 15(a) and 15(b) show the Direct Differences and Standard Deviation respectively of the night time temperature differences between GPS and Loran radiosondes from 3 twin ascents launched after 1715 GMT using the Loran radiosonde temperatures as reference. Results from this small sample show good agreement between the temperature measurements of the 2 radiosondes from surface to burst as would be expected.

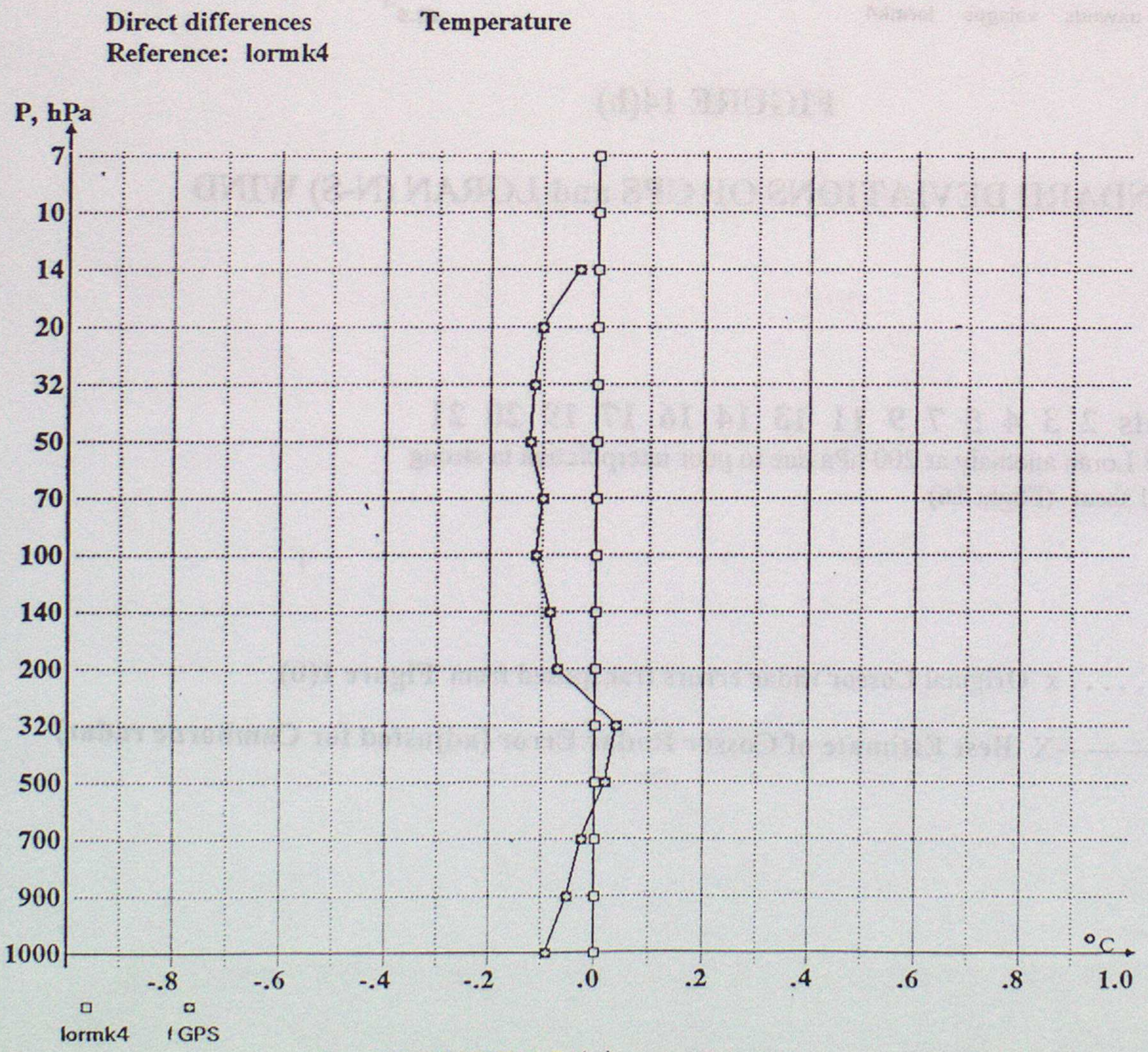


FIGURE 15 (a)
DIRECT DIFFERENCES BETWEEN MEAN TEMPERATURES - NIGHTTIME
Flights: 7 12 17

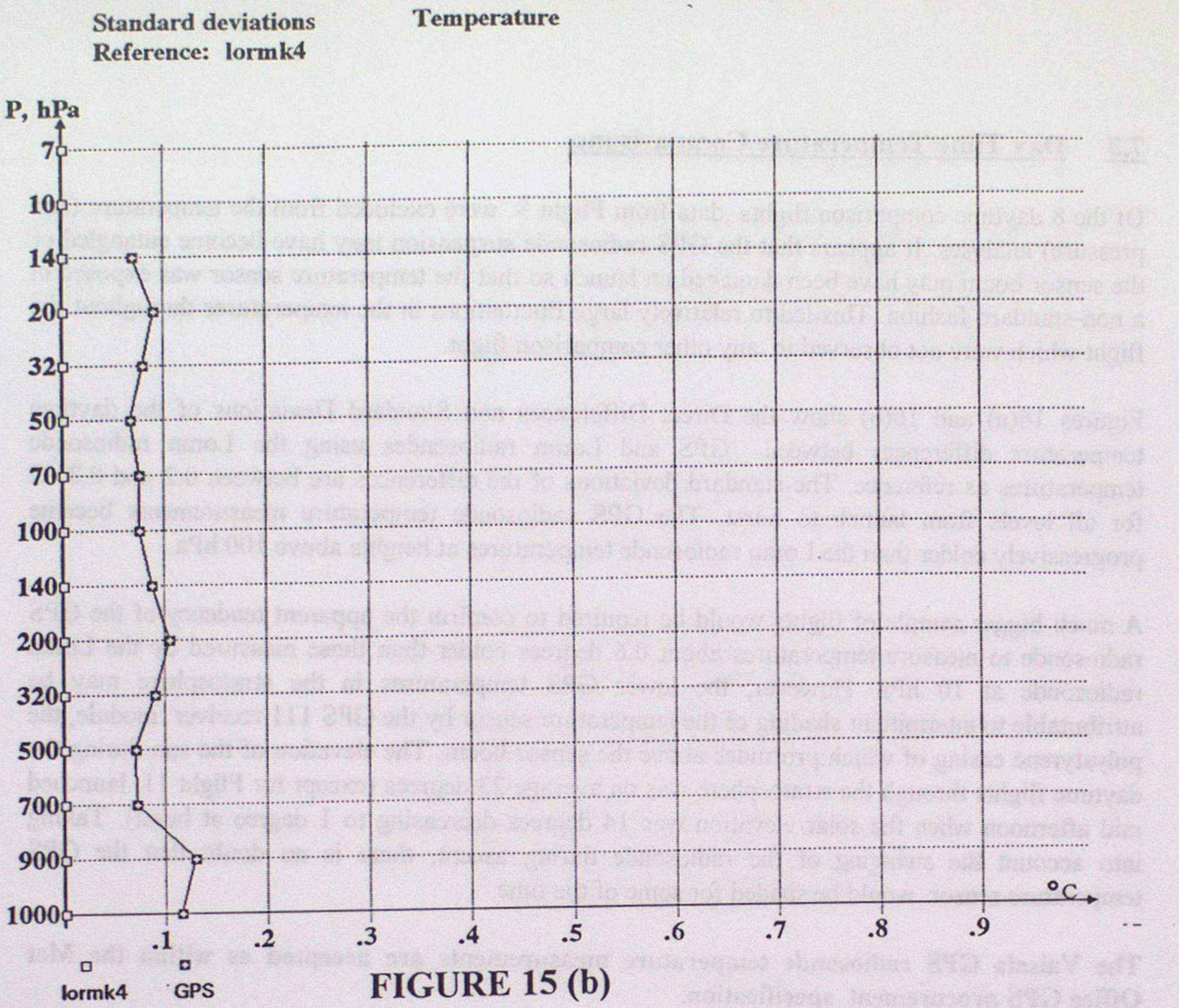


FIGURE 15 (b)

STANDARD DEVIATION OF 2 SECOND TEMPERATURE DIFFERENCES - NIGHTTIME
Flights: 7 12 17

7.3 Day Time Temperature Comparisons.

Of the 8 daytime comparison flights ,data from Flight 9 were excluded from the temperature (and pressure) analyses. It appears that the GPS radiosonde suspension may have become entangled or the sensor boom may have been damaged on launch so that the temperature sensor was exposed in a non-standard fashion. This led to relatively large fluctuations in the temperatures throughout the flight which were not observed in any other comparison flight.

Figures 16(a) and 16(b) show the Direct Differences and Standard Deviations of the daytime temperature differences between GPS and Loran radiosondes using the Loran radiosonde temperatures as reference. The standard deviations of the differences are between 0.2 and 0.3° C for all levels from launch to burst. The GPS radiosonde temperature measurements became progressively colder than the Loran radiosonde temperatures at heights above 100 hPa.

A much bigger sample of flights would be required to confirm the apparent tendency of the GPS radiosonde to measure temperatures about 0.6 degrees colder than those measured by the Loran radiosonde at 10 hPa. However, the lower GPS temperatures in the stratosphere may be attributable to intermittent shading of the temperature sensor by the GPS 111 receiver module, the polystyrene casing of which protrudes above the sensor boom. The elevation of the sun during the daytime flights through the stratosphere was on average 23 degrees (except for Flight 11, launched mid afternoon when the solar elevation was 14 degrees decreasing to 1 degree at burst). Taking into account the swinging of the radiosonde during ascent, there is no doubt that the GPS temperature sensor would be shaded for some of the time.

The Vaisala GPS radiosonde temperature measurements are accepted as within the Met Office GPS procurement specification.

Further simultaneous ascents, both at low and high solar elevations, should be made to confirm the bias of the GPS temperature measurements at pressures lower than 30 hPa as such biases could lead to errors in climate studies in the high stratosphere.

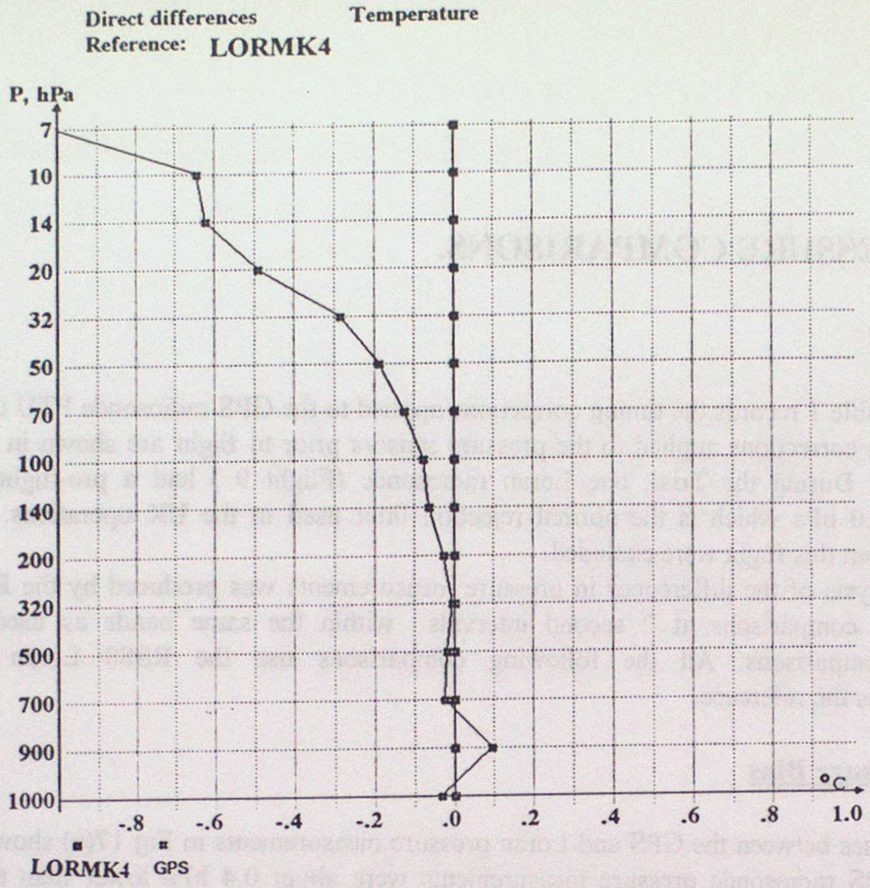


FIGURE 16 (a)
DIRECT DIFFERENCES BETWEEN MEAN TEMPERATURES - DAYTIME
Flights: 5 11 14 16 19 20 21
(Anomalous flight 9 excluded)

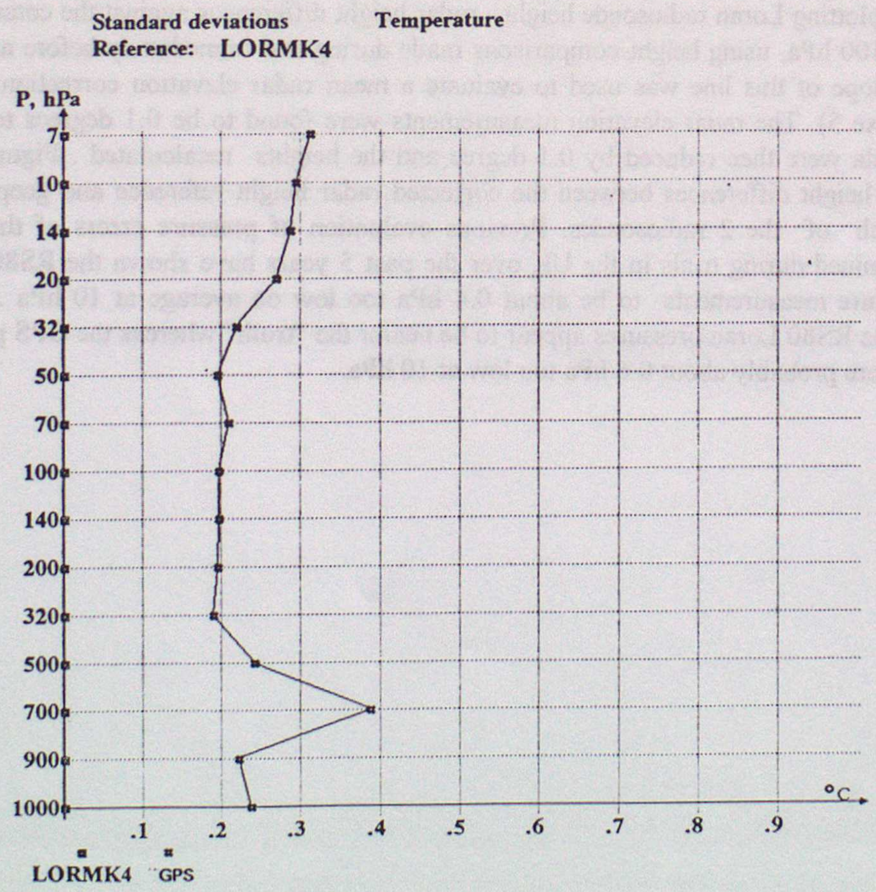


FIGURE 16 (b)
STANDARD DEVIATION OF 2 SECOND TEMPERATURE DIFFERENCES - DAYTIME
Flights: 5 11 14 16 19 20 21
(Anomalous Flight 9 excluded)

8. PRESSURE COMPARISONS.

8.1 General

Column 19 , Table 1 records the timing corrections applied to the GPS radiosonde PTU data . The ground controls corrections applied to the pressure sensors prior to flight are shown in the flight log, Annexe 6. During the Trial, one Loran radiosonde (Flight 9) had a pre-flight controls correction of 2.0 hPa which is the normal rejection limit used in the UK operations. Pressure comparisons from this flight were excluded.
An overall analysis of the differences in pressure measurements was produced by the RSKOMP software using comparisons at 2 second intervals within the same bands as used for the temperature comparisons. All the following comparisons use the RS80 Loran pressure measurements as the reference.

8.2 Pressure Bias

The mean biases between the GPS and Loran pressure measurements in Fig 17(a) shows that on average the GPS radiosonde pressure measurements were about 0.4 hPa lower than the Loran pressures at the same height . This mean difference was maintained from the surface to 10 hPa.

In order to ascertain which pressure measurements were nearer the truth, an independent check on the radiosonde pressure measurements was made by comparing the radiosonde geopotential with simultaneous radar geopotential heights. Any significant bias in the radar elevation measurements was checked by plotting Loran radiosonde height - radar height differences against the cotangent of the elevation at 100 hPa, using height comparisons made during and immediately before and after the Trial. The slope of this line was used to evaluate a mean radar elevation correction for the Trial. (see Annexe 5). The radar elevation measurements were found to be 0.1 degrees too high. The elevation data were then reduced by 0.1 degree and the heights recalculated . Figure 17(b) shows the mean height differences between the corrected radar height reference and geopotential heights from each of the 2 radiosondes. Previous evaluation of pressure errors of the RS80 "barocap" determined during trials in the UK over the past 5 years have shown the RS80 Loran radiosonde pressure measurements to be about 0.4 hPa too low on average at 10 hPa . In this limited sample the RS80 Loran pressures appear to be nearer the "truth" whereas the GPS pressure measurements were probably about 0.6 hPa too low at 10 hPa.

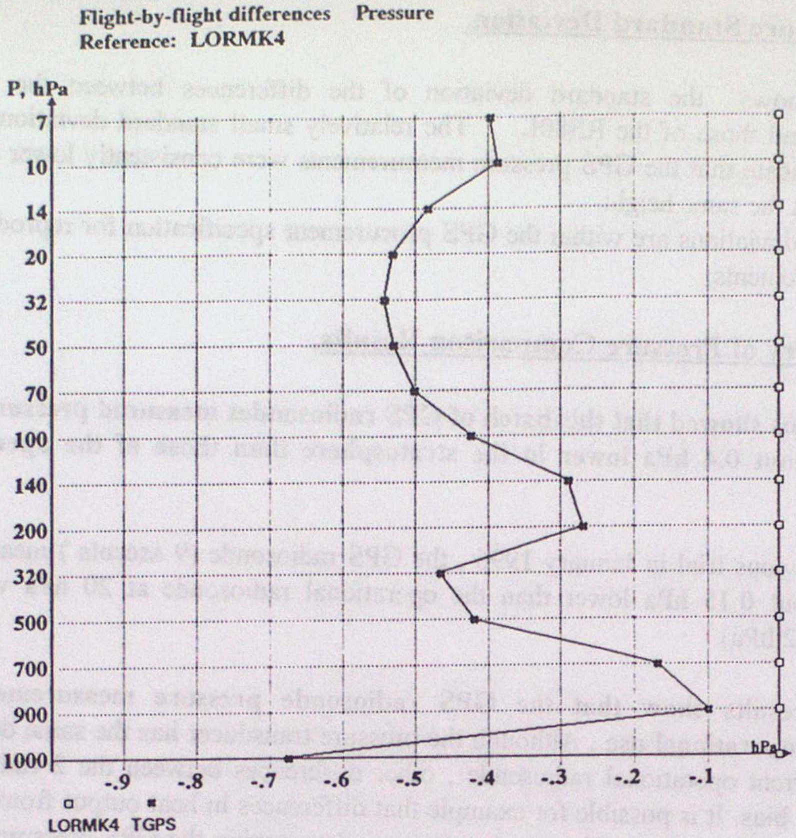


FIGURE 17 (a)

Flights: 5 7 11 12 14 16 17 19 20 21

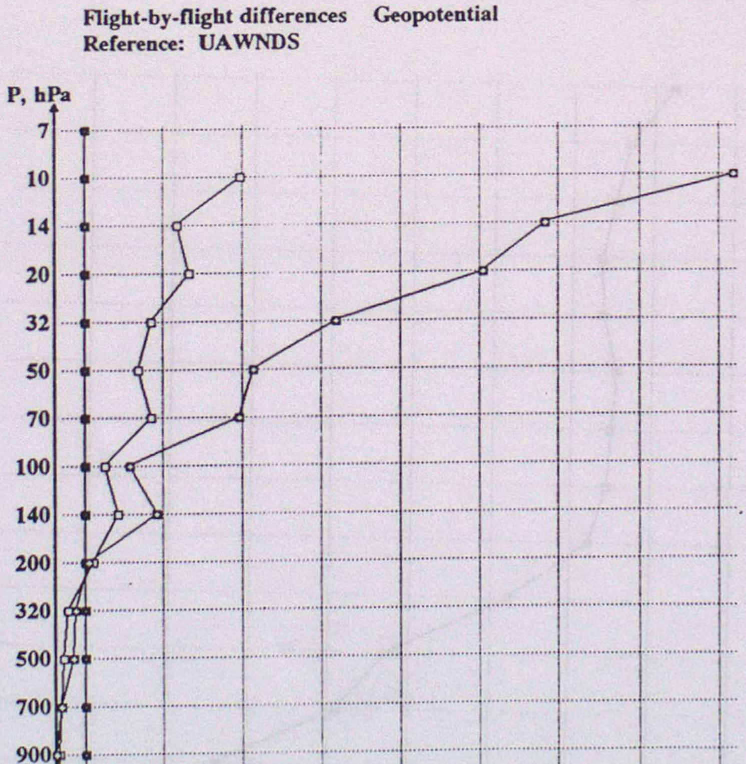


FIGURE 17 (b)

HEIGHT COMPARISON - HAVING ADJUSTED FOR 0.1 DEGREE RADAR ELEVATION ERROR

Flights: 5 7 11 12 14 16 17 19 20 21 25 26 27 28 29 30

8.3 Pressure Standard Deviation.

Figure 17(c) shows the standard deviation of the differences between the GPS pressure measurements and those of the RS80L. The relatively small standard deviations in the higher stratosphere indicate that the GPS pressure measurements were consistently lower than the Loran measurements at the same height.
These standard deviations are within the GPS procurement specification for reproducibility of the pressure measurements.

8.4 Summary of Pressure Comparison Results.

The comparisons showed that this batch of GPS radiosondes measured pressures which were consistently about 0.4 hPa lower in the stratosphere than those of the operational Loran radiosondes.

(During the previous trial in January 1996 , the GPS radiosonde (9 ascents) measured pressures on average about 0.15 hPa lower than the operational radiosonde at 20 hPa with a standard deviation of 0.22 hPa).

These Trial results show that the GPS radiosonde pressure measurements would be acceptable for operational use . Although the pressure transducer has the same design as the one used in the current operational radiosonde , other differences between the 2 radiosonde designs could cause the bias. It is possible for example that differences in heat output from the larger GPS radiosonde battery have some effect on the circuitry determining the GPS pressure measurements. Alternatively these results are indicative of batch to batch variability in pressure sensor performance.

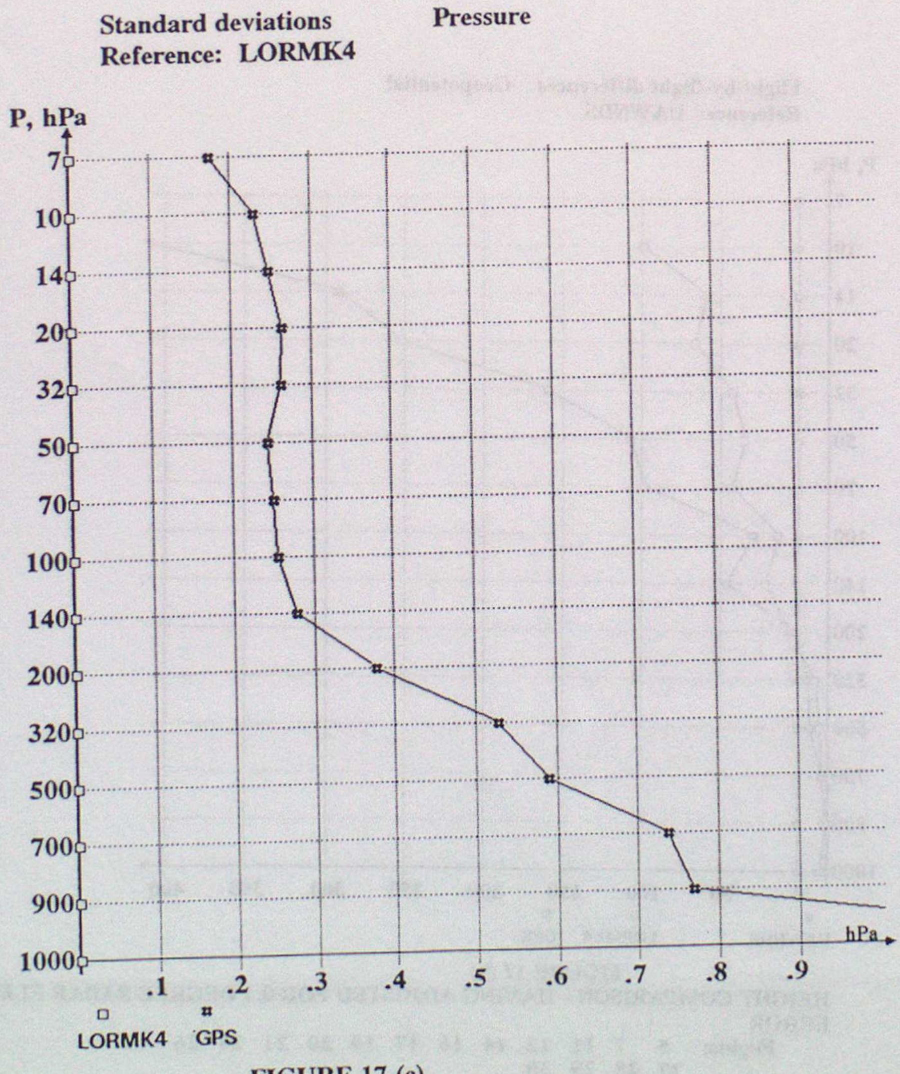


FIGURE 17 (c)
Flights: 5 7 11 12 14 16 17 19 20 21

9. HUMIDITY COMPARISONS.

9.1 Different Humidity Sensors Used

The GPS radiosondes provided by Vaisala used "A" Humicap humidity sensors whereas the operational Loran radiosondes used the newer "H" Humicaps. Operational monitoring has shown that the "H" Humicaps regularly report higher humidities in conditions at or near to saturation. (Vaisala have confirmed that the GPS radiosonde is now available using "H" Humicaps. The radiosonde type is RS80-15GH). Another characteristic of the "H" humicap is that it tends to measure higher relative humidities than the "A" humicap in medium or high cloud.

As an example, Figure 18 shows profiles of humidity measurements from the 2 sensors at minute intervals from launch. (The times of the GPS values have been corrected to adjust for the 30m suspension difference). The "H" humicap measured marginally higher humidities in the low level cloud on this ascent, but generally throughout the GPS Trial there were no significant differences in humidity measurements in low level cloud conditions. More significant differences were observed however at medium and high cloud levels where the "H" humicap measured relative humidities 15 to 20 per cent higher than the "A" humicap. These differences in characteristics have been observed on other Vaisala RS80 twin comparisons.

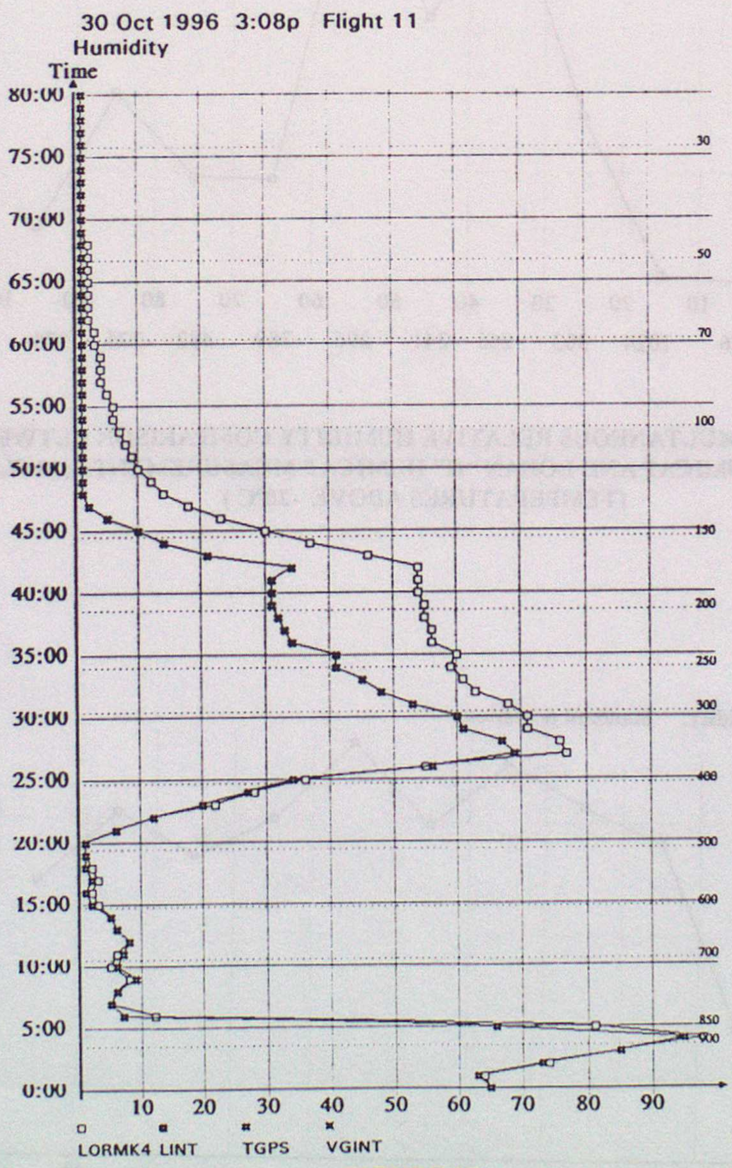


FIGURE 18
COMPARISON BETWEEN OPERATIONAL "H" HUMICAP AND GPS "A" HUMICAP MEASUREMENTS.

9.2 Humidity Comparison Statistics.

Comparison of the humidity measurements in the 2 Second Data Base were performed by computing the bias and Standard Deviation for measurements grouped in 10 humidity bands from 0 to 100 percent in increments of 10 per cent. Results are separated into measurements at temperatures above and below -20ºC. in Figures 18(a)/(b) and 18(c)/(d) respectively.

Figure 18(a) shows that the systematic bias between the 2 sets of humidity measurements at temperatures above -20ºC was less than 3 per cent with the larger discrepancies at relative humidities between 30 and 60 per cent. The 3 per cent standard deviation of the humidity differences displayed in Figure 18(b) is within the UK procurement specification for the reproducibility .

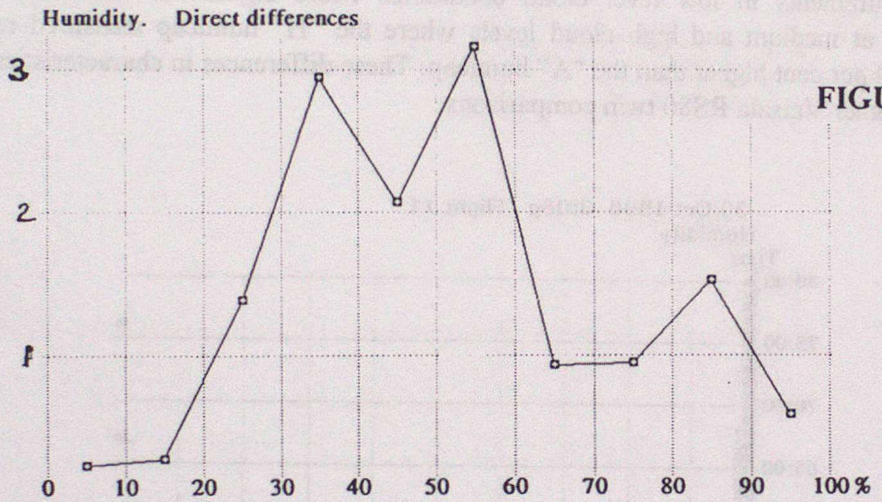


FIGURE 18(a)

1826 1024 303 265 241 296 389 482 275 578 - SAMPLE SIZES

SIMULTANEOUS RELATIVE HUMIDITY COMPARISON BETWEEN GPS "A" HUMICAP AND LORAN "H" HUMICAP MEASUREMENTS (10 FLIGHTS) (TEMPERATURES ABOVE -20ºC)

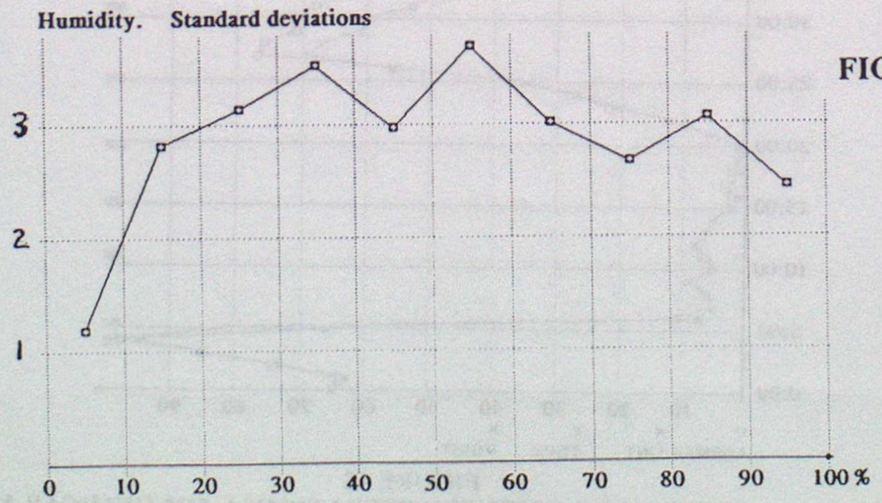


FIGURE 18 (b)

Flights 5 7 9 11 12 14 17 19 20 21

Figures 18(c) and 18(d) show much larger differences between the "A" an "H" Humicaps found in the higher troposphere and stratosphere by comparing all humidity measurements made at temperatures below -20°C. The "H" Humicap on the operational radiosonde reported humidities 10 to 15 per cent higher than the "A" Humicap at these lower temperatures.

The standard deviations of the differences displayed in Figure 18(d) were greater than those recorded for the humidity comparisons made at temperatures warmer than -20°C. These characteristics are consistent with results from Phase IV of the WMO Radiosonde Comparison, see Yagi et al. [6].

The GPS radiosonde/RS80L-H humidity characteristics observed in this trial were not significantly different from those observed on previous comparisons between "A" and "H" Humicaps on RS80 Loran or PTU radiosondes . The Met Office would require that the "H" Humicap be made available on the GPS radiosonde for its operations.

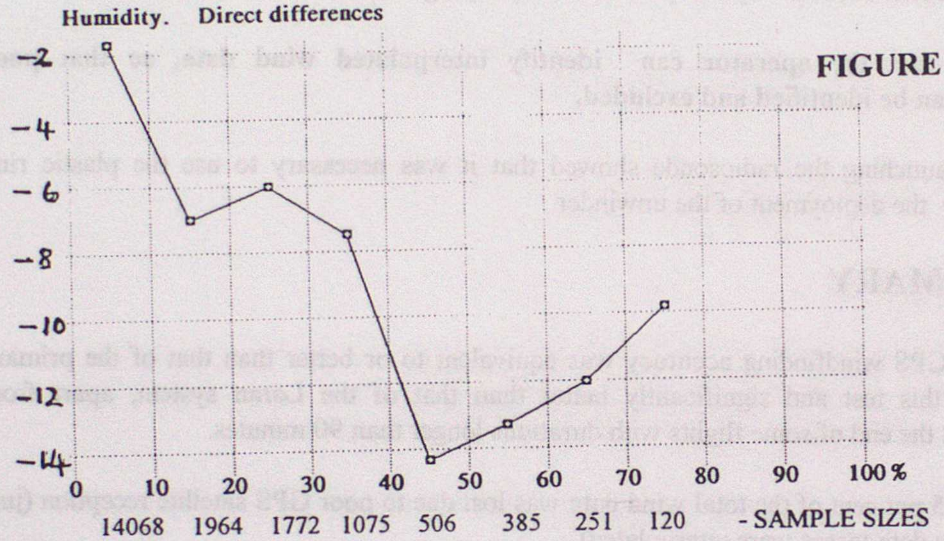


FIGURE 18(c)

SIMULTANEOUS RELATIVE HUMIDITY COMPARISON BETWEEN GPS "A" HUMICAP AND LORAN "H" HUMICAP MEASUREMENTS (10 FLIGHTS) (TEMPERATURES BELOW -20°C)

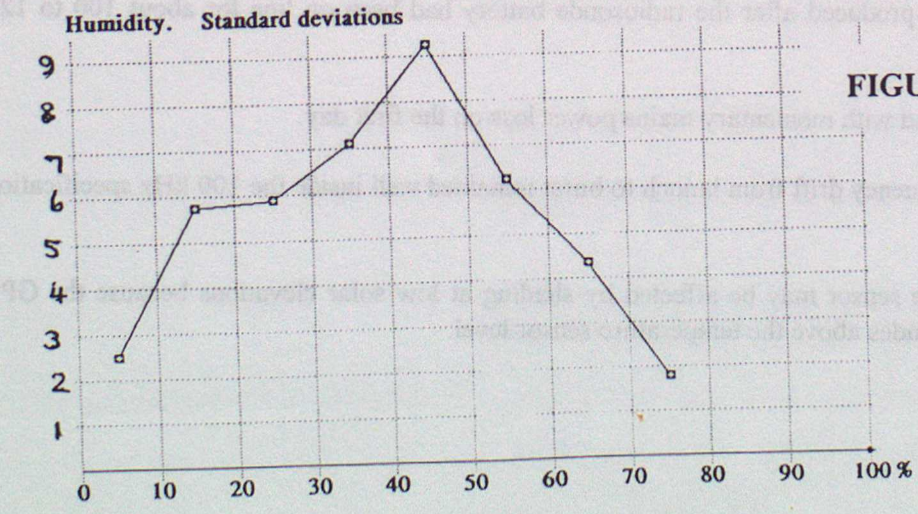


FIGURE 18 (d)

Flights 5 7 9 11 12 14 17 19 20 21

10. OPERATIONAL CONSIDERATIONS.

The system display uses MetGraph to enable the operator to view the data and profiles using similar facilities to those in PC-CORA systems. **The current standard MW15/ Metgraph system does not record and archive the RAWPTU data. Although not an operational necessity, this raw data archive is required in the UK for development and research and operational monitoring of the relative humidity sensor .**

The system is very similar in operation to the existing operational PC-CORA Loran windfinding system. The operator is informed when the local satellite receiver is synchronised. The ground checking (using touchpads on the main MW15 unit) and in-flight editing (using the attached MetGraph facility) progress in the same way. No problems were encountered operationally when the staff at Camborne successfully completed 2 ascents (Flights 20 and 21) on their own.

It is essential that the operator can identify interpolated wind data, so that poor interpolations can be identified and excluded.

Experience of launching the radiosonde showed that it was necessary to use the plastic ring provided to slow the deployment of the unwinder .

11. SUMMARY

1. The Vaisala GPS windfinding accuracy was equivalent to or better than that of the primary radar used for this test and significantly better than that of the Loran system, apart from measurements at the end of some flights with durations longer than 90 minutes.

2. Only about 3.5 per cent of the total wind data was lost due to poor GPS satellite reception (just over half of these data losses were interpolated).

3. Of the 21 GPS radiosondes flown, only one failed (Flight 12). All other ascents could have been successfully edited and reported, generally to 10 hPa or burst, whichever was the earlier.

4. Only 4 out of 21 ascents obtained sufficient GPS satellite data immediately prior to and after launch to compute the lowest level winds.

5. Above the boundary layer, only small amounts of interpolated data were substituted during short periods of poor satellite reception. Apart from near the ground, the greatest amounts of interpolation were produced after the radiosonde battery had been on line for about 100 to 120 minutes.

6. The system coped with momentary mains power loss on the first day.

7. Radiosonde frequency drift from launch to burst remained well inside the 100 kHz specification on all ascents.

8. The temperature sensor may be affected by shading at low solar elevations because the GPS 111 receiver protrudes above the temperature sensor level.

12. RECOMMENDATIONS

1. The Vaisala GPS system is considered suitable for deployment at overseas sites operated by the Met. Office.

2. The most significant improvement to the Vaisala GPS system could be made by improving the satellite reception in the first minute of ascent . This low level data is important for forecasting and especially for ballistic and acoustic soundings at some mainland UK sites.

3. The battery lifetime should be increased for future use of the radiosonde in high altitude soundings.

4. Further investigations into the effects of the GPS 111 receiver casing and the 60m suspension on solar radiation errors are required.

5. The line fitting to the raw 0.5 second wind data should be optimised during further tests (see section 5.2.5).

13. ACKNOWLEDGEMENTS.

The authors gratefully acknowledge the support given by Mr D G Drew (Station Manager ,Camborne Met. Office), scientific staff based at Camborne, Mr D Lyth from the Trials team, Mr S Farmer (Met. Office (OL)), Messrs V Karttunen and K Mesiainen from Vaisala Oy and Dr R Pettifer and Mr M Brettle from Vaisala UK. The support from Mr K Gibson (ATO) and technical staff at Camborne was also much appreciated.
The display and analysis software was developed by Mr S Kurnosenko (Central Aerological Observatory, Dolgoprudny) for WMO Radiosonde Intercomparisons .

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ANNEXE 1 - THE VAISALA GPS RADIOSONDE SYSTEM
(information as supplied by the manufacturer)

1. INTRODUCTION

GPS, a satellite-based radionavigation system is operated by the U.S. Department of Defense (DOD) and jointly managed by the DOD and the Department of Transportation (DOT). The Standard Positioning Service will be available to all users on a continuous, worldwide basis, for the foreseeable future, free of any direct user charge.

When augmented to satisfy civil requirements for accuracy, coverage, and integrity, GPS will be the primary Federally provided radionavigation system for the foreseeable future. [FRP94]

2. GPS WINDFINDING

GPS (Global Positioning System) is a global navigational system, consisting of 25 satellites, designed for high accuracy and world wide coverage. Each satellite transmits a digitally modulated spread spectrum signal on two carrier frequencies (1.226 GHz and 1.575 GHz) with a power level below thermal background noise.

Normally the L1 (1.575 GHz) carrier is used which is modulated by a binary phase shift keying (BPSK) with a satellite specific pseudo random noise (PRN) code (C/A-code) with a chipping rate of 1.023 MHz and hence a 2 MHz wide signal results.

The satellites are identified through the individual PRN code. Four satellites are required for accurate three dimensional positioning, and consequently for wind computation.

The performance of the GPS windfinding system is improved by using differential corrections, since many of the error sources (SA, propagation delays etc.) in the signals are common to the receivers in the radiosonde and at the base station and thus a mathematical compensation can be made.

2.1. Vaisala GPS Windfinding System

Vaisala advanced GPS Wind Finding System consists of a RS80-15G radiosonde, and a base station GPS receiver MWG201 in MW15 DigiCORA II ground equipment (figure 1.). It provides advantages to the user in the respect to conventional GPS and Navaid wind finding systems.

Optimization of the satellite configuration is continuous during the sounding - no other actions are needed prior to the launch than normal battery activation and ground check.

New independent measurements are provided twice every second from the radiosonde, making the calculated wind vector update rate 2 Hz. No filtering or integration times is needed for the wind vector (except for removing the pendulum effect).

The use of FSK modulation (digital transmission of received GPS) with a high performance 400 MHz transmitter provides a long range telemetry (up to about 200 km) without any degradation of the accuracy due to link budget problems.

Due to the high frequency band of the GPS system, it is not sensitive to the high electric field gradient of the atmosphere (unlike the long Navaid string antennas) or varying propagation conditions. Thus the GPS wind finding can be used in worse weather conditions than the traditional Navaids.

The users can upgrade the present Vaisala DigiCORA and MARWIN installations for GPS windfinding without losing the original Navaid capabilities.

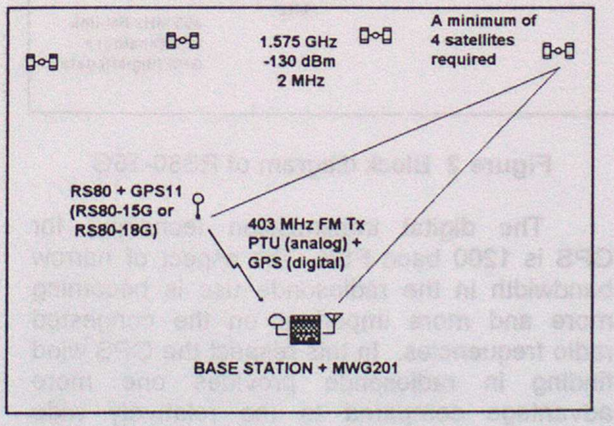

Figure 1 Vaisala GPS windfinding

2.2. Codeless GPS Technique

The GPS signal is 2 MHz wide meaning that the radiosonde GPS receiver can not relay the signal as it is to the base station because this would require too much bandwidth. The radiosonde must have some signal processing capability to extract the necessary information and code it for further transmission.

Commercial code-correlating GPS engines are sold at about 100$ in volumes which is too much for a disposable radiosonde and therefore the cost of the GPS receiver should be kept as low as possible. This is achieved by keeping the data processing in the radiosonde at the absolute minimum by a code-less approach, and the actual wind computation is done in the ground station receiver and consequently a low cost GPS sonde is achieved.

The GPS receiver in the Vaisala radiosonde is designed to extract the necessary information by removing the spread spectrum PRN code of each satellite, measuring the carrier dopplers and pack the measurements in a suitable form for a narrow bandwidth transmission [Kai95], [Saa96]. The substance of this processing relies on Vaisala codeless Digital Signal Detector (DSD) which contains a 1-bit A/D-converter, a digital squaring device for removing the satellite PRN code and an 8-channel digital Phase Locked Loop (PLL) (figure 2.). The carrier frequencies of up to 8 satellites are continuously tracked with these PLL's.

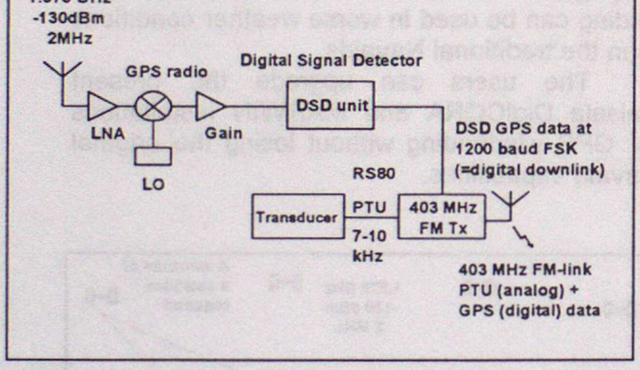

Figure 2 Block diagram of RS80-15G

The digital transmission technique for GPS is 1200 baud FSK. The aspect of narrow bandwidth in the radiosonde use is becoming more and more important on the congested radio frequencies. In this respect the GPS wind finding in radiosonde provides one more advantage compared to the relatively wide bandwidth required by the Omega and Loran-C signals.

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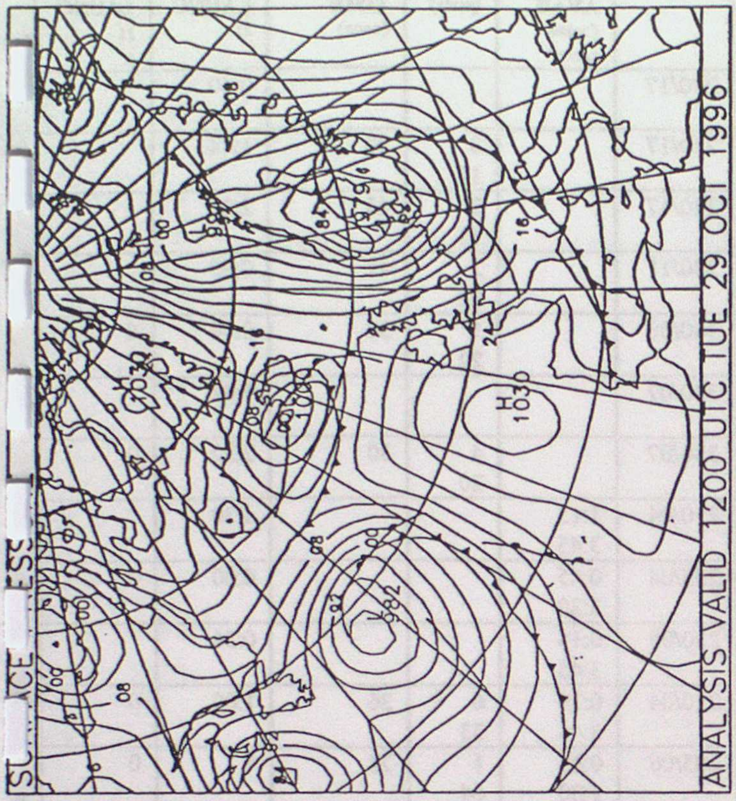
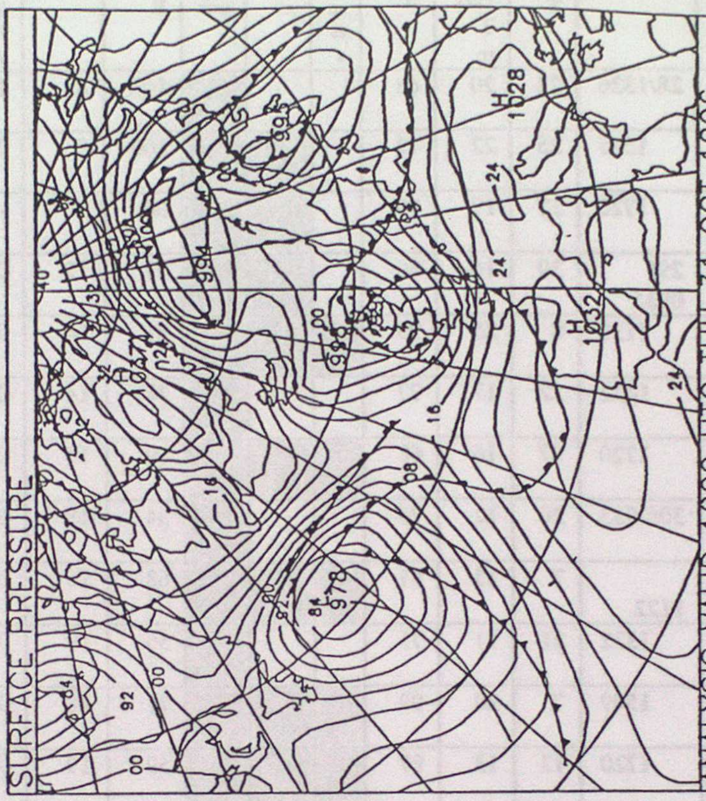
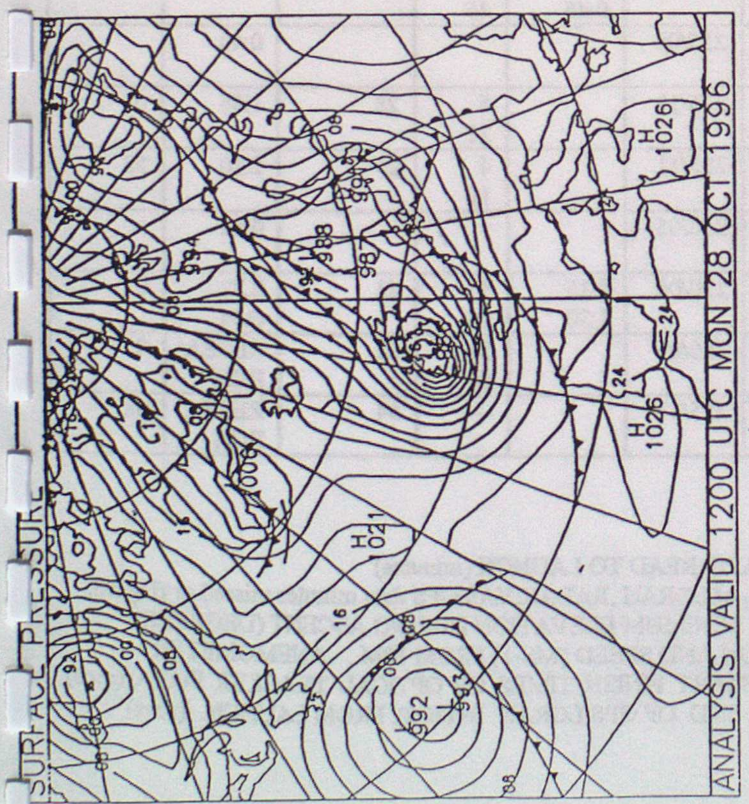
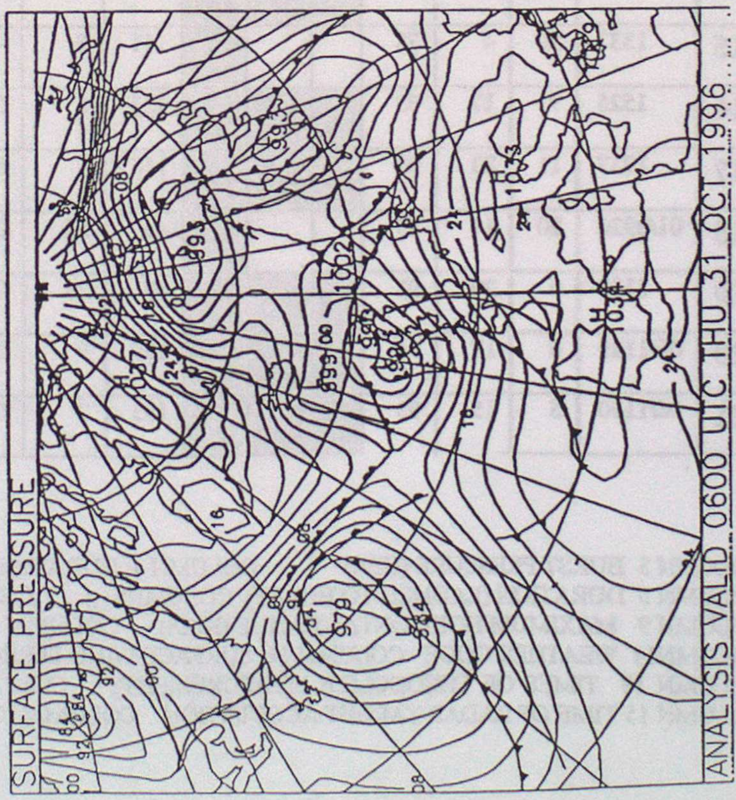
ANNEXE 2

SURFACE ANALYSES DURING THE TRIAL









ANNEXE 3 WIND DATA ACQUISITION

1 FLT	2 TIME	3 BURST	4 PREFLIGHT m	5 MINS	6 LOR mis	7 RDR mis	8 VAIS mis	9 RANGE	10 ELEV	11 WEATHER	12 SURF WIND (m/s)	13 THEOD-OLITE DATA AVAIL (mins :secs)	14 OPT TRACK DATA (secs)	15 RADAR LOCK ONTO TARGET TIME (secs)	16 GPS INTERPOLATE FROM LAUNCH	17 LORAN INTERPOLATE FROM LAUNCH
1	28/1326	22	20	68			1	109	8	15	220/17				0:40	
2	1525	25	22	72		18	2	100	9	25	230/17		3 12	30	1:44	
3	1720	27	17	70		1	3	90	9	—	240/17		3 11	43	2:26	
4	29/ 0935	30	16	80		1	1	77	12	02	330/11		2 22	42	0:40	
5	1130	8	25	93	2	0	1	81	14	02	340/08		5 22	36	0:04	0
6	1422	22	17	77			1	73	14	02	340/07				1:02	
7	1720	37	16	68	0	7*	3	69	15	02	330/07		4 20	30	2:22	0
8	30/0933	20	12	75			2	54	19	02	210/04	1:15 3:45			1:30	
9	1122	7	13	97	4	4*	2	68	19	02	235/04	0:45 3:30			0:00	0
10	1322	21	11	75			1	56	19	02	230/05	0:15 3:45			0:36	
11	1509	7	20	99	4	1	2	71	18	02	210/04	0:30 3:45	6 33	36	1:00	0
12	1720	13	13	87	4	0	20 *	59	19	02	205/06	0:45 1:30	1 64	74	*	0
13	31/0936	28	16	80		0	0	92	10	50	235/08	0:30 0:45	? 24	30	10,20 &22	
14	1123	7	14	102	2	0	4	112	9	51	235/08	0:30 0:45	3 46	56	1:42	68
15	1337	20	4	78			1	111	8	—	255/08				0:40	
16	1525	9	17	95	4	0	3	123	8	50	275/11		5 21	28	1:56	0
17	1737	11	23	93	6	0	3	116	9	51	285/11		4 19	29	2:20	58
18	01/0926	20	14	75			1	45	21	02	250/05				0:42	
19	1133	6	20	92	3	0*	1	67	23	02	230/06	0:15 1:30	4 59	63	2,32 &34	0
20	05/1129	6	17	94	3	3	4	159	9	03	280/05		31 54	62	RESEA RCH	0
21	06/1130	5	15	93	2	9	12	193	7	03	255/11		—	54	RESEA RCH	68

COLUMN 3 BURST PRESSURE (HPA) COLUMN 4 DURATION TAPE READ TO LAUNCH (minutes)
COLUMN 5 DURATION (LAUNCH TO BURST) COLUMNS ,6 , 7 & 8 No. of LORAN ,RADAR, VAISGPS data minutes missed or flagged.
COLUMN 9 MAXIMUM HORIZONTAL RANGE (KMS). COLUMN 10 MINIMUM ELEVATION DURING ASCENT (DEGREES)
COLUMN11 WEATHER CODE COLUMN 12 SURFACE WIND DIRECTION AND SPEED (MS-1) FROM 10M . ANEMOMETER
COLUMN 13 TIMES OF THEODOLITE MEASUREMENTS . COL. 14 START FINISH TIMES OF OPTICAL TRACKER DATA (secs)
COLUMN 15 TIME OF RADAR TARGET ACQUISITION COLUMN 16 ,17 END OF GPS,LORAN INTERP. FROM LAUNCH. (secs)

ANNEXE 3 (continued)

DATA EXCLUSIONS AND PTU TIME CORRECTIONS

18	19		
FLAG (RADAR DATA unless indicated GPS)	PTU TIME COR (SECS)	REMARKS	FLT
		GALE FORCE SURFACE WINDS	1
		GALE FORCE SURFACE WINDS . POWER CUT. RADAR OUTAGE. GPS UNAFFECTED	2
		GALE FORCE SURFACE WINDS WORST CASE GPS INTERPOLATE 9m/s E-W component error at min 1	3
			4
	+6		5
			6
23:20-27:50 29:40-32:10	+8	RADAR DPU FAULT mins	7
			8
5:40-6:40,9:50-10:50, 12:20:13:20,20:40-21:40	+4	RADAR DPU FAULT mins. ANOMALOUS LORAN PRESSURE. GPS TEMPS CORRELATE WPENDULUM . PRESSURE /TEMPS EXCLUDED	9
			10
	+10		11
LORAN WETBULBS FLAGGED 5:10-8:40.	-4	RADAR INTERFERED WITH GPS. SATELLITE RECEPTION? FIRST 7MINS GPS WINDS MISSING	12
			13
	+2		14
	+10		15
		GPS SONDE GRAZED GROUND ON LAUNCH . NO HUMIDITY REPORTED. 0 to 2.5 minutes Anomalous GPS TEMPS. EXCLUDED	16
	+8		17
			18
	+2		19
89:50-94:00 GPS 90:50-94:00 RADAR	0	GPS RESEARCH MODE, GPS WINDS CEASED 4 MINS BEFORE BURST	20
49:10-53:20,69:18-70:18 84:00-93:00 RADAR 81:30- 93:00 GPS	0	GPS RESEARCH MODE> GPS WINDS CEASED 12 MINUTES BEFORE BURST	21

COLUMN 18 TIMES OF FLAGGED WINDS (UNUSED BY ANALYSES) . COL 19 TIME CORRS SUBTRACTED FROM GPS PTU DATA

ANNEXE 4

COSSOR RADAR ERROR EVALUATION - HIGH PRECISION RADAR TRIAL

Cossor radar errors were originally evaluated during 1984, by tracking the same balloon with two similar Cossor radars at 50 Km separation, see Edge et al. [3]. This test utilised measurements obtained from the UK Mk III Radiosonde sounding system which sampled wind data every 8 seconds rather than the 1 second sampling of the PC-CORA system . Further evaluations have since been carried out at Aberporth in West Wales using a high precision radar on the same site (within 1 km) as another operational Met Office Cossor. Only four comparison ascents have so far been made, but the results from this limited sample suggest that the Cossor radar errors determined in 1984 were larger than those currently obtained with PC-CORA.

Estimate of the GPS E-W Component Error.

During both the GPS Trial and the High Precision Radar Trial the winds were mainly westerly and therefore produced smaller errors in the E-W components. The mean flat range (km) at each of the pressure levels is shown on the right hand side of the Figures 14(a) and 14(b) (Section 6.2.3). A smooth curve fitted through the standard deviation of the (Cossor minus High Precision Radar) differences shown in Figure 1(a) (Section 4.1) has been transposed onto Figure 14(a) at the flat ranges associated with the pressure zones analysed in this GPS Trial. The transposed error curve for the E-W component closely follows the profile of the standard deviations of the VAISGPS -UAWNDS differences .

The standard deviation of the differences between any 2 measurements which each have uncorrelated errors can be evaluated from the following relationship:-

SD^2 (measurement difference) = SD^2 (measurement 1) + SD^2 (measurement 2)

Applying this relationship to evaluate the standard deviation of the GPS measurement errors in isolation :-

SD^2 (GPS error) = SD^2 (measurement difference) - SD^2 (radar error)

From Figure 14 (a) at 700 hPa therefore :-

SD^2(GPS error)= $0.24^2 - 0.15^2 = 0.04$, therefore **SD(GPS) @ 700 hPa= 0.19 m.s^{-1}**

Similarly at 32 hPa :-

SD^2 (GPS error)= $0.47^2 - 0.40^2 = 0.06$, therefore **SD(GPS) @ 32 hPa = 0.24 m.s^{-1}.**

The above calculations assume that the High Precision Radar had no errors of its own and that the Camborne and Aberporth Cossor radars had identical errors. However, even if the radar error at 32 hPa was the same as that at 700 hPa this would result in a value for the GPS error at 32 hPa no greater than 0.44 m.s^{-1}). The Aberporth tests have not evaluated errors at flat ranges greater than 90 km, but there is no reason to suppose that the errors at 20 and 14 hPa would be significantly different from those at 32 hPa.

A realistic estimate of the errors in the GPS (E-W) component measurements is that they are between 0.2 and 0.4 m.s^{-1} for all levels up to about 14 hPa. These errors were only generally exceeded at heights less than about 500m above the surface and at pressures lower than 14 hPa where diminishing battery power caused the satellite reception to degrade in the high stratosphere.

Estimate of the Loran E-W Component Error.

Applying the above method in calculating the Loran error using the observed Loran standard deviations and the radar error curve in Figure 14 (a)
at 700 hPa therefore :-
SD^2 (Loran error)= $0.54^2 - 0.15^2 = 0.27$, therefore **SD(Loran) @ 700 hPa= 0.51 $m.s^{-1}$**
Similarly at 32 hPa :-
SD^2 (Loran error)= $0.84^2 - 0.40^2 = 0.55$, therefore **SD(Loran) @ 32 hPa = 0.74 $m.s^{-1}$.**

Estimate of the GPS N-S Component Error.

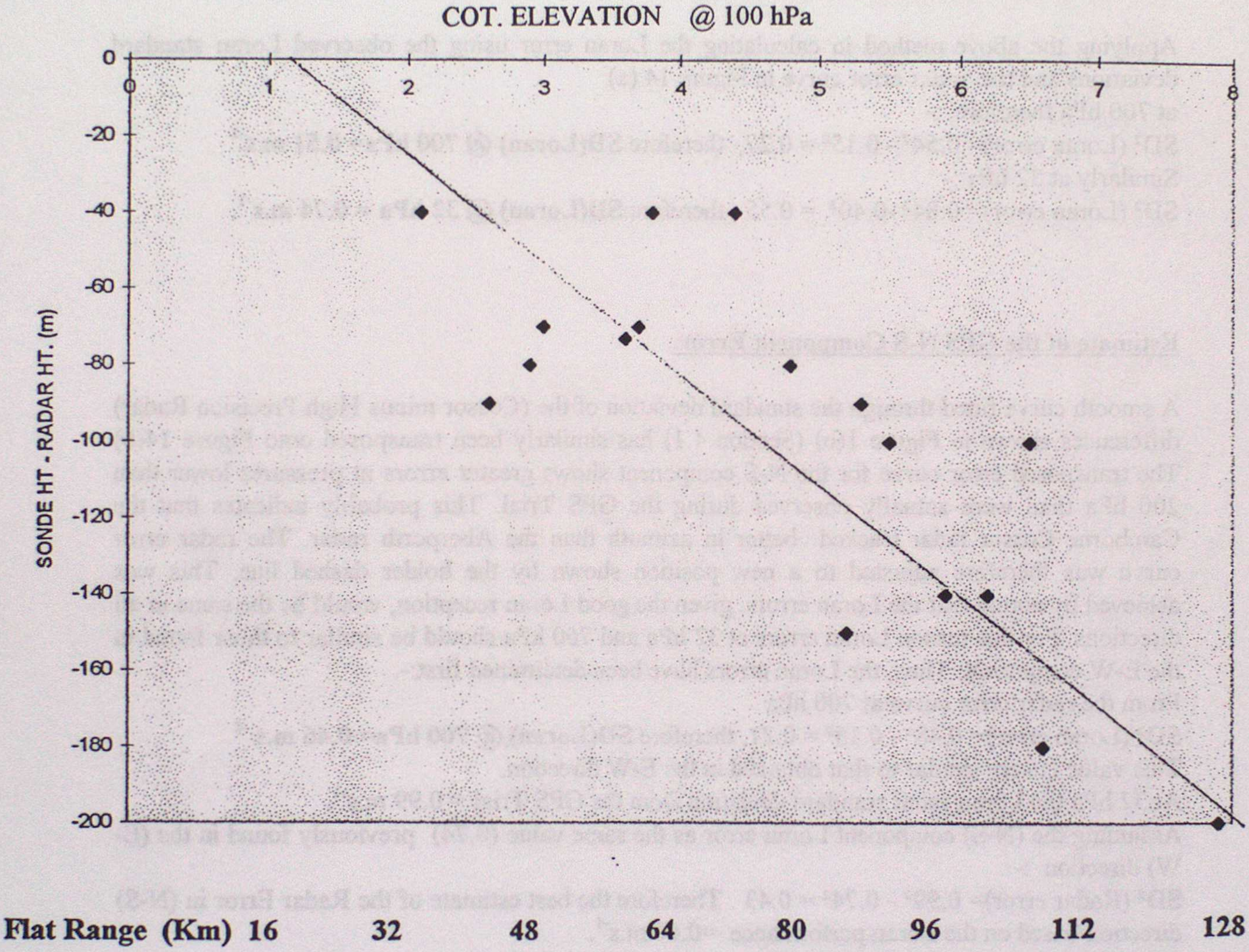
A smooth curve fitted through the standard deviation of the (Cossor minus High Precision Radar) differences shown in Figure 1(b) (Section 4.1) has similarly been transposed onto Figure 14(b) The transposed error curve for the N-S component shows greater errors at pressures lower than 200 hPa than were actually observed during the GPS Trial. This probably indicates that the Camborne Cossor radar tracked better in azimuth than the Aberporth radar. The radar error curve was therefore adjusted to a new position shown by the bolder dashed line. This was achieved by noting that the Loran errors, given the good Loran reception, would be the same in all directions. For this reason Loran errors at 32 hPa and 700 hPa should be similar to those found in the E-W component. Thus, the Loran errors have been determined first:-.
From the radar error curve at 700 hPa
SD^2 (Loran error)= $0.48^2 - 0.15^2 = 0.21$, therefore **SD(Loran) @ 700 hPa= 0.46 $m.s^{-1}$**
This value is very similar to that obtained in the E-W direction.
At 32 hPa the Loran-radar standard deviation from the GPS Trial = 0.99 $m.s^{-1}$.
Assuming the (N-S) component Loran error as the same value (0.74) previously found in the (E-W) direction :-
SD^2 (Radar error)= $0.99^2 - 0.74^2 = 0.43$. Therefore the best estimate of the Radar Error in (N-S) direction based on the Loran performance =0.66 $m.s^{-1}$.
The transposed curve has accordingly been adjusted through this point

From Figure 14 (b) at 700 hPa therefore :-
SD^2 (GPS error)= $0.30^2 - 0.15^2 = 0.07$, therefore **SD(GPS) @ 700 hPa= 0.26 $m.s^{-1}$**
Similarly at 32 hPa :-
SD^2 (GPS error)= $0.73^2 - 0.66^2 = 0.10$, therefore **SD(GPS) @ 32 hPa = 0.32$m.s^{-1}$.**

Thus the GPS errors in the N-S direction appear to have similar magnitude to those in the E-W direction.

ANNEXE 5

EVALUATION OF RADAR ELEVATION ERROR



Slope of line = 200/108000 m = .0018
Arc Tan (.0018) = 0.10 degrees correction

ANNEXE 6

GPS TRIAL OCT/NOV 1996 - RS80 GPS FLIGHTLOG

Flt.	DDHH.	Actl.	SondeNum.	CONTROLS CORRECTION ..P	---T	---U.	SURFACE Pres-	Tmp	L	Hum-	DD	WMO GROUP -FF.	Cloud	MX%
1	2813	1326	638209707	5	1	1	985+	14	M	66	220	18	724//	100
2	2815	1525	638107804	8	0	0	984+	13	M	71	230	17	784//	100
3	2817	1720	638107810	6	-1	0	983+	12	M	72	240	17	724//	100
4	2909	935	638108401	10	-1	0	1009+	10	M	58	330	11	75600	100
5	2911	1130	638107815	7	-1	0	1011+	10	M	64	340	8	685//	100
6	2914	1422	638107805	11	3	-1	1012+	10	M	59	340	7	58500	98
7	2917	1720	638108314	7	-1	-1	1014+	10	M	57	330	7	685//	95
8	3009	933	638107800	8	0	0	1018+	11	M	70	210	4	785//	100
9	3011	1122	638107814	5	-1	0	1018+	11	M	68	240	4	785/2	100
10	3013	1322	638108015	5	1	0	1017+	11	M	62	230	5	856//	100
11	3015	1509	639530905	13	-2	0	1016+	11	M	65	210	4	885//	97
12	3017	1720	639530808	12	0	0	1015+	11	M	69	210	6	885//	99
13	3109	936	638107700	18	0	0	1005+	14	M	92	240	8	872//	100
14	3111	1123	639530803	10	0	0	1004+	14	M	94	240	8	873//	100
15	3113	1337	639530802	***	***	***	1005+	13	M	96	260	8	872//	100
16	3115	1525	639530915	13	-2	0	1005+	13	M	92	280	11	853//	N/A
17	3117	1737	639530807	15	0	0	1007+	12	M	93	290	11	873//	100
18	109	926	638108315	11	1	0	1016+	13	M	92	250	5	762//	100
19	111	1133	639530910	11	0	0	1016+	13	M	87	230	6	854//	100
20	511	1129	639530911	7	-1	0	1006+	11	M	71	280	5	785//	95
21	611	1130	639530812	13	-1	1	999+	13	A	68	260	11	38531	88

		MAXWIND FF-	-DRN-	-HGT..	Max Rge.	HUM Min-	Max.	TEM Min.	ELEV Min.	hPa Heights 100----	----50------	30...	Ascent Rate(m/s)
1	96102813	55	234	5229	108	1	100	-65	7	16214	20507	23658	6.3
2	96102815	41	259	1485	100	1	100	-65	9	16196	20477	23631	5.7
3	96102817	43	266	2438	90	1	100	-64	8	16188	20491	23648	5.8
4	96102909	34	349	9779	76	1	100	-63	12	16163	20483	23650+	4.9
5	96102911	37	344	10489	81	1	100	-64	14	16151	20469	23630	5.7
6	96102914	34	333	10762	73	1	98	-63	14	16169	20490	23652	5.5
7	96102917	34	341	10650	69	1	95	-63	15	16163	20487	23651+	5.5
8	96103009	34	309	12712	54	1	100	-68	19	16231	20508	23674	5.8
9	96103011	31	311	12840	67	1	100	-69	19	16252	20543	23722	5.7
10	96103013	30	302	12809	55	1	100	-68	18	16234	20521	23687	5.7
11	96103015	28	265	33315	72	1	97	-68	18	16232	20514	23669	5.6
12	96103017	25	305	13981	60	1	99	-68	18	16252	20527	23691	5.6
13	96103109	41	298	10586	92	4	100	-65	10	16236	20506	23660	5.0
14	96103111	46	306	9583	113	1	100	-64	9	16259	20539	23707	5.4
15	96103113	53	314	11359	110	1	100	-64	8	16254	20529	23694	5.6
16	96103115	55	310	11285	124		U/S	-64	8	16210	20475	23633	5.5
17	96103117	50	315	11949	116	1	100	-67	9	16253	20534	23689	5.4
18	9611 109	17	268	2409	45	1	100	-69	20	16301	20541	23693	5.8
19	9611 111	33	268	30464	66	1	100	-69	23	16315	20552	23690	6.2
20	9611 511	69	268	34474	200	0	95	-69	9	16174	20448	23586	6.1
21	9611 611	66	273	10239	230	0	88	-69	7	16165	20397	23475	6.4

MESSAGE SELECTION

		BURST						TRO,PAUSE		WIND INTERP			BB		DD		
		Azi	Rge	hPA	t	Tim	HGT	Tmp	HGT	Tot	Lt4	fgv	TU	DF	TU	DF	TESM*
1	96102813	66	108	22	5	68	2565	-63	1621	52	38	42	22	21	12	15	1204
2	96102815	80	100	25	5	72	2479	-62	1591	142	102	106	31	10	8	19	1333
3	96102817	88	90	27	5	70	2432	-60	1562	146	144	148	18	14	6	20	1040
4	96102909	152	76	30	5	80	2358	-52	951	72	38	42	20	13	3	18	959
5	96102911	143	81	8	5	93	3189	-56	1018	58	2	6	19	14	13	31	1490
6	96102914	145	73	22	5	77	2562	-59	1083	60	60	64	16	4	7	0	1033
7	96102917	146	69	37	5	68	2240	-61	1082	140	140	144	15	11	3	10	979
8	96103009	126	54	20	5	75	2619	-68	1258	96	88	92	18	23	3	20	690
9	96103011	113	67	7	5	97	3336	-69	1285	88	0	2	21	19	12	31	763
10	96103013	107	55	21	5	75	2600	-68	1248	52	26	28	25	12	7	13	674
11	96103015	102	72	6	5	99	3332	-68	1255	146	58	62	17	18	9	27	1223
12	96103017	-99	-99	12	5	87	2920	-68	1257	584	0	400	22	18	9	32	796
13	96103109	100	92	27	5	80	2421	-51	992	6	6	6	16	12	5	16	953
14	96103111	102	113	7	5	102	3323	-58	1200	206	100	104	21	13	13	35	852
15	96103113	114	110	20	5	78	2613	-62	1290	38	38	42	17	15	6	3	237
16	96103115	116	124	8	5	95	3171	-62	1155	158	114	118	19	16	4	26	1022
17	96103117	123	116	10	5	93	3047	-67	1265	162	138	142	15	15	9	31	1376
18	9611 109	95	45	20	5	75	2618	-68	1283	40	40	44	25	20	8	24	840
19	9611 111	86	66	6	5	91	3397	-67	1304	100	2	4	21	21	13	37	1179
20	9611 511	-99	-99	5	0	94	3472	-9	-99	0	0	12	0	0	0	0	996
21	9611 611	-99	-99	4	0	92	3575	-9	-99	0	0	12	0	0	0	0	929

mean corr. press... .98 stand.dev press... .36
mean corr. hum..... .00 stand.dev hum..... .46
mean corr. temp.... -.02 stand.dev temp.... .12

KEY :-

CONTROLS CORRECTIONS P mbsX10, T degrees C X10, U %

Actl = Time of launch (GMT)
L = Start Mode (M=Manual, A=Auto)
MX% = MAX Humidity recorded in flight
DD = Surface Wind Direction (anemometer @ 10m, 10 minute mean)
FF = Surface Wind Speed m/s
ELEV Min = Min Elevation (degrees)
Azi = Bearing degrees
Rge = Flat Range km
WndInt= WIND INTERPOLATION:-
TOT = Total number of seconds of wind interpolation
Lt4 = Total number of seconds of wind interpolation in first minute
fgv = First non-interpolated wind time (seconds from launch)
TU = No. of selected points in message
DF = No. of selected wind points in message
TESM = Elapsed Time of Start Moment (No of seconds from tape read to launch)
t = flight end code (5 = burst)