An Intercomparison of Aircraft Turbulence Measurements Made During JASIN

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ABSTRACT

During the Joint Air-Sea Interaction (JASIN) experiment over the North Atlantic, three aircraft equipped to measure turbulent fluctuations of wind, temperature and humidity flew together in close formation, in order to compare results. These aircraft were the MRF C130, the NCAR Electra and the DFVLR Falcon. Most runs were made in the atmospheric boundary layer. This paper presents the results of this intercomparison exercise. Results are presented in terms of comparisons between variances and covariances which are further investigated by comparing spectra and co-spectra.

Overall, very good agreement is found between the C130 and the Electra, although small differences can be detected. However, these are negligible compared to the scatter usually observed when making measurements in the turbulent atmospheric boundary layer. The Falcon, at an earlier stage of development, also shows reasonable agreement although the amount of available data was much more limited.

1. Introduction

Instrumented aircraft are now widely used for examining the structure of the turbulent atmospheric boundary layer (ABL); for example, Nicholls and Readings (1979, 1981), Lenschow *et al.* (1980), Rothermel and Agee (1980), Coulman (1980), Wyngaard *et al.* (1978). Instrumentation is now sufficiently advanced to enable accurate measurements to be made of a variety of properties, e.g., wind components, temperature and humidity over a wide range of frequencies. With the additional ability to sample large distances in a short time, a comprehensive program of ABL measurements can now be undertaken using a single aircraft. These capabilities have also ensured that research aircraft have played major roles in many large field experiments involving a large number of investigators and are at the center of many research projects. The quality of the data obtained by the aircraft considered in this paper is therefore of central importance to many research workers and will continue to be so for many years to come. However, the calibration and correction procedures which must be applied to the raw data are complex and must often be derived from measurements made in flight in addition to static or laboratory calibrations. Research aircraft, therefore, usually perform a number of specially designed self-calibration maneuvers at regular intervals. Although these allow the effect of deliberately induced maneuvers to be assessed, the unique sampling capability of an aircraft makes it very difficult to compare results obtained in flight with any other form of instrumentation except another aircraft. Carefully executed intercomparisons between aircraft are therefore of considerable importance in objectively assessing the quality of their data and can reveal a great deal about the performance characteristics of their instrument systems which cannot be obtained in any other way. For example, possible systematic errors due to flow distortion are very difficult to quantify experimentally (in a different context, see the papers by Wyngaard, 1981; Weiringa, 1980). Inter-aircraft comparisons provide an important source of information on the possible nature of such effects, even though differences in overall geometry between the aircraft remain fairly limited. Such data thereby complement the results of comparisons with ground-based methods (Nicholls and Readings, 1981), although the range of application of the latter are equally as restricted albeit by different considerations.

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This paper describes the results of side-by-side intercomparisons conducted between three aircraft (the MRF[3] C-130, the NCAR[4] Electra and the DFVLR[5] Falcon) which participated in the Joint Air–Sea Interaction Project (JASIN). This was an international, collaborative exercise designed to investigate the structure of the atmospheric and oceanic boundary layers over an area of the North Atlantic (60°N, 12°W) about 150 km across. The experiment took place during a six-week period in the summer of 1978 and involved the use of buoys, ships, balloons and aircraft. A summary of the whole experiment is given by Pollard *et al.* (1983). The aircraft were used to increase the vertical resolution of ABL measurements by flying in loose formation at different levels. Thus intercomparisons between the different aircraft are clearly vital if measurements are to be correctly interpreted.

These intercomparisons provide a stringent evaluation of the relative performance of the systems, since the aircraft are entirely independent and the comparisons are direct (no assumptions such as Taylor's hypothesis need be invoked as in comparisons with fixed point measurements since the aircraft travel at the same speed). The levels of turbulent fluctuations in the JASIN experimental area and during these intercomparisons were generally rather small, making considerable demands on the instrumentation. In addition, these results also provide a guide to the quality of the measurements obtained from the aircraft during the rest of the JASIN experiment. A series of papers summarizing the main results from JASIN including those from the aircraft program is contained in Royal Society (1983).

The relative accuracies of time averaged parameters measured by aircraft during JASIN have already been investigated by intercomparisons between aircraft and between aircraft and surface measurements (Nicholls, 1983). These results generally display very good agreement, although small but significant biases were revealed in the temperature and dewpoint data. These differences were consistent with the expected accuracies of the calibration methods. A brief summary of some of these results is contained in the Appendix. The main part of this study is confined to fluctuation measurements and extends the work of LeMone and Pennell (1980) who used GATE data to compare certain aspects of the C130 and the Electra. The JASIN experiment was the first field trial of the Falcon turbulence measurement system which was therefore at a much earlier state of development than either of the other aircraft.

2. Instrumentation

The systems used on each aircraft are capable of measuring fluctuations of wind in three dimensions, temperature and humidity, although the actual sensors used are often quite different. Fairly detailed descriptions of instrumentation and methods have appeared in previous publications (Axford, 1968; LeMone and Pennell, 1980; Lenschow, 1971; Nicholls, 1978, 1983) so only a brief summary will be given here. Some important characteristics of the instrumentation are given in Table 1. Details concerning the location and mounting of sensors may be found in the JASIN field phase summary (Royal Society, 1979).

a. Wind measurements

The measurement of wind components from an aircraft is a twofold process, the wind vector being the difference between air motion relative to the aircraft and the aircraft motion relative to the Earth. Each of the aircraft relies on an inertial navigation system (INS) to specify the attitude and velocity of the aircraft with some form of Pitot–static probe to determine airspeed. The wind vector may then be determined if the angles of attack and sideslip (or some equivalent) are measured. Here different techniques are employed on each aircraft: rotating values on the C130 and a combination of fixed and rotating vanes on the Electra while the Falcon uses an instrument with five pressure ports located on a hemispherical probe from which the flow angles may be calculated. (A three axis hot film probe was also mounted on the Falcon, but these data are not included in this paper.)

The results of the wind intercomparisons are presented in an aircraft-oriented co-ordinate system. This maintains the distinction between fluctuations measured by different sensors regardless of aircraft heading. The u component is along the aircraft longitudinal axis, and v is the lateral component.

b. Temperature

All three aircraft were fitted with open-wire reverse flow Rosemount platinum resistance thermometers. The response of this instrument falls off at frequencies above about 1 Hz requiring correction procedures during processing of the data (e.g., Nicholls, 1978). While the devices on the C130 and the Falcon worked well throughout the experiment, temperature fluctuation data from the Electra Rosemount instrument were subsequently found to be seriously in error (see Section 4c). However, a second, independent open-wire resistance thermometer (the "*K*-probe") was also

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TABLE 1. Aircraft instrumentation.

Aircraft	Measurement parameter	Recording resolution	Data frequency (samples per second)	JASIN** Absolute accuracy (rms)	Primary instrument sources
C130	u	0.07 m s^{-1}	20	±0.4 m s^{-1}	Compensated pitot-static probe/INS/Doppler radar/Decca Navigator/LORAN-C mix
	v	0.05 m s^{-1}	20	±0.4 m s^{-1}	Compensated pitot-static probe/Rotating sideslip vane/INS/Doppler radar/Decca Navigator/LORAN-C mix
	w	0.03 m s^{-1}	20	±0.1 m s^{-1}	Compensated pitot-static probe/Rotating angle of attack vane/INS/pressure altimeter mix
	T	0.006 K	20	±0.5 K*	Rosemount open-wire platinum resistance thermometer/Compensated pitot-static probe
	q	0.02 g kg^{-1}	20	±0.5 g kg^{-1}	Microwave refractometer/E.G. & G, dew-point hygrometer/Rosemount thermometer
Electra	u	0.02 m s^{-1}	20	±0.5 m s^{-1}	Pitot-static probe/INS + C130 position update
	v	0.03 m s^{-1}	20	±0.5 m s^{-1}	Pitot-static probe/Fixed sideslip vane/INS + C130 position update
	w	0.03 m s^{-1}	20	±0.1 m s^{-1}	Pitot-static probe/Fixed angle of attack vane/INS
	T	0.02 K	20	±0.5 K*	Rosemount open-wire platinum resistance thermometer/NCAR '*K*-probe' open-wire thermometer/Pitot-static probe
	q	unserviceable	1	±0.5 g kg^{-1}*	Lyman-α hygrometer/E.G. & G. dew-point hygrometer
Falcon	u	0.05 m s^{-1}	100	not determined	Rosemount 858J. 5-hole probe/INS
	v	0.05 m s^{-1}	100	not determined	Rosemount 858J 5-hole probe/INS
	w	0.01 m s^{-1}	100	not determined	Rosemount 858J 5-hole probe/INS
	T	0.025 K	100	±0.5 K*	Rosemount open-wire platinum resistance thermometer
	q	0.01 g kg^{-1}	100	±0.5 g kg^{-1}*	Lyman-α hygrometer/Humicap

* Biases were detected between the aircraft which stayed constant throughout the experiment. Differential accuracy is ±0.1 K and ±0.1 g kg^{-1}.

** During straight and level flight in cloud-free air (Nicholls, 1983).

fitted which proved a successful replacement. Therefore in what follows all Electra temperature data have been derived from the "*K*-probe" unless specifically noted otherwise. On the Falcon, the associated electronics limited the frequency response of the system to about 2.5 Hz.

c. Humidity

Over the oceans fluctuations of humidity are a significant, and frequently dominant, source of buoyancy. The C130 used a refractometer to determine humidity fluctuations, while the Falcon and the Electra were fitted with Lyman-α devices. The Electra instrument failed to work in the boundary layer and consequently no humidity fluctuation data are available from this source. Due to the limited amount of Falcon data available, comparisons with the C130 could be made on only one run. Therefore few conclusions could be drawn and only an example time series is presented here.

3. The data

A total of twenty intercomparison runs were flown at various levels above the Atlantic ocean in the JASIN experimental area. Turbulence data were processed from nine of these runs, seven being within the boundary layer and two well above. Data were obtained from the C130 and the Electra for each of these runs; Falcon data were available for one run only. Furthermore, calibration problems affected the quality of the u and w data from the Falcon on this run, so the comparisons are mainly between the C130 and the Electra. Other details are shown in Table 2. The aircraft were flown in close formation in clear air, the length of the runs varying between 30 and 65 km. The vertical separation of the aircraft was less than 10 m, based on intercomparisons between the pressure and radar derived altitude data (Nicholls, 1983), and the horizontal separation was of the order of 200 m. The data were shifted slightly in time to give maximum correlation of the signals since one plane was often slightly ahead or behind the others and the aircraft clocks were not synchronized to better than 1–2 s. The data were block averaged to give a common 20 s^{-1} sampling rate.

Linear trends were removed from each run prior to calculating the statistical moments and the temperature data were corrected for excursions of the aircraft from the run average altitude by assuming a dry adiabatic lapse rate.

The data were further examined by spectral analysis to detect relative frequency response characteristics. These calculations were performed using a fast Fourier transform routine on records 204.8 s (4096 points) long yielding 26 segments from the nine runs analyzed. The resulting power spectral and co-spectral estimates were then band-averaged to yield six points per frequency decade. For display purposes, all spectra and co-spectra have been multiplied by frequency and normalized with a standard scaling velocity u_s (=0.25 m s^{-1}) or temperature T_s (=0.1 K).

TABLE 2. Details of intercomparison runs.

Date	GMT	Height (m)	Heading (deg)	Aircraft[2]	Plotting symbol
28 July	1519–1524	175	225	C, E	●
28 July	1530–1540	400	047	C, E	■
29 July	1444–1451	90	092	C, E, F	▲ △[3]
29 July	1545–1555	1550[1]	147	C, E	⊙
7 August	1549–1559	95	295	C, E	◆
7 August	1707–1718	1530[1]	138	C, E	○
21 August	1537–1547	185	162	C, E	▼
25 August	1318–1326	145	104	C, E	+
25 August	1330–1340	45	283	C, E	×

[1] These runs were above the ABL.

[2] C = C130; E = Electra; F = Falcon.

[3] Falcon versus C130.

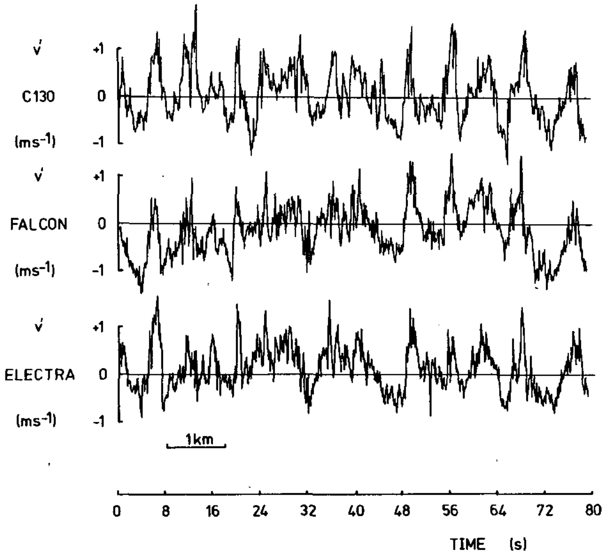

FIG. 1a. Lateral velocity v' from part of the intercomparison run at z = 90 m on 29 July. The Falcon flew in the center; the C130 to port and the Electra to starboard.

Since instrumental characteristics are the primary concern, time and frequency are used as abscissas. These may be converted to distance units with little error by using an average airspeed of 100 m s^{-1}.

4. Results

a. Time series

Examination of time series plots can often reveal problems that are hidden by simple statistical comparisons or spectral analysis, (e.g., spikes in the data); however no such problems are evident. Some examples

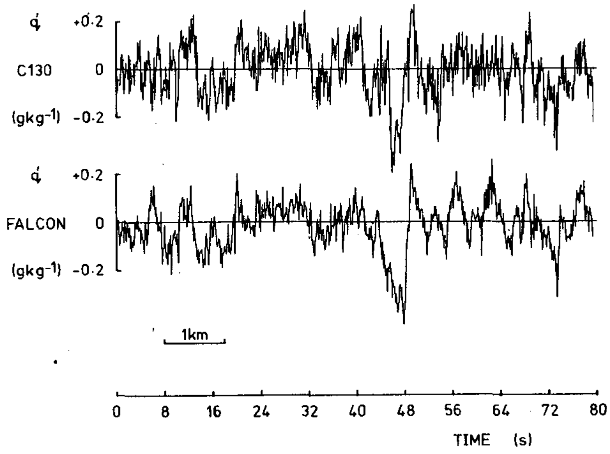

FIG. 1b. As in Fig. 1a, but for specific humidity q'. No Electra data are available.

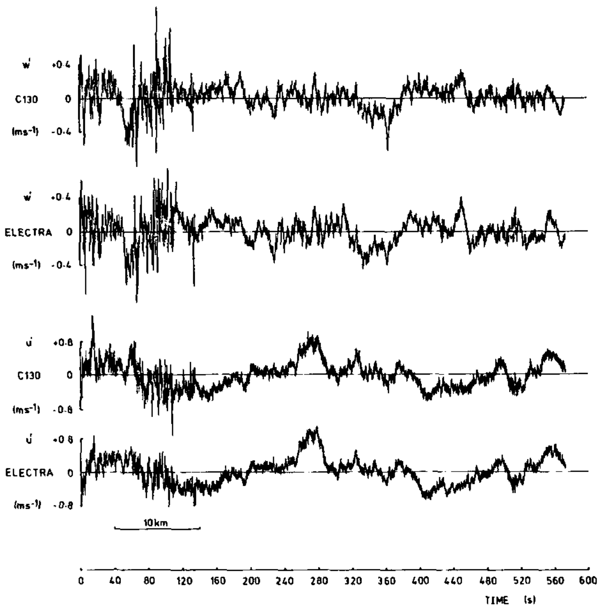

FIG. 1c. Examples of u' and w' from the intercomparison between the C130 and the Electra at $z = 1530$ m on 7 August. This run is well above the boundary layer. Note the change of scale.

of time series are shown in Figs. 1a–d. Figs. 1a,b show data from part of the run at 90 m on 29 July and show good agreement, although the q fluctuations are rather small. The data shown in Fig. 1c comprise the entire run above the boundary layer on 7 August and show excellent agreement over longer periods. Fig. 1d is taken from the same part of the flight as Figs. 1a and 1b and illustrates the small temperature fluctuation levels which were typical of low altitude runs during JASIN. Some correlations between traces can be discerned at longer periods, but the amplitude of the high frequency temperature fluctuations measured by the C130 and the Electra are close to the anticipated noise levels (a few hundredths of a degree for the C130). This is discussed further in Section 4c. High frequency fluctuations are filtered out of the Falcon data by the limited response of the electronics.

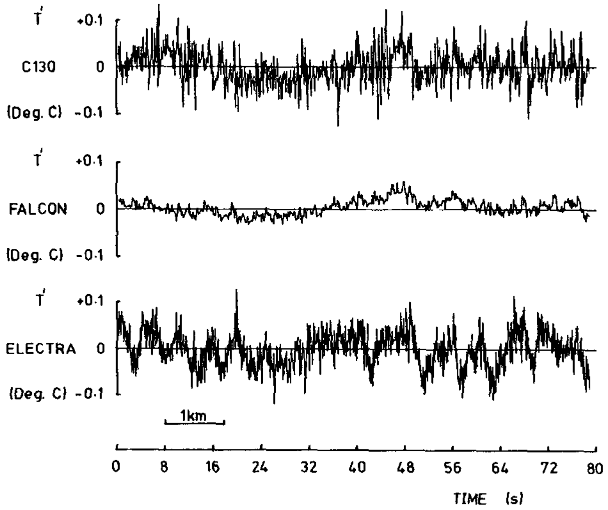

FIG. 1d. As in Fig. 1a, but for temperature T'. The Electra K-probe derived temperature is shown.

Analysis of time-series data during deliberately induced aircraft maneuvers is also useful in determining the effectiveness of the procedure used to compensate for aircraft motion. Fig. 2 shows a typical example taken from a pitch, roll and yaw maneuver performed by the C130 during JASIN. These maneuvers are many times larger than the perturbations normally encountered in nominally straight and level flight, but even so, the effect on the measured wind velocity components is seen to be small. However, the lateral velocity v is sensitive to asymmetric flight conditions, especially during the yaw maneuver where fluctuations of order 1 m s^{-1} are correlated with sideslip angle, as shown by the arrows. This is believed to reflect flow distortion effects which are particularly severe in large angle asymmetric maneuvers. For this reason, wind measurements are not as reliable during turns and seldom used. This effect is usually negligible in straight and level flight.

b. *Variances and covariances*

The variances measured by the aircraft on each run are compared in Fig. 3. Overall, the agreement is excellent between the Electra and the C130 although the Electra estimates of $\overline{u'^2}$ appear to be slightly lower than those from the C130, while the vertical fluctuations are slightly higher. The Falcon lateral velocity variance agrees well with the other aircraft. The temperature variance agrees well between the C130 and the Electra K-probe although the Falcon, as expected, measured a considerably lower value due to the fault already mentioned. Examination of individual spectra and the analysis presented in Section 4c suggests that the agreement between the C130 and the Electra at the smallest values of $\overline{T'^2}$ probably reflects their similar noise levels as well as the accurate measurement of small temperature fluctuations.

In consideration of all nine runs, the log-average ratios of variances measured by the C130 and the Electra were found to be:

Average variance ratio	$\overline{u'^2}$	$\overline{v'^2}$	$\overline{w'^2}$	$\overline{T'^2}$
$\frac{\text{Electra}}{\text{C130}}$	0.87	0.94	1.06	1.05

Logarithmic averaging of the distribution of ratios is used to ensure that random scatter in the variance

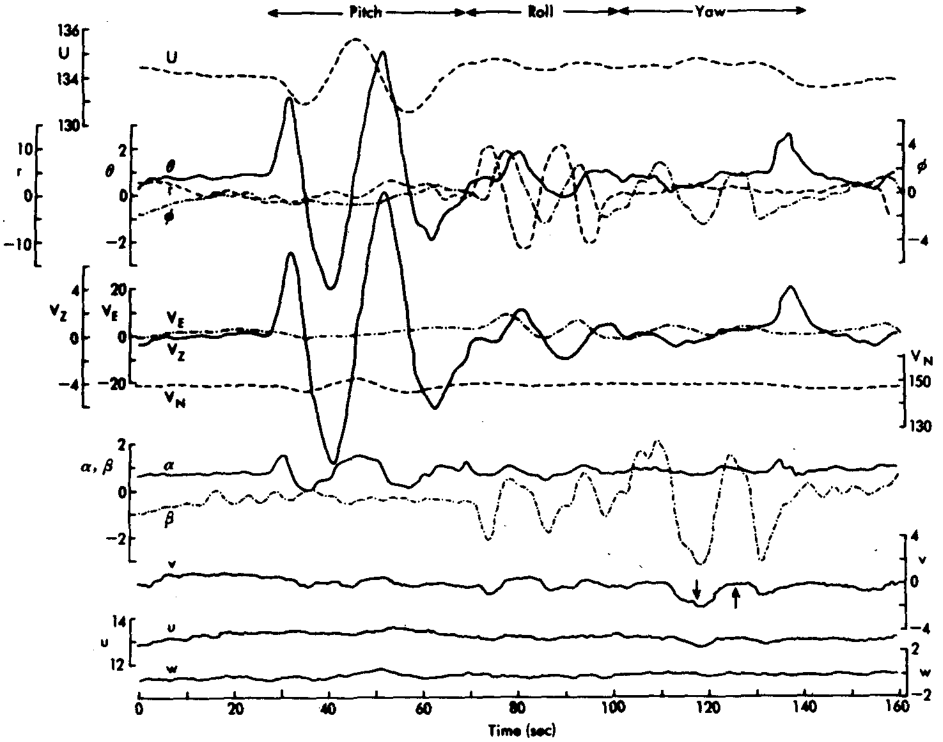

FIG. 2. Traces from a pitch roll and yaw test performed by the C130. The lowest three traces show the variation of the measured wind components u, v and w. The other traces show attack and sideslip angles (α, β); aircraft velocity components (V_N, V_E, V_Z); pitch, roll and heading angles (θ, r, ϕ) and the true airspeed (U). The velocity components have not been corrected for low frequency drift (see Appendix). Units in the figure are degrees (angles) and m s^{-1} (velocities).

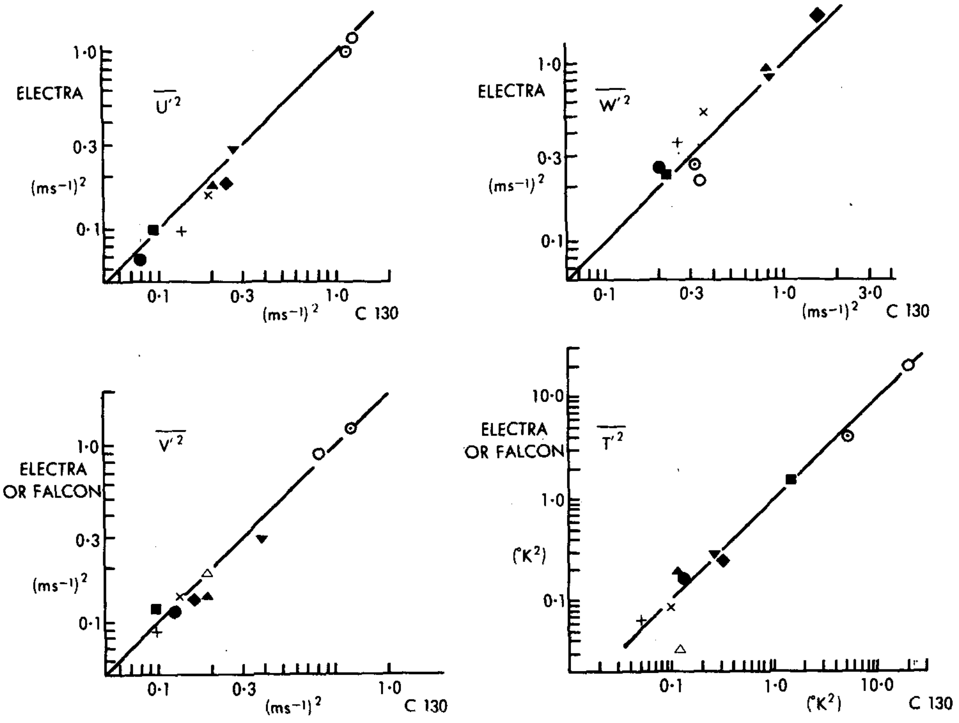

FIG. 3. Comparisons of variance measurements. The lines represent perfect agreement; a key to the symbols is given in Table 2.

measurements will yield an unbiased mean ratio (i.e., 1).

Figures 4a,b show comparisons of the *uw*, *vw* and *wT* covariances. The measurements made above the boundary layer have been excluded as covariance measurements in stably stratified, intermittently turbulent conditions (e.g., see Fig. 1c) are not statistically reliable. Here, a small spatial separation can lead to widely divergent results.

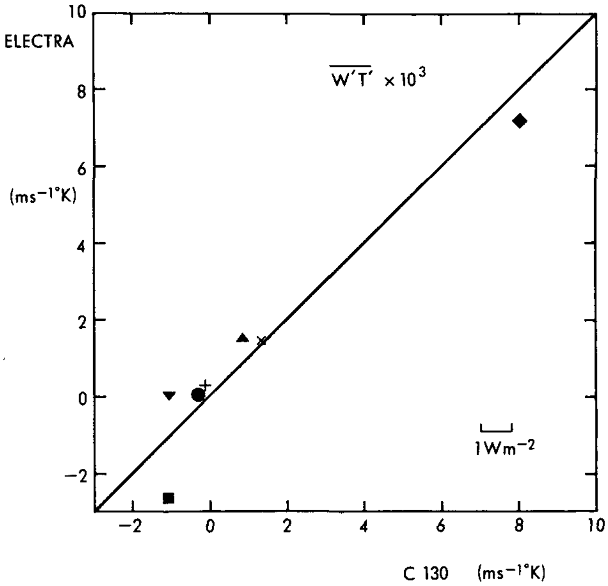

FIG. 4b. As in Fig. 2a, but for $\overline{w'T'}$ measurements.

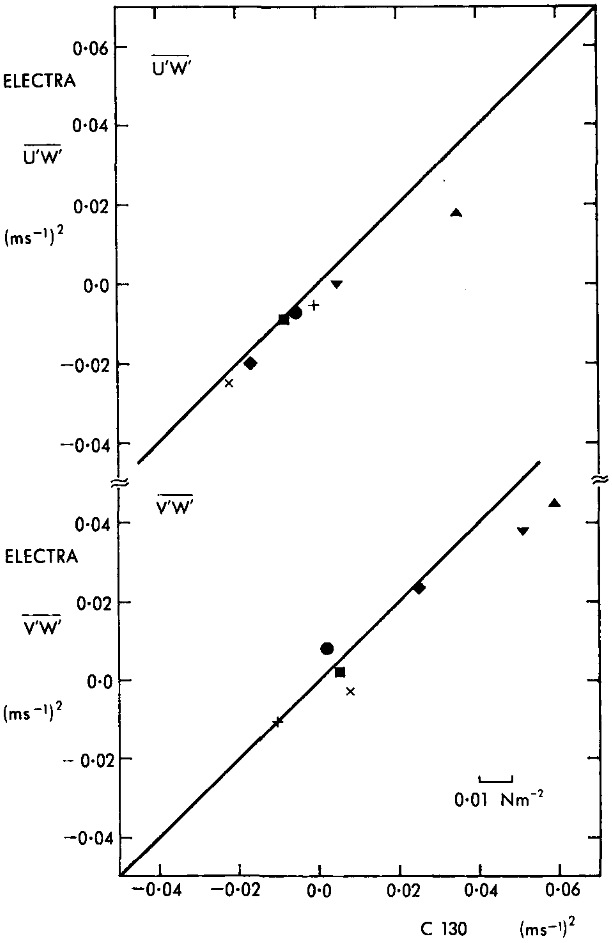

FIG. 4a. As in Fig. 2a, but for $\overline{u'w'}$ and $\overline{v'w'}$ measurements.

There is clearly a good measure of agreement and although the $\overline{u'w'}$ and $\overline{v'w'}$ values from the C130 tend to be slightly more positive than those from the Electra, the differences are very small. The largest disagreement occurs on 29 July where differences of about 0.015 m^2 s^{-2} are observed in $\overline{u'w'}$ and $\overline{v'w'}$. Closer investigation of this run reveals rather large variations in $u'w'$ and $v'w'$ especially near the start of the run, with much closer agreement in the latter part. This difference therefore appears in response more to sampling than instrumental deficiencies. To put these differences into perspective, it is worth noting that the sizes of the diagreement seen in Figs. 4a and b are considerably less than the scatter usually observed between successive repeated measurements in the boundary layer made with identical instrumentation because of natural statistical variability. For example, to measure an average quantity $\bar{f}$ to an accuracy ϵ (i.e., $\bar{f} \pm \epsilon\bar{f}$) in turbulent conditions, Lumley and Panofsky (1964) show that the distance over which the average must be taken is given by

$$D \approx 2\frac{\overline{f'^2}}{\bar{f}^2}\frac{l}{\epsilon^2}, \qquad (1)$$

where $\overline{f'^2}$ is the variance of f about the mean $\bar{f}$ and l is the integral scale of f. If [following Wyngaard (1973)] we approximate l by the dominant eddy scale λ_m, the wavelength of the w-spectral peak, then the expected accuracy of a single measurement of $\overline{u'w'}$ may be expressed as

$$\epsilon_{uw} \approx \left(2\frac{\overline{(u'w')^2}}{(\overline{u'w'})^2}\frac{\lambda_m}{D}\right)^{1/2}. \qquad (2)$$

Close to the surface, in neutral conditions $\lambda_m \approx 2z$ (e.g., see Fig. 5 or Kaimal *et al.* (1972), Nicholls and Readings (1981)]. Also Wyngaard (1973) reported that $\overline{(u'w')^2}/(\overline{u'w'})^2 \approx 10$ in the surface layer with near neutral stability so that

$$\epsilon_{uw} \approx \left(\frac{40z}{D}\right)^{1/2}. \qquad (3)$$

Provided this expression can be extended to aircraft flight levels, the insertion of typical JASIN values of $z = 100$ m and $D = 70$ km yields $\epsilon_{uw} \approx 0.25$. This

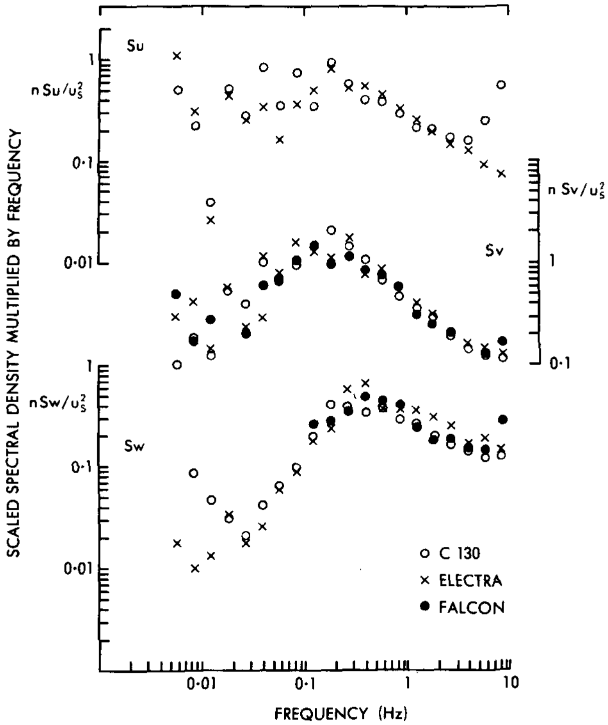

FIG. 5. Examples of velocity spectra taken from the intercomparison run on 29 July at $z = 90$ m. The spectral estimates are multiplied by frequency and scaled by u_s^2.

is in agreement with the scatter observed from corresponding measurements made during JASIN. Since typical values of $\overline{u'w'}$ at low levels were 0.1 $m^2\ s^{-2}$, this scatter was generally observed to be ± 0.025 $m^2\ s^{-2}$ which is considerably larger than that seen in Fig. 4a.

c. Spectra

Examples of the velocity spectra are given in Fig. 5. These show that the C130 and Electra are broadly in good agreement, although some small differences are apparent which are investigated more thoroughly below. The Falcon v-spectrum is also in close agreement with the other aircraft. Due to known shortcomings in the calibration and processing of these data, the Falcon vertical velocity data were contaminated by aircraft motion at frequencies below 0.1 Hz. The w-spectrum has therefore been cut off at this point (thus no cospectral measurements could be shown in Fig. 4). At higher frequencies good agreement is observed, but the Falcon spectra display increased values at about 8 Hz owing to vibration of the nose boom at this frequency. The C130 u-spectrum also increases rapidly at about 3 Hz due to the combined effects of noise generated in the tubing of the Pitot-static system and aliasing (Nicholls, 1978). The noise is believed to be due to "organ-pipe" resonance of air within the 7 m long pressure tubes connecting the ports at the tip of the noseboom with the transducers located aft. Using the geometry applicable to the C130 installation, we note that the theoretically derived response predicts a noticeable increase in amplitude at frequencies greater than 3 Hz which peaks at about 10 Hz (e.g., LeMone and Pennell, 1980). This is very similar to the characteristics observed in the spectra as shown in Fig. 5 if allowance is made for the effects of aliasing around the 10 Hz Nyquist frequency.

To investigate further the relative differences between the C130 and the Electra, we have chosen to present ratios of spectra (denoted R_u, R_v, etc.) rather than power spectra themselves. This allows any differences due to instrumental effects to be demonstrated independent of the actual forms of the individual spectra which will vary considerably from run to run. The entire intercomparison set of 26 spectra from each aircraft can then be combined to increase the statistical significance of the final results considerably. The procedure followed was to ratio the pairs of band-averaged spectral estimates and then to average logarithmically the resulting 26 ratios in order to define the mean ratios as a function of frequency. These are shown in Fig. 6. Estimates of the standard error δR, have also been calculated for each band from

$$\frac{\delta R}{R} = 2(sg)^{-1/2}, \tag{4}$$

where s is the number of spectral estimates per band and g (=26) is the number of ratio estimates averaged (Bendat and Piersol, 1971). For clarity, these error values are represented by shaded areas on either side of $R = 1$ on each of the graphs in Fig. 6.

Although R_u, R_v and R_w are close to unity over a wide band of frequencies, some consistent differences are apparent. The Electra appears to measure u and v spectral densities which are slightly lower than those measured by the C130 over a wide range of frequencies centered on ~0.1 Hz. In fact the average R_u in the frequency band 0.01–1 Hz is only 0.85. This is a frequency range where the u-variance is large which, together with the additional noise in the high frequency C130 u-measurements, explains the slight bias in the $\overline{u'^2}$ measurements seen in Fig. 3. In the same frequency band the average values of R_v and R_w are 0.89 and 1.08, respectively. However, $\overline{w'^2}$ is affected more than $\overline{v'^2}$ since this range of frequencies contains a larger proportion of the total vertical velocity variance than the horizontal velocity variances.

The cause of this slight disagreement at mid-frequencies is difficult to determine, but it would appear to be due to a slight mismatch between the high frequency flow measurements and the aircraft motion compensation terms. These are checked on both aircraft by monitoring the effect of deliberately inserted maneuvers (as shown in Fig. 2). One possibility might

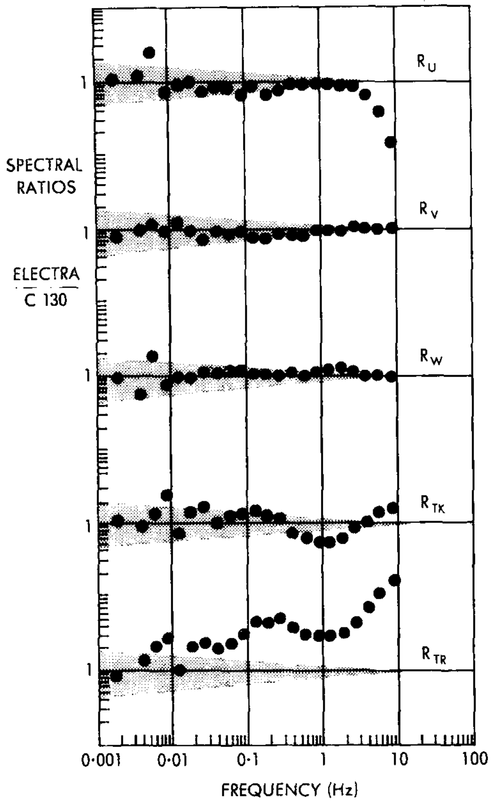

FIG. 6. Average ratios of spectra from the C130 and Electra. Ratios have been calculated using both Electra Rosemount (R_{TR}) and K-probe (R_{TK}) temperature data. The stippled areas represent the expected standard errors of the ratios (see text) but are centered on $R = 1$ for clarity.

be that the airflow near the sensors is disturbed during these maneuvers relative to straight and level flight, leading to a slight miscalibration of certain terms. However, such effects are extremely difficult to investigate and the overall effect remains small.

Another small but significant and presently unexplained feature occurs at $f \approx 2$ Hz where R_w increases to about 1.3. This can be observed in individual spectra (e.g., Fig. 5), although at this frequency it will generally have little effect on either variance or covariance measurements. However, it could affect the determination of the turbulent kinetic energy dissipation rate by inertial subrange methods (e.g., Nicholls and Readings, 1981) if spectral values near this frequency were to be used.

The comparisons of temperature spectra show larger deviations from unity. Two examples are shown in Fig. 6, using data from both Electra thermometers. The Electra Rosemount derived temperature is clearly in error over the entire frequency range although the K-probe values agree reasonably well with those of the C130. While the slightly larger scatter of points is probably due to the very small temperature fluctuation levels encountered, there are significant deviations at $f > 0.3$ Hz when the general shape is mirrored in both comparison curves. This suggests that the source of disagreement is the C130 temperature data. Moreover, the shape of the R_{TK} curve is similar to that of the frequency response correction routine applied to C130 data (Nicholls, 1978). Thus it is probable that disagreement is caused by the correction routine often operating on a noise dominated spectrum rather than the true temperature signal which lies below the detection threshold.

d. Co-spectra

Figure 7 shows examples of *uw* and *vw* co-spectra measured by the three aircraft on 29 July, but since the heat flux was so small on this run, the *wT* co-spectra shown in the figure are taken from 7 August. In general, the overall shapes of the co-spectra agree reasonably well although differences between aircraft for a single co-spectrum are fairly large, as indicated in the figure. In order to determine whether the factors affecting the spectra noted in the foregoing also influence the co-spectra, it is again necessary to consider the whole data set. However, such an analysis is more complicated than was the case for the power spectra since co-spectral estimates are of either sign and frequently pass through zero. Comparisons of the covariances shown in Fig. 4a suggest that the C130 derived values tend to be slightly more positive than the Electra values. To check whether this could have been caused by persistent spurious correlations, the

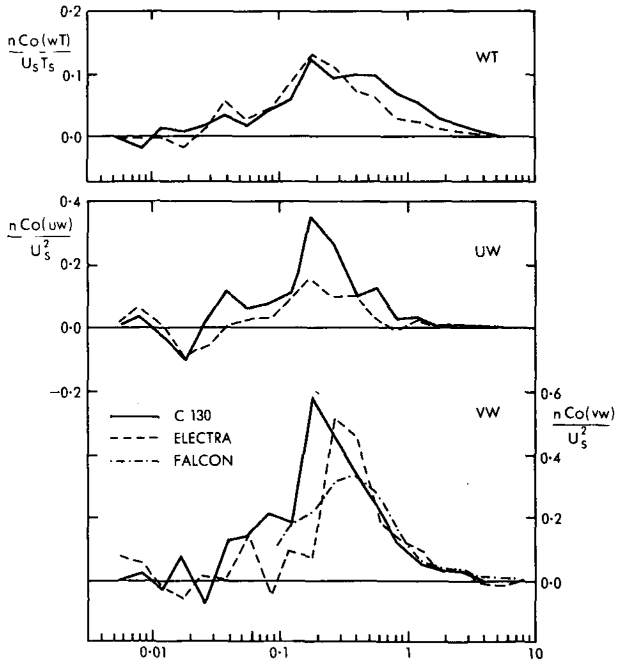

FIG. 7. Example *uw* and *vw* co-spectra taken from the intercomparison run on 29 July at $z = 90$ m and *wT* co-spectra from the 7 Aug run at $z = 95$ m. The co-spectra are multiplied by frequency and scaled by u_s^2 or u_sT_s.

differences between pairs of Electra and C130 co-spectral estimates were computed. The averaging of these 26 differences together then reveals any characteristic under or over correlation of one aircraft relative to the other, while the scatter about the mean gives an estimate of the magnitude of these differences. The results are shown in Fig. 8. The size of the differences can be compared with the typical co-spectra shown in Fig. 7, which are normalized in exactly the same way and are therefore directly comparable numerically. As a further guide to the scaling used in Fig. 8, the square area represents a momentum flux of about 0.004 N m^{-2} (about 5% of a typical surface value during JASIN) or a sensible heat flux of about 1.5 W m^{-2}. Both the *uw* and *vw* differences shown in Fig. 8 tend to be positive over a wide frequency range, which is consistent with the slight bias observed in Fig. 4a, but suggest that the causes of the differences observed in the power spectra do not seriously affect the covariance measurements. The differences are in any case small and while this analysis is rather crude, no further investigation would seem to be justified. The average *wT* co-spectral differences are very small, as are most of the covariances themselves, precluding any further conclusions being drawn.

5. Conclusions

During the JASIN experiment, a large body of data was obtained from side-by-side intercomparison runs between the C130 and the Electra. Some similar data was also obtained from a third aircraft, the Falcon, although this was its first trial and consequently much of the instrumental system and subsequent processing were still at an experimental stage. The results of the analysis of these data may be summarized as follows:

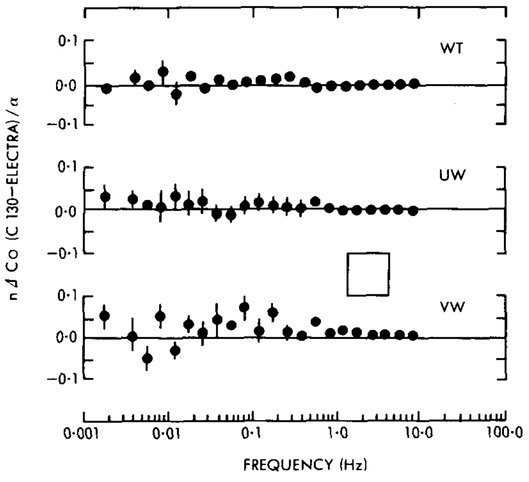

FIG. 8. Mean differences of co-spectra from the C130 and Electra. The differences are multiplied by frequency and scaled by $\alpha = u_*^2$ for *uw* and *vw* co-spectra and $\alpha = u_*T_*$ for *wT* co-spectra. The error bars illustrate the scatter of the differences (1 σ). The covariance represented by the square area is given in the text.

1) Overall, a high degree of agreement has been achieved between the aircraft for velocity and temperature fluctuation measurements (but see result 5). This is particularly encouraging since the instrument systems were significantly different in many respects and were entirely independent, including the calibration and data processing stages. These intercomparisons demonstrate the quality of the aircraft data obtained during the JASIN experiment and confirm that quantities measured by the different aircraft may be combined freely together.

2) Small biases were detected between the C130 and Electra velocity variance measurements. The Electra measured slightly lower values of $\overline{u'^2}$ and $\overline{v'^2}$ but slightly larger $\overline{w'^2}$ values. On further investigation using spectral techniques, the C130 *u* and *v* data had relatively higher contributions from a mid-frequency band ($0.01 < f < 1$ Hz), while the *w*-spectra were slightly lower than the Electra over a wider range. Additional noise from the C130 Pitot-static system at $f > 3$ Hz was also a major contributory factor to the bias in $\overline{u'^2}$ measurements.

3) The small differences in mid-frequency mentioned above affected the covariances to a much lesser degree although these may have contributed to a small bias in the $\overline{u'w'}$ and $\overline{v'w'}$ measurements. Otherwise, the C130 and Electra *uw* and *vw* covariances agreed well, the differences measured being much smaller than the expected scatter of the measurements about the "true" mean due to statistical variability.

4) As JASIN was the first full trial of the Falcon turbulence measurement system, the amount of data available proved to be limited. However, despite this, the lateral velocity fluctuations agreed well with the other aircraft, as did the high frequency part of the vertical velocity spectrum. However, a more thorough investigation of its capabilities must await a larger collection of data.

5) The Roesmount derived temperature fluctuations from the Electra were found to be totally different to those measured by the independent *K*-probe and the Rosemount derived values on the C130, probably due to a recording or processing fault. The $\overline{T'^2}$ and $\overline{w'T'}$ measurements from the Electra *K*-probe agreed reasonably well with the C130 values although only one $\overline{w'T'}$ measurement was considerably larger than zero. Intercomparisons involving temperature measurement were affected by the very small temperature fluctuations which were often close to the expected instrumental noise levels. A comparison of Electra *K*-probe and C130 temperature spectra showed poorer agreement at frequencies greater than 0.3 Hz, probably caused by the application of the C130 frequency response correction routine to a noise dominated spectrum. However, this implies that the signal

levels in this range of frequencies were extremely small and that the $\overline{T'^2}$ or $\overline{w'T'}$ measurements were not significantly affected.

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APPENDIX

JASIN Mean Value Intercomparisons

The JASIN mean value intercomparisons were designed to assess the quality and stability of the calibrations of individual platforms or sensors and to define the corrections needed, if any, to reduce all of the measurements to a common standard. In practice, this was achieved by separately intercomparing ship and airborne measurements and coupling these together with low-level flights past ships, as the opportunity arose. Some of the results relevant to the main paper are briefly summarized in this Appendix. A full account of these analyses is given by Nicholls (1983). This Appendix is mainly concerned with intercomparisons of winds, temperature and dew point between aircraft, although other findings are summarized.

Data were selected from runs, as explained in Section 3. Each run was subdivided into one minute long subsections during which the mean and standard deviation of each parameter were calculated. Data from parts of runs where the aircraft were not in close proximity or maneuvering were rejected. These averages formed the basis for the analysis, each one being represented by a symbol in the graphs below.

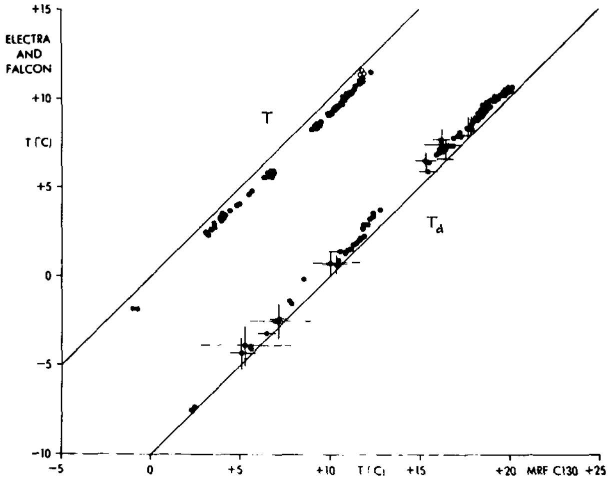

FIG. A1. Comparison of mean temperature and dew-point measurements made by the JASIN aircraft. Each symbol represents a one minute mean value; the error bars show the standard deviation within this period where significant. Electra versus C130 shown as ●, Falcon vs C130 shown as ○. The line represents perfect agreement since the dew-point values are shifted to the right by 10°C.

TABLE A1. Summary of JASIN average quantity aircraft intercomparisons.

Quantity	Aircraft inter-compared*	Bias detected	Relative accuracy following removal of constant offset
Static pressure	C, E	0	±1 mb
Radar altitude	C, E	(C − E) ≈ 2%	2%
Temperature	C, E, F	(C − E) = 0.8 K	±0.1 K
		(C − F) = 0.4 K	±0.1 K
Dew point	C, E	(C − E) = −0.7 K	±0.3 K
Wind components	C, E	0	±0.5 m s^{-1}
Sea surface (radiation) temperature)	C, E, F	0	±0.3 K

* C = C130; E = Electra; F = Falcon.

Figure A1 shows comparisons of temperature and dew-point data. The Electra temperature data have here been taken from the Rosemount thermometer since time averaged data (periods of a minute or longer) were not significantly affected by the fault which rendered the faster fluctuation data unusable (e.g., see Fig. 6). As the Rosemount device was also found to have a slightly more stable calibration throughout the duration of the experiment than the *K*-probe, it was preferred for time averaged measurements. Clear but repeatable biases are evident between the aircraft, although correction to a common standard can be achieved. The magnitude of the bias and the differential accuracy which can be obtained after correction are listed in Table A1, together with corresponding results for other parameters.

The wind component intercomparisons between the C130 and the Electra in Fig. A2 show particularly good agreement. The winds from both aircraft have been corrected by results obtained on self-calibration ma-

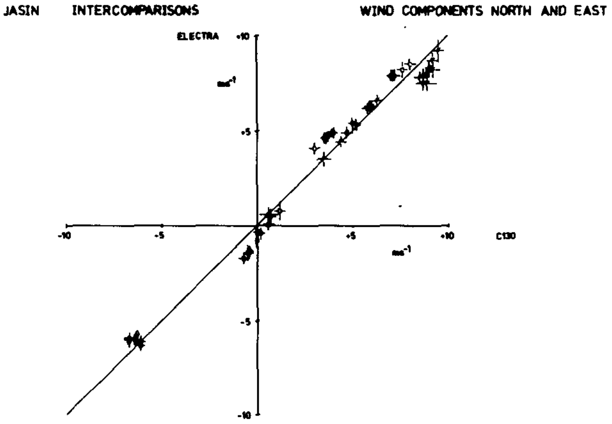

FIG. A2. Comparison of fully corrected wind component measurements between the C130 and the Electra. Symbols as in Fig. A1. Different letters represent results from different intercomparisons.

neuvers and by renavigation. This latter procedure uses recorded navigation aid data to accurately specify the C130 position and thereby remove spurious low frequency aircraft velocity errors from the measured winds, as described in Nicholls (1983). Signals from the Decca Navigator and LORAN-C navigation systems were recorded continuously while in flight and subsequently processed to yield two independent series of precise position information. These generally differed by less than 1 km within the experimental area, whereas the relative accuracy of each system was considerably better. By comparing these with inertially derived positions and with additional reference to Doppler radar ground speed data, errors in the inertially derived aircraft horizontal velocities could be accurately specified and reduced by a factor ~5–10. After successful implementation of these corrections, errors in the measurement of airflow relative to the aircraft, the other major component in wind finding, were deduced using self-calibration maneuvers and reduced by a similar fraction. Since the aircraft generally flew in loose formation, the Electra position could be referenced to that of the C130, enabling a similar correction procedure to be applied. Typical errors removed from the ground speed components of both aircraft were sinusoidal oscillations with an approximate period of 84 min and amplitudes of 1 to 2 m s^{-1}. The results shown in Fig. A2 are therefore in fully corrected form. However, since intercomparisons were performed at the beginning or at the end of a flight, the specification of corrections at these times is actually more uncertain than during the remainder of the measurement runs because of time series end-effects on the derivation of the error terms (Nicholls, 1983). The requirement that the aircraft fly in loose formation for some time prior to the intercomparison has substantially reduced the number of occasions on which comparisons can be made. However, the limited number of points in Fig. A2 show that a substantial improvement in accuracy of the aircraft wind measurements has been achieved, a conclusion reinforced by comparisons between ships and aircraft (Nicholls, 1983). These also suggest that an accuracy of ~ ±0.5 m s^{-1} for a one-minute average wind measurement can be maintained throughout a flight. This value is consistent with a comprehensive error analysis (Nicholls, 1983). Note that without this correction procedure, subsequent wind measurements would have contained m s^{-1} errors. This alone would have prevented any attempt to measure the ageostrophic terms within the boundary layer which are of the same magnitude. In fact, the wind measurements obtained, coupled with a method of accurately determining the horizontal pressure gradient from aircraft data, the direct stress measurements, and supporting information from surface platforms enabled the momentum balance to be satisfactorily closed throughout the depth of the near neutral marine atmospheric mixed layer observed during JASIN (Nicholls *et al.*, 1983).

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