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Three-Aircraft Intercomparison of Dynamical and Thermodynamical Measurements During the Pre-EUCREX Campaign

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Abstract

Aircraft are frequently used as a measuring platform in the atmosphere during boundary layer studies, in situ cloud experiments, and validation programmes for remote sensing tools such as wind profilers. Dynamical and thermodynamical measurements at turbulence resolution obtained by three European instrumented research aircraft during the Pre-EUCREX intercomparison campaign are analysed in order to assess their relative accuracy. Unique formation flights have been performed in intense and weak turbulence fields in the marine boundary layer as well as in the free atmosphere up to an altitude of 8 km, where many sensors work close to their limits. Mean wind and temperature, variances of wind components and temperature fluctuations, and turbulent momentum and heat fluxes are analysed. Spectra of the three wind components for different turbulence intensities are discussed. The intercomparison of mean winds shows differences up to about 2 ms^{-1} between the systems. This is mainly due to position errors caused by the inertial navigation systems (INS), which are identified by comparisons against Global Positioning System (GPS) positions. Typical deviations in temperature range between 0.3 and 0.5 K. In higher intensity turbulence the statistics and spectral results show very good agreement between the three aircraft. In weak turbulence, as often encountered in the free atmosphere, the influence of measurement systems on the results is quite evident. Such measurements should be conducted and interpreted with care. This study indicates some possibilities for improvement of the measurements. For mean wind measurements, to obtain the accuracy needed for many studies, the use of GPS data for wind component calculations is indispensable. Some of the findings of this study have already motivated modifications by the aircraft operating agencies.

Zusammenfassung

Flugzeuge werden immer häufiger als Meßträger in der Atmosphäre eingesetzt. Ihre Eigenschaften werden insbesondere für Grenzschichtexperimente, wolkenphysikalische Experimente und Validationsprogramme für Fernmeßgeräte, wie z.B. Windprofiler, geschätzt. Hier werden dynamische und thermodynamische Messungen in Turbulenzauflösung analysiert, die von drei instrumentierten europäischen Forschungsflugzeugen während des Pre-EUCREX Vergleichsflugexperimentes gewonnen wurden, um die relative Genauigkeit der Messungen abzuschätzen und die Anwendbarkeit und Grenzen der Messungen aufzuzeigen. Vergleichsflüge wurden in Gebieten mit hoher und geringer Turbulenzintensität in der Grenzschicht und auch in der freien Atmosphäre bis zu einer Höhe von 8 km durchgeführt. Mittlere Winde und Temperaturen, Varianzen der drei Windkomponenten und Temperaturfluktuationen sowie turbulente Impuls- und Wärmeflüsse werden verglichen. Energiedichtespektren der drei Windkomponenten für unterschiedliche Turbulenzintensitäten werden diskutiert. Der Vergleich von mittleren Winden zeigt Abweichungen von bis zu 2 ms^{-1} zwischen den Meßsystemen, die hauptsächlich auf Fehler in der Bestimmung der Flugzeugposition durch die Trägheitsnavigationssysteme zurückzuführen sind, wie ein Vergleich mit Positionen vom Global Positioning System (GPS) zeigt. Typische Temperaturabweichungen liegen im Bereich von 0.3 bis 0.5 K. In den Fällen mit höherer

Turbulenzintensität stimmen die statistischen Größen und auch die Turbulenzspektren sehr gut überein. In schwacher Turbulenz, wie sie häufig in der freien Atmosphäre vorherrscht, wird der Einfluß der Meßsysteme auf die Meßgrößen deutlich. Die Interpretation dieser Daten ist dann nur bedingt möglich. Die Studie zeigt auch einige Möglichkeiten zur Verbesserung der Messungen auf. Zur Berechnung des mittleren horizontalen Windes mit einer Genauigkeit, wie ihn viele Untersuchungen benötigen, ist die Verwendung von GPS-Daten unverzichtbar. Die gewonnenen Erkenntnisse aus den Vergleichsflügen haben inzwischen schon zu Modifikationen von Komponenten in den Meßsystemen geführt.

1 Introduction

Instrumented research aircraft are nowadays an indispensable tool used during many meteorological field studies. They are applied as a carrier of all types of measurement equipment including both *in situ* instruments and remote sensing devices. The measurements are gathered with high spatial resolution, in a line/area averaging or vertical profiling mode, or a combination of both. Aircraft have the advantage of high mobility in three dimensions and are able to sample over large areas in a relatively short time, to reach remote locations or to follow events such as plumes or clouds and sample them in a quasi lagrangian mode. Therefore they are often used with other measurement systems for boundary layer studies over complex terrain, cloud- or pollution studies or validation experiments for ground based or spaceborne active and passive remote sensors such as windprofilers, radars or radiometers.

Beside the aforementioned advantages there are some disadvantages which are also based on the high mobility and speed of the aircraft. Attitude angles and velocity of the platform over the ground have to be determined with the highest accuracy if vector quantities are to be measured. Because of the high speed of immersed sensors relative to the free airstream compressibility effects and adiabatic or non-adiabatic heating corrections have to be applied. Flow distortion by the fuselage of the aircraft or by sensors might affect the results seriously in the case of flux and scalar measurements (Wyngaard, 1981; 1988). Some of these distortion problems can be addressed by wind tunnel investigations or numerical flow simulations (Cooper and Rodgers, 1991).

The high demands for accuracy and time resolution of airborne sensors require a careful calibration programme of the whole system, starting on the ground. However, ground calibration alone is not sufficient, since many effects occur only on moving platforms or are dependent on airspeed and therefore must be determined in flight. Apart from tower fly-bys, special manoeuvre procedures as described in Guillemet et al. (1977) and Bögel and Baumann (1991) are helpful for tests and calibration of a wind measuring system of a single aircraft. If several aircraft are available and relative accuracy is of interest, close formation intercomparisons directly sensing almost the same flow might also be extremely useful, as shown by earlier studies (e.g. LeMone and Pennell (1980); Nicholls et al. (1983); Richner (1985); Grant and Zank, (1986); MacPherson et al. (1992)). The latter have concentrated only on measurements in the boundary layer. Here we present results from formation flights both in the boundary layer and also in the upper troposphere. In this region of the atmosphere the high aircraft speed, low temperatures, very low humidity, and frequently weak turbulence cause many sensors to come close to their specified limits. Since the turbulence characteristics of the upper troposphere are not very well known, there is a special need for reliable observational data for this region to validate assumptions used by various numerical modelling approaches. The needs of specific research areas for airborne instruments and their required performance are summarised by Cooper and Baumgardner (1989).

Cloud research studies like the International Cirrus Experiment (ICE)/European Cloud and Radiation Experiment (EUCREX) programme (Raschke, 1988; Raschke et al., 1991) very often rely on aircraft measurements to assess the relevant flow characteristics in the cloudy environment. Mean horizontal wind vectors and turbulence statistics which characterize the fine scale structure of the velocity field, turbulent fluxes of momentum, heat and moisture, and dissipation rates of turbulent kinetic energy (TKE) are of interest. Therefore, both high accuracy and high resolution in time is required. During previous and planned ICE/EUCREX intensive field campaigns multi-aircraft missions have been or will

be essential to gathering sophisticated, complex datasets of atmospheric variables. In order to construct consistent datasets it is fundamental to compare accurately the measurements of the participating aircraft relative to each other. This comparison is even more valuable where it is known that one aircraft has superior sensors or better calibration procedures.

Results from intercomparison segments analysed for ICE 1989 revealed that some uncertainties existed in measurements of wind and turbulence, humidity, and longwave radiation (Quante et al., 1991; Saunders et al., 1992), which need to be addressed further. During the Pre-EUCREX campaign conducted in January 1992 dedicated intercomparison flights were carried out between the Falcon (German Aerospace Research Establishment, DLR), Hercules (Meteorological Research Flight, MRF), and Merlin (French Met. Office) aircraft. The main objectives of this campaign were to assess and improve the accuracy of aircraft measurements in the upper troposphere under conditions typical of those encountered at cirrus level. Humidity measurements were of prime interest, but in addition other thermodynamical, dynamical, radiation, and microphysical parameters were subject of investigation. Initial results concerning all sensors can be found in Quante et al. (1993). Ström et al. (1994) summarized the findings of the intercomparison of humidity measuring instruments. In this paper we report on the selected results of dynamical and thermodynamical measurements.

After a brief presentation of the basic principles of airborne sensing of wind and temperature, we introduce the aircraft and relevant sensors in Section 3. Section 4 provides information on missions flown during Pre-EUCREX and discusses briefly the synoptic situations. Section 5 presents and discusses the method of data processing and the results of the comparison. The paper is concluded in the final section.

2 Basic Principles of Airborne Wind and Temperature Measurements

Since air flow and temperature measurements by an instrumented aircraft are not straight forward, the underlying principles are briefly presented in this section.

Wind Components

Most atmospheric studies require the measured data within some earth based reference system in order to combine the results with those of other available platforms. Therefore the wind measured by an aircraft with respect to its own coordinate system has to be transformed to a ground based system. This implies that the movement of the aircraft in a ground system has to be measured with high accuracy. This is the meaning of the well-known wind equation (Figure 1a.)

$$\vec{V}_W = \vec{V}_E - \vec{V}_A$$

where $\vec{V}_W$ is the wind vector, $\vec{V}_E$ is the velocity of an aircraft fixed reference point (e.g. the tip of a nose boom) relative to the earth, and $\vec{V}_A$ is the velocity of the same reference point relative to the

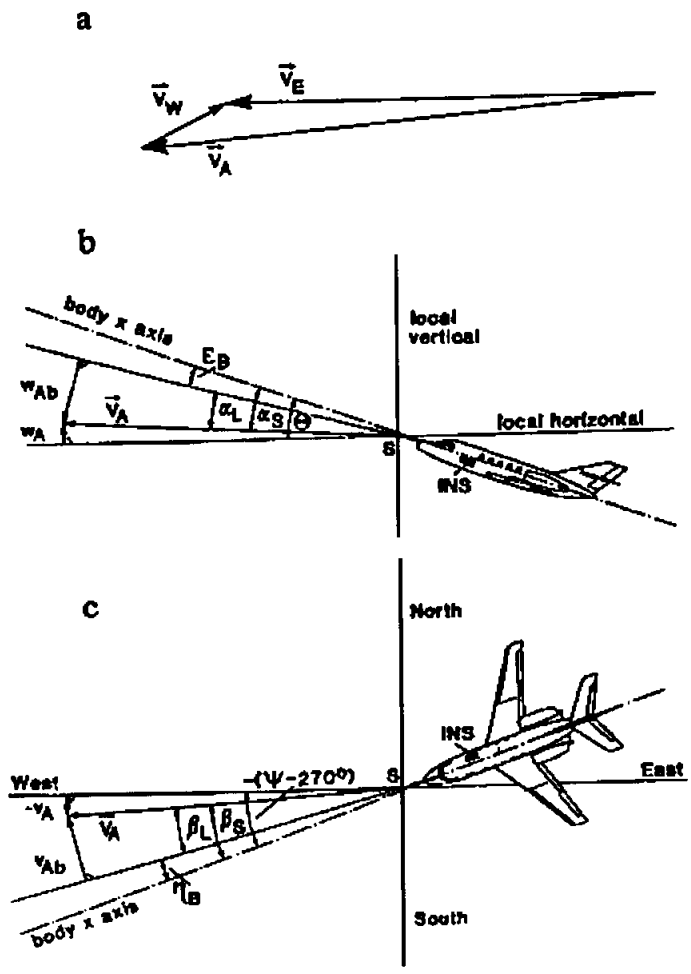

Figure 1 Vectors and angles used in the calculation of wind components as measured by aircraft. (a) wind triangle. (b) angles and components of the true airspeed in a pitching motion. (c) angles and components of the true airspeed in a yawing motion. See text for notation. The figure is adapted from Bögel and Baumann (1991) with permission by the authors.

air, its magnitude is called true airspeed (TAS). The wind vector equation can also be written in components. In the meteorological convention these are denoted as u, υ and w. The u-component is directed eastward, υ northward and the vertical component w reads positive upward.

In order to obtain the time dependent wind components, several angles (i.e. pitch, yaw, roll, attack, and sideslip) as well as the accurate three-dimensional velocity of the aircraft in an earth based system have to be known with high time and space resolution. Figure 1b and 1c sketches two of them, the detailed notation is given in Bögel and Baumann (1991). Within the scope of this paper the full set of equations cannot be given, they differ slightly between the three participating systems due to different algebraic defactorization, sequences of coordinate transformation and aircraft rotation compensation, and slightly different definitions of flow angles. These differences do not affect the final wind accuracy for normal operational flight conditions. Lenschow (1986) and Lenschow et al. (1987) derive algorithms similar to those applied here.

Temperatures

Most airborne temperature measurements are made with immersion instruments in contact with the air flow. The basic sensor is comparable to those also used at the ground, where thin wire (platinum) resistors located in special housings are commonly used. Airflow approaching the sensor and its housing at high velocity generates dynamical heating for which a correction is required. The dynamical heating due to flow stagnation on the sensor has to be subtracted from the total temperature in order to obtain the desired static air temperature T_s. As a result, the calculated static air temperatures are not independent of dynamical measurements or, therefore, their errors.

In addition, the local air speed at the sensor might differ from that at the point where the dynamical pressure is measured. The correction in many systems is based on the assumption that the dynamical heating is close to adiabatic, which is not the case in very moist air or clouds (situations not addressed here). Even under clear and dry conditions the inability to achieve 100 % adiabatic compression within the housing of temperature sensors causes problems and the recovery temperature T_r is less than the total temperature T_t (see e.g. Lenschow et al., 1987). Often a recovery factor r is used to determine the static temperature, this being the fraction of the free-stream kinetic energy that is isentropically recovered as thermal energy in the fluid adjacent to the sensor; $r = (T_r - T_s)/(T_t - T_s)$. The characteristics of the recovery factors are not very well known and are a major source of uncertainty for airborne temperature measurements. The magnitude of the recovery error correction is typically in the range 5 to 10 K.

For turbulence measurements fast response of the sensors is essential. The time constant of a temperature sensor is not a simple parameter to quantify, being dependent on the construction of the sensing element itself as well as on the housing. Numerical techniques are available for some sensors to retrieve to a certain degree some of the lost high frequency data. Friehe and Khelif (1992) discuss this subject in more detail.

3 Aircraft and Instrumentation

Aircraft

Three aircraft participated in the Pre-EUCREX campaign. All of them were equipped with sensors to measure the three wind components, temperature, humidity, and attitude angles at a resolution sufficient for turbulence calculations in an earth based reference frame. The Falcon 20 operated by the German Aerospace Research Establishment (DLR, Oberpfaffenhofen) is a twin-engine jet, the Hercules C-130 operated by Meteorological Research Flight (MRF, Farnborough) of the UK Meteorological Office is a four-engine turboprop, and the Merlin operated by the Meteorological Aviation Centre (CAM, Bretigny) of the French Weather Service is a twin-engine turboprop. A summary of the characteristic performance and instrumentation relevant to this study is given in Table 1. The calibration procedures and data processing algorithms to transform the primary sensor readings into physical data are normally provided by the relevant aircraft operating agency. An exception is the algorithms for turbulence resolution data from the Merlin measurements, which are provided by LaMP, Clermont-Ferrand. The data used for the intercomparison have been derived by applying the standard software packages as normally supplied to users and have not especially been prepared for this purpose.

Table 1 Operating agency, performance, sampling rate, and relevant instruments of the three aircraft participating in the Pre-EUCREX intercomparison campaign.

Aircraft	Falcon 20	Hercules C-130	Merlin IV
Operator	DLR*	MRF*	CAM*
Top altitude	12 km	10 km	8 km
endurance	3–4 h	8 h	6 h
Wind	five-hole-probe (Rosemount, J 858) IRS* (Honeywell, Lasernav YG1779)	wind vanes (Penny&Giles, E23001) INS/GPS* (Ferranti, Fin 1012)	five-hole-radome INS* (SAGEM ULISS 45M)
Temperature	total-temp.-probe (Rosemount 102)	total-temp.-probe (Rosemount 102)	total-temp.-probe (Rosemount 102) reverse-flow (NCAR)
Humidity	Lyman-α (Buck Research L5) Humicap (Vaisala HMP11) cryo-dewpoint (Buck Research CR-1)	Lyman-α (UK Met. Office) dewpoint (GE 1011 B) fluorescence (UK Met. Office)	Lyman-α (AIR-LA1) dewpoint (GE 1011 B) carbon plate (Meteo France)
Sampling rate	100 Hz	32 Hz	25 Hz

* DLR: German Aerospace Research Establishment, Oberpfaffenhofen, Germany
MRF: Meteorological Research Flight, Farnborough, UK
CAM: French Meteorological Aviation Center, Bretigny, France
IRS: inertial reference system
INS: inertial navigation system
GPS: global positioning system

Instrumentation

The three participating aircraft employ different systems for air-motion sensing. Accurate determination of mean wind velocities and turbulence involves data from several sensors. Here we will only list the principal ones. Dynamic and static pressure are used for true airspeed derivation. Angles of attack and sideslip are measured by either differential pressure readings or vane movements, both systems being limited by either line damping or inertia. Aircraft motion in a ground based system is given by the integration of acceleration measurements. Attitude angles are derived from high resolution angular measurements against a stabilized platform within the inertial navigation systems. Temperature on all aircraft is measured by platinum resistance sensors. The airstream is decelerated in a 90 degree bend and passes a thin wire resistance thermometer. A numerical correction for adiabatic dynamical heating is essential in order to obtain the static temperature. This is a major source of uncertainty among the three systems.

a. Wind Components

Falcon

On the Falcon a 5-hole flow angle sensor (Rosemount, J 858) mounted on the tip of an 1.8 m nose boom is used for measuring true airspeed and angles of attack and sideslip. The measured pressure fluctuations are transferred through pressure lines to the pressure transducers in the nose of the aircraft, which is a possible source for signal damping. The data is sampled and recorded at a rate of 100 Hz. It has been found that the eigenfrequency of the nose boom is slightly dependent on pressure and centres around 19 Hz (with an amplitude of about ± 10 μm). The aircraft velocity relative to the earth is measured by a Honeywell Lasernav YG 1779 inertial reference system (IRS) mounted in the rear of the passenger cabin. Therefore, position corrections have to be applied. For more details and information on additional sensors on the Falcon system see Meischner (1985) and Fimpel (1987).

Hercules

The true airspeed on the Hercules is measured by a pitot-static system at the tip of a nose boom. Attack and sideslip angle measurements are performed by two perpendicular potentiometric wind vanes also mounted near the tip of the aircraft nose boom. The length of the boom is approximately 7 m. Attitude angles and ground speed measurements are made by an inertial navigation system (INS), Ferranti Fin 1012, located at the base of the nose boom. On the Hercules, in addition to conventional navigation procedures, a GPS receiver (Farrell, 1976; Denaro and Geier, 1988) is available for position measurements, which are used to remove errors caused by Schuler oscillation and drifts in the INS output. High frequency data is recorded at 32 Hz. Further information on the Hercules can be found in Gloster (1990) and Nicholls (1983) provides a good description of the turbulence instrumentation.

Merlin

Five pressure ports on a nose radome in conjunction with static pressure ports on either side of the radome are used on the Merlin to measure true airspeed and angles of attack and sideslip. The radome technique is described by Brown et al. (1983). It has the advantage in comparison to nose booms that pressure transducers can be installed close to the pressure ports so that line damping is negligible. On the other hand the ports are very close to or within the flow field distorted by the fuselage. Aircraft attitude and ground speed are determined from measurements made by an inertial navigation system, SAGEM ULISS 45M. Fast response data is available at 25 Hz. A description of the Merlin and its instrumentation is given in CAM (1989) and Villien (1991).

b. Temperatures

On all three aircraft a Rosemount total-temperature-probe type 102 is employed but different models are used. On the Merlin a reverse flow probe is also available which seems to have advantages in clouds or precipitation, but is not evaluated on clear air segments analysed here. On the Falcon the total-temperature-probe is located underneath the nose of the aircraft, on the Hercules it is mounted underneath the nose boom, and on the Merlin on a side of the radome. Dynamical heating effects are corrected by using the dynamic and static pressure measurements of the airflow system. Therefore, static temperature data is not independent of dynamical measurements. Uncertainties come from the recovery factors which are empirically determined for several true airspeeds and are different for all three aircraft. They also differ from those supplied by the manufacturer of the sensors, which were derived from measurements in a wind tunnel.

4 Pre-EUCREX Flight Missions

During the third week of January 1992 the three participating aircraft met for Pre-EUCREX flights at Farnborough, UK. Intercomparison measurements were made during three flight missions on January 21, 22, and 23, each lasting between 3 to 4 hours addressing in parallel several scientific and technical topics.

The synoptic situation during the week of the experiment was almost perfect for the scientific objectives of the campaign. The whole target region, South-West England and the coastal Atlantic, was influenced by a high pressure area centered over Northern Germany, leading to a cloud-free troposphere (essential for side by side flights) with very low humidity, light wind and weak turbulence, as desired. Broken boundary layer cumulus formed over the south-west peninsula, thickening to stratocumulus over the sea, providing an area for testing microphysical probes and dynamical behaviour of humidity sensors (Ström et al., 1994). On January 23 an approaching frontal band was observed over the English Channel, supplying higher wind speeds and strong turbulence intensities in the upper troposphere.

Air motion measurements were obtained in regions of low and medium wind velocities during ascents, descents, and on horizontal flight legs (between 50 and 80 km long) at different altitudes between 300 m and 8 km. Turbulence measurements were intentionally made in regions with weak to moderate turbulence intensities, in order to match conditions which are typically found at the altitude of high level clouds. Only data gathered outside clouds in close formation are discussed here. The raw aircraft data were processed using the standard software packages as supplied by each aircraft operator. The data series were then adjusted in time according to time checks performed every day during the campaign. These shifts have been confirmed and optimized by inter-aircraft crosspectral analysis.

Four typical flight legs have been selected to be analysed in more detail. Information on the lengths, altitude, and location of the legs is provided in

Table 2 Information on flight legs from the Pre-EUCREX intercomparison campaign selected for the evaluation for this study as well as basic aircraft parameters.

Parameter		EUCREX-1 leg 2.1	EUCREX-2 leg 4	EUCREX-3 leg 1.1	EUCREX-3 leg 1.2
Day	(dd.mm.yy)	21.01.92	22.01.92	23.01.92	23.01.92
Start time	(hh:mm:ss)	14:49:06	15:01:00	12:48:47	12:59:30
Aircraft*	(initial)	F, H, M	F, H, M	F, H	F, H
Length	[km]	110	60	75	85
Altitude	[km]	6	0.3	8.5	8.5
True airspeed	[ms^{-1}]	140	100	160	160
Heading	[deg]	145	185	200	293
Location		SW coast of England, sea	SW coast of England, sea	Channel sea	Channel sea
Synop. Situation & clouds		high pressure area bl-stratus	high pressure area bl-stratus	pre-frontal bl-cumulus	pre-frontal bl-cumulus

* F = Falcon; H = Hercules; M = Merlin; bl = boundary layer

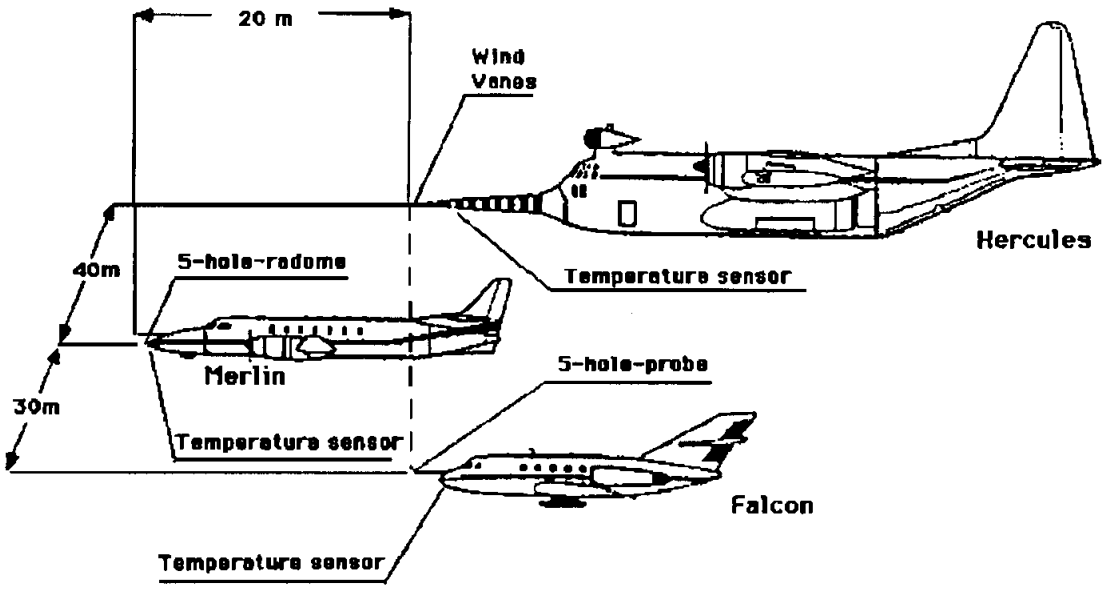

Figure 2 Drawings of the three aircraft involved in this study showing the location of relevant sensors as well as the typical line up during side-by-side flights.

Table 2 along with basic aircraft parameters. Figure 2 shows a typical line up of the three aircraft in close formation, Merlin leading with Hercules on the right wing and Falcon on the left, also typical distances between the aircraft are given. All formation flights were designed so that the horizontal distance between two adjacent aircraft would be not more than 50 m perpendicular to their track. Along track distances were of the order of 20 to 30 m, and in the vertical the separation was about ± 10 m. Since the three aircraft have a totally different flight performance, the maximum altitude at which they can stay airborne together is about 6 km, and the highest common true airspeed is around 140 ms^{-1}. The values for Falcon/Hercules only-missions are 8 km and 160 ms^{-1} for maximum altitude and TAS respectively.

5 Results

In this section, we present selected results of the intercomparison flights which show typical problems in the sensing systems which can and should be improved. In order to keep the intercomparison reasonably objective the data products (files con-

taining calibrated physical quantities) have been taken as provided by the aircraft operating agencies, in case of the Merlin, the LaMP at Clermont-Ferrand is responsible for turbulence data. No bad data points have been edited out other than those eliminated by spike and/or step removal procedures in the primary software packages. However, it is acknowledged that a constructive dialogue between user and supplier might improve the data quality considerably. The three basic data sets have been analysed using identical numerical tools. Numerical filters, spectral-, and cross-spectral analysis codes have only been modified to match the three different sampling rates of the aircraft, so that essentially the same time segments were used for comparison.

a. Mean horizontal winds

Horizontal wind components in the earth based meteorological coordinates, westerly (U) and southerly (V), were averaged without further data treatment along the horizontal formation legs or ascent segments to obtain mean quantities. Mean wind speed as well as the mean wind direction were computed from the U and V components. Table 3 displays mean wind components, wind speed, and direction for the horizontal flight legs. As can be seen, winds were fairly weak for EUCREX-1 and EUCREX-2, between 5 and 10 ms^{-1}. Stronger winds were encountered during mission EUCREX-3. Hercules winds were computed with GPS aircraft position correction for missions EUCREX-l and EUCREX-2, but not for mission EUCREX-3.

The comparison of Falcon and Hercules mean wind speeds shows deviations of about 1 ms^{-1} for the cases with Hercules GPS correction and higher differences (1.3 ms^{-1} and 1.8 ms^{-1}) for the legs without position correction. The mean difference between Merlin and Hercules wind speeds on horizontal legs is about 1.5–2 ms^{-1}. It can also be seen that for all aircraft combinations the deviations are not systematically distributed between the components. As a result, the difference in wind direction can be quite substantial especially for situations with low wind speeds.

It is not easy to quantify the error sources for the observed differences because aircraft tracks were not sufficiently aligned with the direction of either one of the wind components. The analysis of true airspeeds shows that they differ by less than 0.5 ms^{-1} between Hercules and Falcon. The TAS measured by the Merlin was up to 5 ms^{-1} lower compared to those of the other two aircraft. So, errors in wind measurements by Falcon and Hercules seem to be mainly due to errors in the ground speed, while errors in Merlin winds are caused by true air speed problems during these missions. This problem with TAS on the Merlin true airspeed has never been seen before except in the case of icing of the radome, but it is unlikely that radome icing occurred during the present cases.

Table 3 Mean wind and temperature for selected intercomparison flights performed during the Pre-EUCREX intercomparison campaign in 1992. The values represent averages along horizontal flight legs.

Parameter		Aircraft	EUCREX-1 leg 2.1	EUCREX-2 leg 4	EUCREX-3 leg 1.1	EUCREX-3 leg 1.2
U	[ms^{-1}]	Falcon	-7.91	-4.75	-0.75	-2.02
		Hercules	-7.78	-4.60	-1.44*	-4.42*
		Merlin	-5.04	-6.59	-	-
V	[ms^{-1}]	Falcon	-5.97	1.43	-28.54	-25.22
		Hercules	-4.58	4.06	-27.22*	-23.05*
		Merlin	-10.17	3.35	-	-
$\lvert\vec{V}\rvert$	[ms^{-1}]	Falcon	9.91	4.96	28.55	25.30
		Hercules	9.03	6.14	27.26*	23.47*
		Merlin	11.35	7.39	-	-
direction	[degree]	Falcon	53	107	2	5
		Hercules	60	131	3*	11*
		Merlin	26	117	-	-
T	[°C]	Falcon	-22.25	2.58	-41.23	-40.53
		Hercules	-22.62	2.64	-41.75	-41.01
		Merlin	-	3.94	-	-

* no GPS correction for Hercules wind data

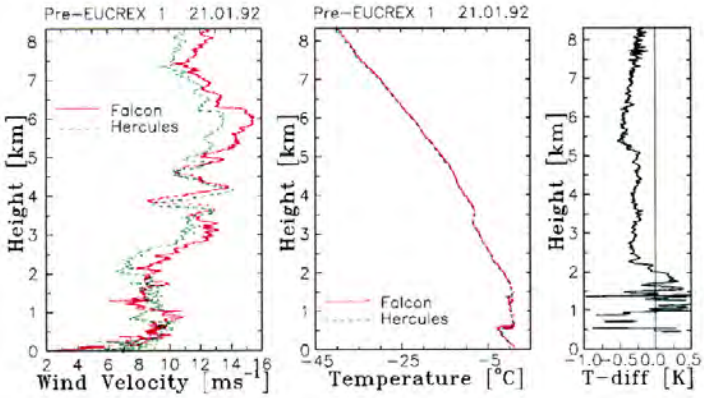

Figure 3 Vertical profiles of the horizontal wind velocities in 1 Hz resolution, mean temperatures, and their difference ($T_{\text{Falcon}} - T_{\text{Hercules}}$) as measured by the Falcon and Hercules on January 21, 1992, during a formation ascent up to an altitude of 8 km starting in the boundary layer.

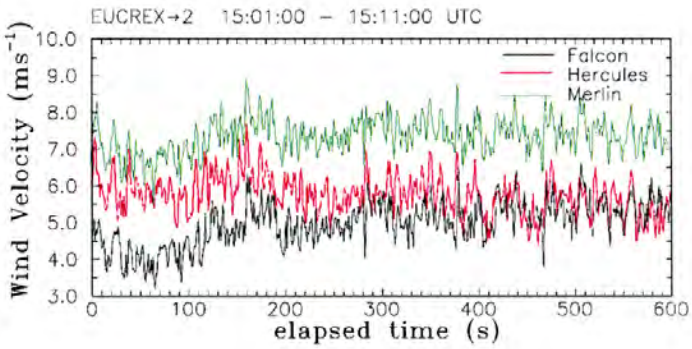

Figure 4 Horizontal wind velocities along a 60 km long flight leg at an altitude of 300 m in the marine boundary layer measured by Falcon, Hercules, and Merlin on January 22, 1992.

At the beginning of the first flight mission (EUCREX-1), the Falcon and Hercules performed a formation ascent starting at an altitude of about 1 km up to 8 km. The ascent was completed within about 37 minutes. Profiles of the horizontal wind velocities measured by the two aircraft are shown in Figure 3. Here the wind velocities from the synchronised time series for Falcon and Hercules are plotted versus pressure altitude of the Hercules. During the ascent the two aircraft stayed very close together with a deviation in altitude of ± 5 m. It can be seen that the difference between the wind velocities changes with height and varies between 0 and 2 ms^{-1}. Looking at the data in time space, the apparent oscillation in the difference between the velocities superimposed on the probably existing Schuler period (84.4 min) is of the order of 15 minutes. Indications for such additional oscillations with a period between 10 and 20 minutes are sometimes also observed on horizontal flight legs. In Figure 4, time series of the wind speed along leg 4 of mission EUCREX-2 for Falcon, Hercules, and Merlin are shown. It can be seen that many small scale events with almost the same amplitude and duration are sensed by all three aircraft. On the other hand, whilst the deviation between the Falcon and Merlin wind is quite large but constant along the leg, the Hercules wind speed deviation relative to the other aircraft changes with time. By inspecting a longer part of the time series (only the close formation section of the leg, 10 minutes, is shown in Figure 4) it can be seen, that the differences in wind velocity between the aircraft oscillate with a period comparable to that described above. The origin of this oscillation is not known and subject of further investigation. Since this 15 minute oscillation does not occur when Hercules GPS positions are compared with IRS readings of the Falcon, one possibility could be that the GPS position correction procedure for the Hercules winds induces oscillations of this kind. Currently at MRF, a revised INS position correction procedure using a Kalman filter is being implemented. Loran-C radio navigation information can also be used to correct errors in INS position and, hence, in wind velocity. Unfortunately this data was not available for this study.

As mentioned before, a most likely source for errors in mean winds is the determination of the aircraft speed in an Earth-based coordinate system. In the following subsection an example is given to show how this error can be determined using the intercomparison flights. Here the Hercules GPS position data from the side by side flight segments have been used as position information to improve Falcon winds.

b. Correction of aircraft velocity errors

The main contribution to low frequency errors (i.e. < 0.01 Hz) of the measured wind comes from errors of the inertial reference system, IRS (here we use the term IRS, since the following calculations have been made for the Falcon), which measures the velocity of the aircraft with respect to ground. For the time scales of interest herein, i.e. from 0 to about 3 h, the typical IRS-velocity error has a very characteristic time dependance due to drifts of the IRS's gyros and accelerometers, a combination of an offset and sinusoidal oscillation which is called the 'Schuler oscillation' with the well known period of 84.4 minutes. In practice, the amplitude and phase of the oscillation are initially unknown and

may be slowly modulated. Because of the low frequency of the IRS-error, it affects the mean wind but not the turbulence measurements. It is possible to approximate the error by comparison of the IRS-position (which is the integral of the velocity) with an alternative measurement of position which does not have an error in the same frequency range. By subtracting this modelled error from the original data, it is possible to improve the absolute accuracy of mean horizontal wind components from roughly 1.5 to 2 ms^{-1} to 0.3 to 1 ms^{-1} (depending on the accuracy of airspeed and attitude measurement).

Most common techniques apply sophisticated Kalman filters (Leach and MacPherson, 1991), complementary filters, or low-pass filters to calculate the IRS-errors. Figure 5 shows the velocity errors calculated from an iterative least-squares fit of the difference between the Falcon IRS-position and the Hercules GPS position during intercomparison phases of the EUCREX-2 flight on January 22, 1992, where the two aircraft were less than 40 m apart. In calculating the fit, this difference is taken as a good approximation of the real position error of the IRS, because the fit-model cancels out the 'high frequency' errors of the GPS-position (Denaro and Geier, 1988). The form of the fit was given by:

$$\Delta x = x_{meas} - x_{true} = \\ = a + bt + (c \cdot \cos \omega_s t + d \cdot \sin \omega_s t)\,(e + ft),$$

where Δx is the latitude respectively longitude error, ω_s the Schuler frequency ($= 2\pi/84.4\ \mathrm{min}^{-1}$), and a to f are the unknown fit constants. c and d are constrained to $c^2 + d^2 = 1$.

Although the two position measurements, Falcon IRS and Hercules GPS, are not coincident (but from aircraft flying closely together) the least square fits, bridging a few gaps where the aircraft flew their own courses, to the positions show a good correspondence to the measured difference of positions. A typical fit deviation in longitude and latitude of about 75 m and 55 m, respectively, was found which is small compared to the position error amplitudes in this case of 1.5 km respectively 0.4 km. The final calculated velocity differences for the north-south and east-west components given in Figure 5 show amplitudes up to 2 ms^{-1} (N-S) and up to 0.6 ms^{-1} (E-W). This is a good example of how information from a better-equipped aircraft can be used to estimate measurement errors of others involved in a multi aircraft campaign, if close intercomparison formations are part of a flight mission. Since 1993 the Falcon has been equipped with its own GPS receiver for this purpose.

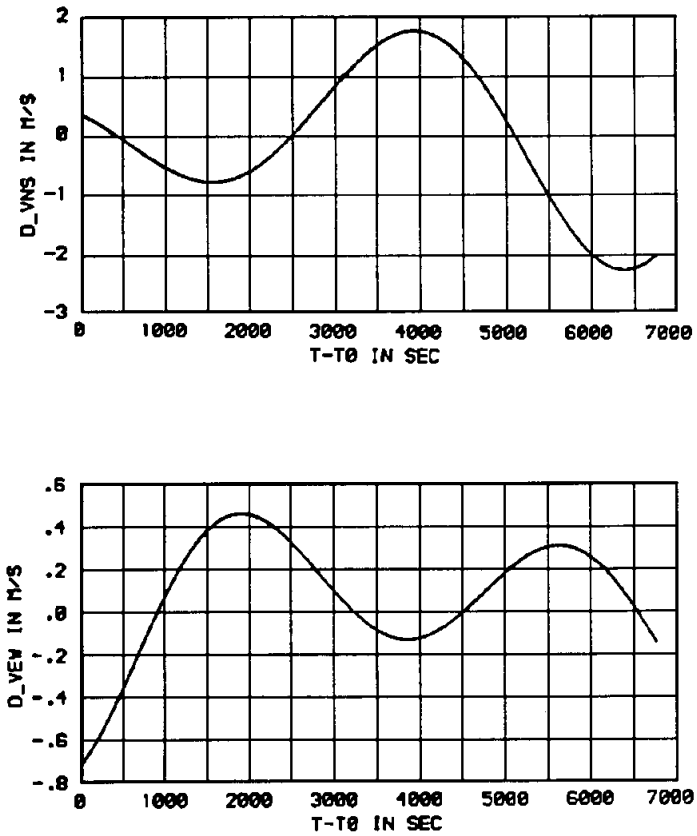

Figure 5 Velocity error in the north-south (upper graph) and east-west (lower graph) components of the Falcon IRS, calculated by differentiation of the fitted position error. The position error could be estimated by use of the superior GPS positions from the nearby (less than 40 m distance) Hercules. The data are from the flight on January 22, 1992, covering about 2 hours of flight at altitudes between 300 m and 6 km.

c. Large scale vertical wind fluctuations

There is a recognised problem in obtaining mean vertical wind speed from aircraft measurements representative for large areas (Cooper and Baumgardner, 1989), since the up- and downdrafts on these scales are only a few cms^{-1}. It is not possible to measure the vertical aircraft velocity with the required accuracy. In practice, vertical wind fluctuations from aircraft measurements representative for intermediate scales are often obtained by subtracting a horizontal average from the instantaneous readings with the underlying assumption that the large area average is either very small or not relevant for the problem under investigation. As an example the vertical wind components measured by Falcon, Hercules, and Merlin are plotted above each other in Figure 6. The data shown are block-averaged from turbulence resolution down to 1 Hz in order to better visualize the large-scale fluctuations. For this figure no leg mean has been subtracted and no trend has been removed.

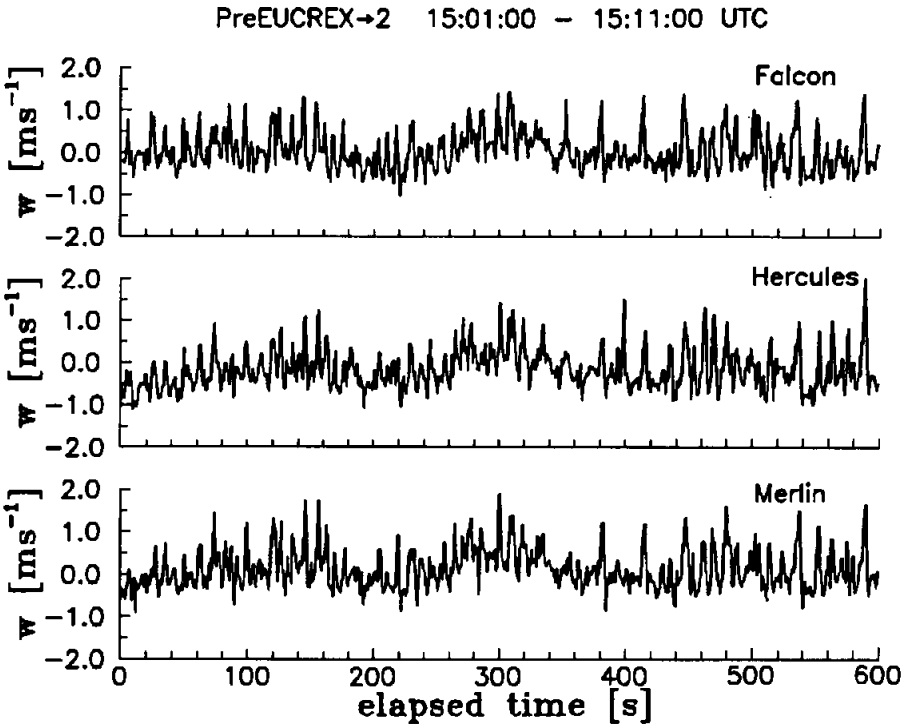

Figure 6 Time series of the vertical wind component for the flight leg described in Figure 4. Unfiltered and non-detrended data at a resolution of 1 Hz is plotted.

The measurements were obtained in the marine boundary layer and show typical updrafts as a dominant feature with amplitudes around 1 to 1.5 ms^{-1} and a horizontal extent of a few hundred meters. These updrafts show up in the time series of all three aircraft and agree very well in amplitude and width. It is not expected that the details of the velocity fluctuations agree exactly with each other since the aircraft are separated by distances which are not small compared to the event width. Some up- and down-draughts are sensed simultaneously by all three aircraft. It has to be kept in mind that the atmospheric variability significant on the scale of the spacing of the aircraft (in the order of 100 m) influences the results and may even alter the statistics if the sampling times are not sufficiently long. The good agreement of the vertical velocity fluctuations on the scales discussed here was also found for the other flight legs analysed.

Besides the intermediate scale fluctuations in w, the longer wave length behaviour is also matched in Falcon, Hercules, and Merlin measurements. In this case the wavelength is about 15 km with an amplitude of about 0.5 ms^{-1}. Other data segments analysed for vertical velocity fluctuations (not shown here) suggest that wavelengths up to about 20 km can be obtained from the 60 to 100 km long horizontal legs. High frequency fluctuations of the vertical velocity component are discussed in subsections e and f.

d. Mean temperatures

Before the temperature measurements are discussed it should be noted that, for the data segments analysed, the de-icing heaters of the sensors were switched off. The magnitude of the de-icing heater correction for Rosemount sensors is typically between 0.2 and 1 K and changes with true airspeed and airflow incidence angle.

Mean static air temperatures averaged along horizontal flight legs are listed in Table 3. Unfortunately, the temperature for the Merlin is only available for one of the two legs flown by this aircraft. Temperature difference between Falcon and Hercules is less than 0.5 K and can be regarded as good, since it is well within the specifications of the sensors. The Falcon is measuring the higher values at all altitudes and wind speeds except for the boundary layer leg (EUCREX-2) where the temperatures match each other. For this leg the Merlin temperature is about 1.3 K higher than those of the other aircraft. For a given combination of aircraft the comparison of time series reveals that the differences are nearly constant along the flight segments. As mentioned at the end of Section 3, the

recovery factor used for the computation of the static air temperature is a source of uncertainty. Since the three aircraft use slightly different recovery factors, the systematic deviation is probably determined largely by this. The differences could possibly be further reduced by slightly altering the recovery factor but, without access to the raw uncorrected input data, this is beyond the scope of the present study. The reason for the relatively large deviation of the mean temperature measured by the Merlin is, in addition to the uncertainty in the recovery factor, mainly due to the observed error in the true airspeed (for EUCREX-1 and EUCREX-2) of about 5 ms^{-1} resulting from an under-estimation of the dynamical pressure by 4 to 5 hPa, which directly influences the dynamical heating correction.

Figure 3 shows the temperature data taken during the formation profile for the Falcon and Hercules at the beginning of mission EUCREX-1. The close formation started at an altitude of about 1 km. The overall temperature structure of the troposphere is captured identically by the two aircraft as can be seen in the figure (plot in the middle). Temperature differences (Falcon minus Hercules) are also shown in Figure 3 (right plot), they range between 0.2 and 0.5 K. Here the Falcon measurement is systematically lower. It should be noted that the two aircraft flew in very close formation during the ascent, and the deviation in altitude cannot explain a difference in temperature of more than 0.1 K. The explanation for the change of sign in the deviations is that the Falcon temperatures used for the profile are from a 1 Hz data set for which readings of the slower capsulated temperature sensor were used. Temperatures for the horizontal legs are from turbulence resolution data sets and were measured by the faster open wire sensor. Typically, temperatures from the open wire sensor are about 0.5 K higher than those of the slower sensor.

The fluctuating differences in the profile (Figure 3) between 1 and 2 km altitude where the aircraft were already close to each other are believed to be due to horizontal inhomogeneities in an unstable region just above the boundary layer inversion (see temperature profile), and therefore they reflect the small scale atmospheric variability.

e. Power spectra

A Fast Fourier Transform (FFT) based routine was used to compute power spectra for the velocity components u, υ, and w. The mean and the linear trend was removed from data segments before calculating the FFTs and a Bartlett window applied to the data in order to minimise spectral leakage (Otnes and Enochson, 1972). Spectral significance was improved by implementing the method proposed by Welch (1967). Time series were subdivided into overlapping segments of 1024 to 4096 points, taking into account the different sampling rates, and a composite spectrum has then been obtained by averaging the resulting 10 to 20 separate spectra. In some cases additional spectra of primary parameters were computed in order to identify possible sources of uncertainty or noise.

Power spectra for u, υ, and w in weak and intense turbulence for all three aircraft are compared in Figure 7. The spectra representing low intensity turbulence are shown in the left column of Figure 7, these data coming from the free atmosphere at an altitude of 6 km (leg 2.1 of mission EUCREX-1). The right column of Figure 7 shows spectra for a high turbulence intensities region, namely the marine boundary layer 300 m above the sea surface along leg 4 of mission EUCREX-2.

It is evident from Figure 7 that in general u, υ, and w-spectra for the intense boundary layer turbulence compare very well at almost all frequencies, whilst obvious differences occur in very weak turbulence. The last two values at the low frequency end of all spectra should be ignored, because they are always slightly influenced by the detrending procedure.

Beside these general comments, the following features should also be noted. An apparently spurious peak occurs in the Hercules υ-spectrum for leg 4, EUCREX-2 centred at around 9 Hz. The spectral amplitude of this peak is about one order of magnitude higher than those of the other aircraft and is due to noise in the INS north-south component. In this case the aircraft track was roughly aligned with the wind in a north-south direction, hence noise in this velocity component feeds strongly into the υ wind component. The 9 Hz noise came from a mismatch in the frequency with which the data system sampled the INS velocity outputs and the frequency at which the INS updated its velocities internally. The u and w-spectra of the Hercules for this leg also appear to be slightly enhanced toward the high frequency end due to noise in the INS-derived aircraft velocity components. In the meantime the Hercules has been equipped with a different INS (a strapdown Honeywell laser gyro system). There is no indication for a noise problem of the kind discussed above.

A commonly-observed feature for Falcon spectra is that they seem to fall off too rapidly at very high

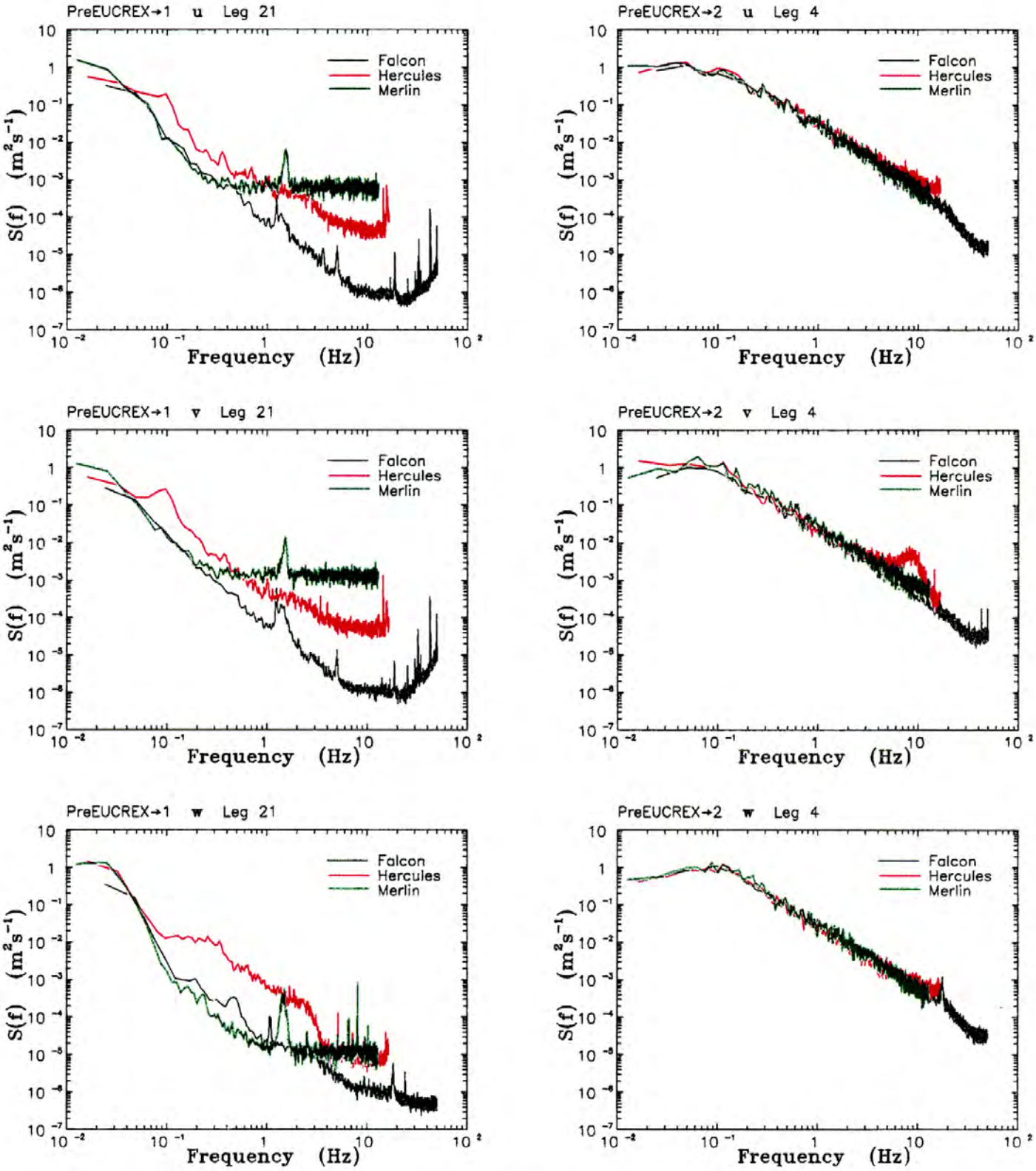

Figure 7 Power spectra of the three wind components u, v, and w as measured by Falcon, Hercules, and Merlin in close formation at an altitude of 6 km (January 21, 1992) in a quasi-non-turbulent flow (left column) and at an altitude of 300 m in the marine boundary layer representing a flow with higher turbulence intensity (right column).

Table 4 Eddy-correlation fluxes and standard deviation values for intercomparisons. The data were filtered using a non-recursive high pass filter with a-cut off wavelength of 5000 m before the turbulence statistics were calculated.

Parameter		Aircraft	EUCREX-1 leg 2.1	EUCREX-2 leg 4	EUCREX-3 leg 1.1	EUCREX-3 leg 1.2
σ_u	[ms^{-1}]	Falcon	0.08	0.46	0.49	0.18
		Hercules	0.13	0.49	0.57	0.17
		Merlin	0.12	0.44	–	–
σ_υ	[ms^{-1}]	Falcon	0.07	0.43	0.35	0.16
		Hercules	0.14	0.49	0.38	0.17
		Merlin	0.14	0.49	–	–
σ_w	[ms^{-1}]	Falcon	0.06	0.49	0.29	0.15
		Hercules	0.10	0.48	0.29	0.18
		Merlin	0.06	0.49	–	–
skew (w)	[–]	Falcon	– 0.26	0.71	0.21	0.24
		Hercules	– 0.09	0.77	0.22	0.08
		Merlin	– 0.29	0.67	–	–
σ_T	[K]	Falcon	0.056	0.063	0.076	0.062
		Hercules	0.035	0.046	0.065	0.042
		Merlin	0.044	0.064	–	–
$\overline{u'w'}$	[m^2 s^{-2}]	Falcon	0.0007	– 0.030	– 0.043	– 0.0047
		Hercules	0.0003	– 0.042	– 0.022	– 0.0028
		Merlin	– 0.0002	– 0.031	–	–
$\overline{\upsilon'w'}$	[m^2 s^{-2}]	Falcon	– 0.0001	– 0.003	0.015	– 0.0013
		Hercules	– 0.0009	– 0.003	0.010	– 0.0001
		Merlin	0.0006	– 0.002	–	–
$\overline{w'T'}$	[ms^{-1} K]	Falcon	– 0.0002	0.0019	– 0.0028	0.0013
		Hercules	– 0.0003	0.0031	– 0.0010	0.0014
		Merlin	– 0.0002	0.0028	–	–

frequencies (> 20 Hz), as long as the signal is above the noise level. This effect is due to response characteristics of the pressure transducers. The narrow peak sometimes visible in the Falcon spectra around 18 Hz is caused by vibration of the nose boom. Since the energies in this part of the spectra are a small fraction of the total turbulent energy, the influence of both effects on turbulence statistics and fluxes is very small.

The power spectra in Figure 7 for very weak turbulence show for all wind components the dominance of different types of noise at higher frequencies. The white noise level for the Merlin is quite high (about 10^{-5} m^2 s^{-1} for w and between 5×10^{-4} to 10^{-3} for u and υ), it dominates in this case frequencies above 0.2 Hz. The peaks at about 1.5 Hz in the Merlin spectra have their origin in the static pressure measurements. Similar peaks occur in the Falcon spectra at about 1.3 Hz, but having lower spectral amplitudes. Red noise seems to be present in the Hercules spectra at frequencies higher than about 0.1 Hz. In the frequency band between 0.1 and 3 Hz the spectral energy level is for

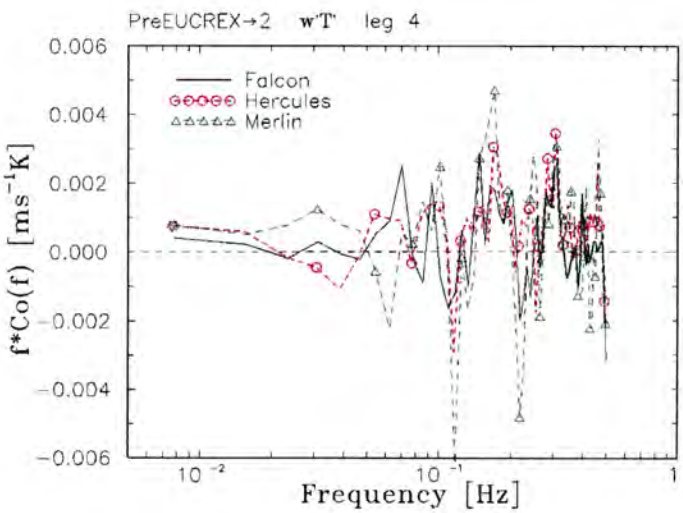

Figure 8 Co-spectra of vertical velocity and temperature for data gathered along a 60 km flight path in the marine boundary layer (EUCREX 2, leg 4). Eight overlapped spectra have been averaged to improve the statistical significance. Contributions of wavelength between 0.2 km and 12 km to the heat flux are shown.

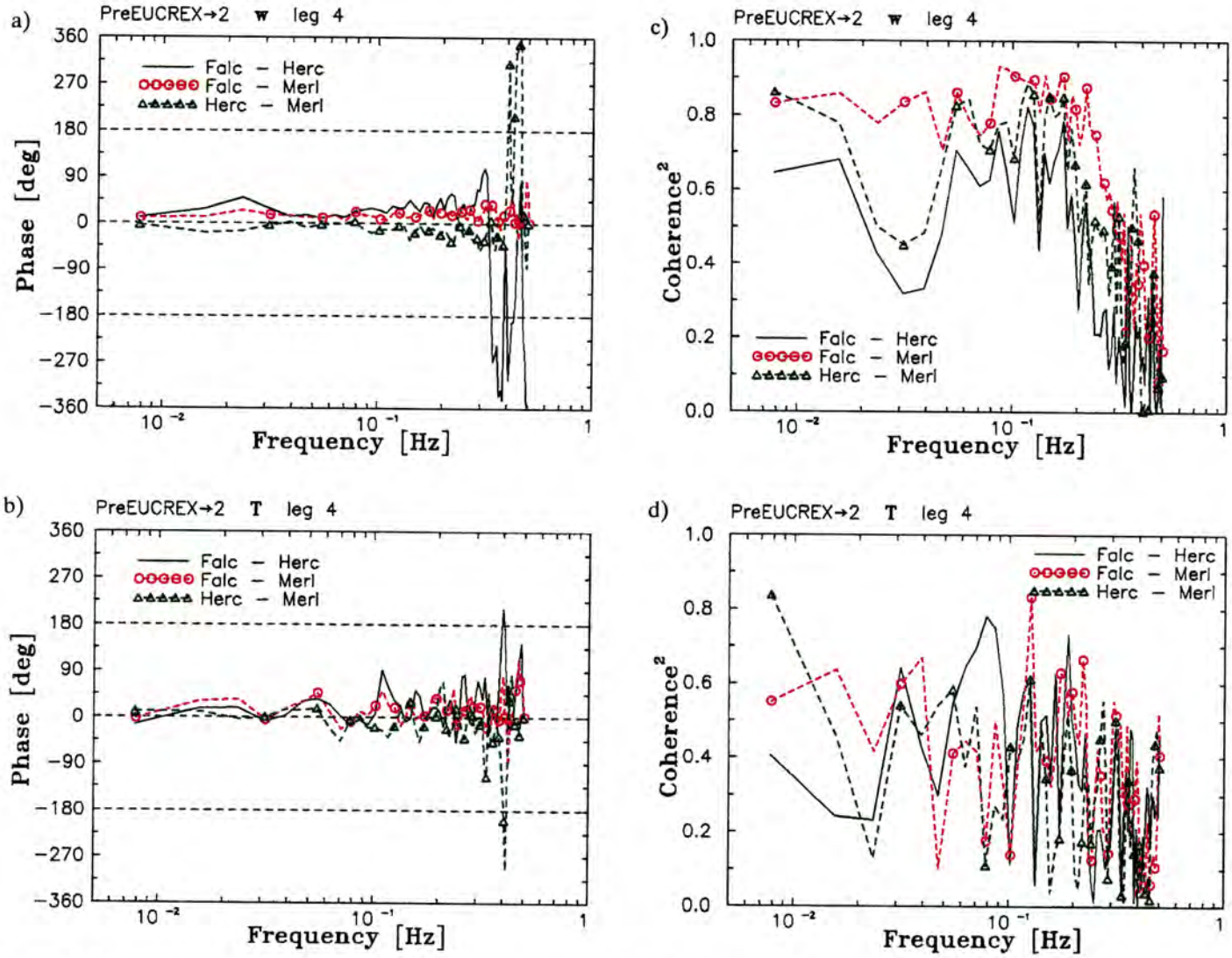

Figure 9 Phase a.) and b.), and squared coherence spectra, c.) and d.), of vertical velocity and temperature for all three aircraft involved. The data were gathered along a 60 km flight path in the marine boundary layer (EUCREX 2, leg 4). Eight overlapping spectra have been averaged to improve the statistical significance. Contributions of wave length between 0.2 km and 12 km are resolved.

u and υ-spectra about a factor of 8 and for the w-spectrum about two orders of magnitude higher than that indicated by the other two aircraft. The origin of this noise is not quite clear and it does not appear in other data segments with weak turbulence. Whilst the Falcon spectra show the lowest white noise level, frequencies above 20 Hz are contaminated by noise coming from the temperature sensor used for corrections in the wind algorithm. All these noise problems have to be considered if low intensity turbulence is of interest.

f. Turbulence statistics

Turbulence statistics have been obtained from numerically filtered time series of u, υ, w, and T. After the inspection of cross-spectra, the cut-off wavelength for the high-pass filter was chosen to be 5 km in order partly to remove known low frequency oscillations and drifts in the data not attributable to atmospheric turbulence. The filter was a non-recursive sin(x)/x-type filter with Hamming smoothing (Stearns, 1984). In order to assess the influence of this filter on resulting statistics (slight phase shifts and Gibbs' phenomenon) some data sets have also been filtered using a Martin-Graham filter (Martin, 1962; Graham, 1963) with a sharp cut-off. The differences were extremely small and not relevant for the purpose of this intercomparison.

Standard deviations of the three wind components and the static temperature and eddy-correlation fluxes for momentum and sensible heat were calculated (Table 4). The cases EUCREX-2 (leg 4) and

EUCREX-3 (leg 1.1), can be classified as turbulent, with standard deviations of the horizontal velocity components of around 0.5 ms^{-1}. For these legs, the standard deviations for the wind components are in very good agreement with a maximum difference of about 10 %. The vertical velocity skewness compares also well. It has been mentioned in Section 5c that a perfect agreement of the statistics cannot be expected, because in addition to instrumental errors, atmospheric variability of the flow field on the analysed scales will also influence the results. See also LeMone and Pennell (1980) for a discussion on the influence of atmospheric variability on intercomparison results.

The standard deviation for temperature shows larger relative differences (up to 20 %) than for wind components. Here, σ_T is systematically higher for the Falcon. The reason for this is the high frequency noise (above 20 Hz) in the temperature data, which also influenced in the u, v-spectra in low intensity turbulence (Section 5d.). Temperature spectra (not shown here) reveal that some noise is also present in the Merlin data.

Eddy-correlation momentum and heat fluxes agree for the turbulent cases within about 30 %. This can be considered as good bearing in mind the finite sampling time and the atmospheric variability. Largest deviations are found for the heat flux which is of course partly due to the above mentioned noise in the temperature data.

Cospectra provide a useful way to explore contributions of different wavelength to the fluxes. As an example of measurements with high data quality, the wT-cospectra for the three aircraft from leg 4, mission EUCREX-2, are shown in Figure 8. In Figure 9, inter-aircraft phase- and squared coherence-spectra are presented. These spectra (each representing an average of 8 separate 128 point spectra) have been calculated from block-averaged turbulence resolution data, averaged down to a common time resolution of one second for all three aircraft. So wavelengths between 12 km and 200 m are resolved. According to a spectral model of Kristensen and Kirkegaard, discussed in Lenschow and Kristensen (1988), for the number of degrees of freedom appropriate to this case the coherence overestimate is about 10 %. It can be seen (Figure 8) that the contributions to the heat flux in the frequency range between 0.1 and 0.5 Hz agree quite well between the aircraft, whilst longer wavelength contributions disagree even in sign. It can be seen in Figure 9 that for this frequency region the vertical velocity and temperature coherence is low if the Hercules values are correlated with those of either the Merlin or Falcon, which show good w coherence between each other. This effect is most pronounced for w at a frequency of about 0.03 Hz (or a wavelength of about 3 km). A possible reason for the deviation at this frequency could be a badly compensated slow rotational motion of the Hercules, but there is no strong evidence for this at present and further dedicated investigation is necessary. A similar drop in the coherence at comparable wavelength has been observed by Richner (1985) for an intercomparison of aircraft participating during ALPEX and could be partly removed by applying numerical corrections. The coherence for temperature is in general lower than that for w. Phase and coherence spectra show that the phase relation between the aircraft starts to disappear at about 0.3 Hz (or 300 m), which is as expected from the lateral distances between the aircraft during the formation flights.

As anticipated from the analysis of power spectra in Section 5d, the standard deviations and fluxes for very weak turbulence (i.e. leg 2.1 from mission EUCREX-1) compare less well than those for the turbulent cases, since they are influenced by various noise sources and errors induced by the measurement systems dominate.

6 Conclusions

During the Pre-EUCREX intercomparison campaign valuable data sets were obtained from side-by-side measurements of the Falcon, Hercules, and Merlin aircraft during profile ascents and descents and level flights at various heights up to an altitude of 8 km. Formation flights were conducted in regions with high and very low turbulence intensities, allowing for the assessment of noise influencing the measurements. Only typical examples concerning two or three aircraft are presented here and more data will be analysed for the quantitative assessment of problems which have been identified. It is emphasized that, through such an aircraft intercomparison, only relative differences between the systems rather than absolute accuracy can be derived.

The results of the intercomparison experiment show for many parameters very good agreement. However, the analysis also revealed a few problems in the Pre-EUCREX data sets, some of them occurring only under certain conditions.

Deviations in the low-pass filtered horizontal winds (cut-off wavelength of 5 km) between the three aircraft vary in time between 1 to 2 ms^{-1}, indicating an error caused by Schuler oscillation. Differences between components of the horizontal wind were sometimes larger. The Merlin horizontal wind measurements deviate most significant from those measured by the other two aircraft. True airspeed of the Merlin (not explicitly presented here) showed significant deviations during this campaign. Compared to Falcon and Hercules differences up to 5 ms^{-1} in TAS occurred during two flights. The TAS problem is the major cause for deviations in mean wind. Vertical wind components compare very well for frequencies below 0.1 Hz (or roughly 1 km spatial scale). Hercules horizontal winds are considered to be the most accurate, since a major source of uncertainty is removed by using GPS information to correct INS positions and velocities. However, there is some indication that the GPS position correction applied to the Hercules INS positions induces oscillations with a period of ten to twenty minutes. A Kalman filter approach is being tested at MRF for GPS position correction, in order to further investigate this problem.

Static temperatures typically deviate by 0.3 to 0.5 K between Falcon and Hercules. The deviation of Merlin temperatures is higher and probably due to the true airspeed problems mentioned above.

In cases with higher turbulence intensities turbulence measurements made by the three aircraft compare well. Spectra of u, v, and w match each other, variances on a scale smaller than 5 km agree to within a few percent and stresses and heat fluxes are within 30 %, showing the same sign even for very low values. In the case of weak turbulence a broad peak shows up in the Hercules spectra, most prominently in the case of the w-component. Its cause could not clearly be identified and has to be further investigated. The level of white noise appears at relatively high power levels in the Merlin spectra. It has also been observed that for the Falcon damping in power due to response characteristics of pressure transducers affects frequencies above 20 Hz. In general, turbulence quantities should be interpreted with care in regions with low turbulence intensity.

The Pre-EUCREX intercomparison campaign has been very useful in the identification of several measurement system problems. Some of the findings discussed here have already motivated modifications and further investigations by the aircraft operating agencies. The results of this intercomparison study can give some hints for future users of data measured by the participating aircraft. But since instrumentation, calibration coefficients, and the evaluation software will change with time, it is recommended that all future multi-aircraft campaigns include intercomparison missions in their flight programme.

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