INTERNATIONAL WORKSHOP ON THE
AIRBORNE MEASUREMENT OF
WIND, TURBULENCE, AND POSITION

26-28 July 1989, Oberpfaffenhofen

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SUMMARY

The goal of this workshop was three-fold: First to exchange information on measurement technology, calibration techniques, and analysis methods; second to discuss possible areas where standardization is beneficial, such as calibrations, data processing procedures, correction algorithms, and measurement uncertainty assessment and reporting; third to discuss possible future collaborations, in particular the development of new sensors, the assessment of uncertainty, and the exchanges of personnel between facilities.

The first half of the workshop consisted of oral presentations describing fundamental problems, new measurement systems, calibration techniques, and applications of the measurements. The second half of the workshop was devoted to working sessions that focused on research needs and measurement limitations, how they affect atmospheric studies, and what steps can be taken to improve the measurements and the methods by which they are analyzed.

This report summarizes the sessions of oral presentations, the working sessions, as well as the conclusions and recommendations. Appendix B contains the extended abstracts of the oral presentations.
ACKNOWLEDGEMENTS

The authors express their appreciation to all people who contributed to the planning, conducting, and reporting of the workshop.

In special we thank the chairpersons of the sessions, the authors of the papers and Reinhold Busen, Norbert Entstrasser, Markus Quante, Frank Rösler, and Joachim Stingl who acted as reporters for the sessions.

Gisela Gersing served as Workshop Administrator and processed the text for the workshop report. Her contribution is gratefully acknowledged.
1. INTRODUCTION AND BACKGROUND

Airborne platforms for atmospheric measurements are operated and maintained by various organizations around the world. These facilities provide in situ measurements of numerous fundamental parameters such as temperature, pressure, humidity, and winds, as well as many other cloud microphysical, chemical, and radiative properties of the atmosphere. A previous workshop, however, has shown that present measurements are not always adequate for satisfying the requirements of the science (Cooper and Baumgardner, 1988). A better understanding of the basic physics of many of these measurements is needed if the quality of the data is to be improved. The integration of datasets from multiple airborne platforms also requires more conformity with respect to calibration and documentation.

Atmospheric research has long been international in scale, and recent major thrusts in world climate and global geosciences have focussed attention on the need for more and better observations. Clearly, atmospheric research aircraft are playing a crucial role in filling this need and in providing "air-truth" measurements for evaluating models and satellite-based sensors. In view of the limited availability of research aircraft facilities throughout the world, improved interactions and collaboration between existing groups in various countries operating such facilities is being considered critical in providing the required operational support. Therefore, an international workshop\(^1\) was held in November 1988 to discuss a variety of topics concerning cooperation and collaboration among research aircraft facilities. The objectives of that workshop were as follows:

- To exchange information regarding the current and planned capabilities of research aircraft and associated instrumentation,
- To explore possible mechanisms for cooperation in the use of such aircraft and instrumentation, and
- To explore possible mechanisms for cooperation in the development of sensors and instrumentation for atmospheric research aircraft.

One of the major conclusions from that workshop was the recommendation to plan a series of specialized workshops, each focussing on a particular class of sensors or parameters (such as wind, turbulence, state parameters, atmospheric chemistry, fluxes, airborne active and passive remote sensing, data quality, data management, and analysis software, etc.). The specific purpose would be to promote the standardization of measurement, calibration, and analysis techniques among flight facilities and to establish a forum to advance the state-of-art in the particular area.

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\(^{1}\) "The International Conference on Cooperation in Research Aircraft." The workshop report is available by contacting Warren Johnson, NCAR, Box 3000, Boulder, CO 80307.
The most important topic, to be addressed in the first workshop, was considered to be the airborne measurement of winds, turbulence, and position. Thus, as a first step, the German Aerospace Research Establishment (DLR) hosted the International Workshop on the Airborne Measurement of Wind, Turbulence, and Position. This meeting was held 26-28 July 1989 at the DLR facilities in Oberpfaffenhofen, West Germany.

The goals of this workshop were four-fold:

• To exchange information on measurement technology and analysis techniques, including:
  • measurement systems,
  • calibration techniques,
  • analysis software,
  • data applications;

• To discuss possible areas where standardization is beneficial, such as:
  • calibrations,
  • data processing procedures,
  • correction algorithms,
  • measurement uncertainty assessment and reporting;

• To discuss possible projects of future collaborations, in particular:
  • the development of new sensors,
  • the assessment of measurement uncertainties,
  • the exchanges of personnel between facilities; and

• To recommend future courses of action where collaboration among flight facilities would be advantageous.

The first half of the workshop consisted of oral presentations describing fundamental problems, new measurement systems, calibration techniques, and applications of the measurements. The second half of the workshop was devoted to working sessions that focused on research needs and measurement limitations, how they affect atmospheric studies, and what steps can be taken to improve the measurements and the methods by which they are analyzed.
This report summarizes the sessions of oral presentations (Section 2) as well as the working sessions (Section 3). The conclusions and recommendations that came as a result of this meeting are summarized in Section 4. Appendix B contains the extended abstracts of most of the oral presentations. Several authors have submitted full-length manuscripts for a special issue of the *Journal of Atmospheric and Oceanic Technology*. Appendix A and C compile the workshop agenda and the list of participants, respectively.
2. SUMMARY OF SESSIONS 1-4

In his keynote address, D. Lenschow first gave a historical survey on air motion measurements. He then described the available measurement techniques that are used in research aircraft and their limitations. The present measurement systems are sufficient for resolving horizontal wind velocities with an absolute accuracy of about ±0.5 m/s and vertical velocities with about ±1 m/s. Relative accuracies are obtainable to about ±0.3 m/s in both lateral and vertical components of the wind.

However, the vertical wind velocities associated with some mesoscale and large scale atmospheric phenomena, such as fronts and sea breeze circulations or flow over irregular terrain, are typical on the order of centimeters per second. Furthermore, better accuracies are needed also for routine measurements of divergence and vorticity.

Comparing these demands on the accuracy with the current status of the measurements, he gave an outlook on the needs for improved measurements, namely more accurate measurement of horizontal and vertical velocity components and more accurate determination of flow distortion effects.

For the future, one can expect that new technologies, such as the Global Positioning System and remote laser air motion sensing systems, will improve the accuracy of the measurements.

2.1 Session 1: Fundamental Problems

In this session, errors caused by the use of aircraft as measurement platforms and fundamental limitations of airborne wind and turbulence measurements were discussed.

The problem of air motion measurement uncertainties was discussed by D. Baumgardner. He used error propagation techniques to show that the accuracy is primarily limited by the uncertainties in measurements of heading, pitch, and angle of attack. These errors are then amplified by airspeed and altitude.

The effect of flow distortion on turbulence measurements from aircraft was studied by J.C. Wyngaard (paper given by W.A. Cooper). He showed that normally the integral scale of the turbulence is small compared to the characteristic length of the aircraft (fuselage) diameter and therefore flow distortion effects, such as attenuation, amplification, and crosstalk seriously affect the measurements. The fields of the scalars that are included in flux measurements (temperature, humidity) are also affected by the flow distortion. Therefore, errors in flux measurements must be expected.
More detailed studies of these effects were presented by W.A. Cooper. using an airflow model developed by H.G. Norment for the NCAR Electra and King Air, he calculated the flow fields at several locations of the temperature and humidity sensors on these two aircraft. The errors resulting from the distorted flow velocities on scalar and flux measurements were found to be quite substantial for some sensor locations.

2.2 Session 2: Measuring Systems

This session covered the description of aircraft used by different groups for meteorological measurements, and of special installations in such systems.

The motorglider of the Flinders University of South Australia was presented by J.M. Hacker. The aircraft is fully equipped for turbulence measurements. Examples of measurements of a sea-breeze front and over a desert lake area showed the capabilities of this small aircraft. In particular, a GPS receiver has been installed, and satellite coverage was reported to be almost eight hours during most of these field projects.

M. Andre and M.P. Le Pipec gave a description of the gustprobe system of the French Merlin aircraft. The air motion relative to the aircraft is sensed by a radome gustprobe. It gives good signals up to 10 Hz. However, the resolution of the Inertial Navigation System (INS) for the determination of the aircraft velocity and attitude seems to be too low.

The University of Uppsala, Sweden, uses a Sabreliner Aircraft in boundary layer research that was introduced by M. Tjemstroem. Air motion measurements are made with a radome gustprobe and an INS. The calibration of the system using analytic flow theory and by flying special maneuvers was demonstrated and flight results were given.

The DLR Falcon had a system upgrade recently. R. Baumann showed that the newly installed laser gyro Inertial Reference System gives smaller post-landing position errors than the formerly used INS. The "blended position," a combination of the data of the IRS, VLF/Omega, and VOR-TAC positioning unit, calculated online by a flight management computer, gives errors of about ±0.25 nm.

The Meteorological Measurement System of the high flying NASA ER-2 aircraft was described by K.R. Chan. It uses a radome gustprobe system and a high resolution INS for air motion sensing. Special efforts have been made to install a stand-alone data acquisition system. Results of a flight over Antarctica showed the ability of the system to measure vertical winds. A unique system for calibrating inertial navigation systems (INS) was described by Chan. A pendulum system was built that swings the INS with multiple degrees of freedom such that biases in the INS can be determined with good accuracy.
To measure gusts with high frequency resolution and precision, the German MBB company developed a gustprobe system for the DLR Falcon. G.K. Lemonis described the system, a five-hole probe with directly attached miniature pressure transducers, to be installed at the noseboom of the aircraft. Calculations show that due to the short pneumatic lines frequencies up to 100 Hz can be resolved without error.

For installation on aircraft or helicopters, the German Aerodata company has developed a pod named METEOPOD containing all sensors necessary to measure air motion, temperature, and humidity. P. Voersmann demonstrated the design of the system and first results of flights where it was attached under the left wing of an aircraft.

Aerodata is also working on array-processors for airborne data systems to speed up the real time computation of wind components. M. Haverland gave an overview of this processor and the algorithms that are used for the calculation of the wind components.

The Swiss Technical University in Zurich uses motorgliders and other light aircraft for meteorological measurements. B. Neininger gave an outline of the measurement systems which are portable and easy to be installed in the different aircraft. Measurements were made in mountain regions and along distance measuring beams for high precision geodetic research. He also described the combination of Omega and radar for navigation.

The Dutch company Geosens operates aircraft for meteorological measurements. M. von Koenigsloew showed how Doppler Radar systems are used for navigation and the determination of wind.

W.B. Johnson reported an aircraft platforms and instrumentation developments at NCAR. The Electra has been improved, and plans are going on to acquire a mid-size jet aircraft. As examples of the instrumentation developments on aircraft, telemetry and a UV-hygrometer were shown.

2.3 Session 3: Analysis Techniques

In this session, techniques to analyze the data of air motion measurements were presented and discussed.

The paper by B. Friederici (presented by P. Voersmann) gave an overview on the algorithms for real-time airborne measurements of wind, turbulence, and position that are used by Aerodata. The error handling and in-flight calibration were shown together with the results of intercomparison measurements between the aircraft and a meteorological tower. Tests to use the Global Positioning System (GPS) for air motion measurements were also shown.
The National Aeronautical Establishment in Ottawa uses a Twin Otter aircraft for atmospheric research. B.W. Leach gave an overview of the installation of meteorological sensors and demonstrated the difficulties of making accurate wind measurements due to the Schuler oscillation of the INS. The combination of data from the INS, a Doppler radar and Loran-C by using Kalman filter techniques, resulted in a remarkable improvement of the results.

Ph.L. Nacass gave an overview of the numerical aerodynamic modeling of the airflow on the nose of the French Merlin aircraft. The results of test flights at calm atmospheric conditions were compared with numerical data from the modeling. The resulting pressure distribution along the fuselage was also shown.

At DLR special flight maneuvers are used for system tests and in-flight calibration of the Falcon wind measurement system. W. Boegel showed how time lags can be determined in the sensors used for the wind measurement through such special maneuvers. They also help to detect instrument malfunctions.

2.4 Session 4: Applications and Measurements

Basic properties of atmospheric turbulence in the inertial subrange can be used to check the accuracy and consistency of data. R. Friesen showed analyses of intercomparison flights where two or three aircraft flew together. Power-spectra and Co-spectra of this data show good agreement between the different aircraft and with theory.

During FASINEX, the NCAR Electra made flights in the marine boundary layer. W.J. Shaw found from this data that due to the Schuler oscillation and the drift of the INS, remarkable errors in the wind arose. Simultaneous position measurements with Loran-C were smoothed by cubic splines and used to correct the data. The improvement was about one order of magnitude.

A. Druilhet gave an overview of the work at the University of Toulouse, France. The first paper described an inertial-dissipative method for calculating turbulent fluxes from low level airborne measurements. It is simpler than the normally used eddy-correlation method and gives good results at moderately unstable conditions, namely for measurements over sea.

The second paper showed measurements of wind fields in inhomogeneous conditions. Velocity field deformations caused by strong contrast in boundary conditions (sea-land transition), orographic divergence, and baroclinicity in the marine boundary layer were analyzed.
At DLR three powered gliders are used for turbulence profiling in the atmospheric boundary layer. A. Jochum gave a description of the present and future instrumentation, and of measurements in the convective boundary layer. The use of multiple aircraft was reported to alleviate the sampling problems associated with airborne flux measurements.
3. SUMMARY OF WORKING SESSIONS

Two sessions of the workshop provided a forum for the discussion of specific issues concerning the implementation of air motion and positioning measurements in both hardware (e.g., aircraft platforms, sensor system, etc.) and software (i.e., analysis techniques). The first session, co-chaired by W.A. Cooper (NCAR) and P. Mascart (LAMP), focused on the hardware aspects, and the second session, co-chaired by A. Jochum (DLR) and D. Baumgardner (DLR/NCAR), was concerned with various aspects of the analysis. This section of the workshop report is a combined summary of these sessions and of part of the final session.

This summary will begin with a discussion of the problems that were identified by the participants. Then the suggested solutions to these problems will be elucidated before discussing problems that still remain to be solved.

3.1 Statement of Problems

The problems of measuring air motion from aircraft were put into perspective by W.A. Cooper, who presented a brief summary of an instrumentation workshop that was held in the Fall of 1988 (Cooper and Baumgardner, 1988). That workshop was attended by a group of technically knowledgeable scientists who use aircraft in their studies but are not necessarily involved in the development or evaluation of instrumentation. One result of that workshop was a statement from this group of what they could use scientifically in the way of "ideal" instrumentation that could provide the measurements necessary to achieve specific scientific objectives. The requirements for air motion measurements were as follows:

- Horizontal wind measurements are needed with accuracies better than 10 cm/s. This accuracy is required for analysis of horizontal fluxes, advection processes, and mass balance calculations.
- Vertical wind measurements are needed with accuracies better than 1 cm/s. Studies of divergence, vorticity, synoptic scale motions, dynamic structure of fronts, pressure perturbations near cloud base or jet streaks, mesoscale circulations, fluxes, and mass balance calculations all require measurements with accuracies of this order.
- Measurements are necessary over the entire range of wavelengths found in the atmosphere. Very long wavelength measurements are needed for studying mesoscale and synoptic scale motions and very short wavelength measurements are needed to study turbulent intermittency and small scale mixing processes.
Better characterization of the limitations and errors associated with the measurements from all airborne instruments is needed. Aircraft facilities have a tendency to treat the users of their data too much as if these users were intimately involved with the taking of the data. This assumes that the user is more cognizant of instrument operating characteristics than is probably the case.

The results of the 1988 workshop served as a starting point for subsequent discussions. The earlier presentations by D. Lenschow and D. Baumgardner had provided estimates of the accuracies with which they thought wind magnitudes could be measured. These are approximately ±0.5 m/s and ±1.0 m/s for the absolute accuracy of the horizontal and vertical wind measurements, respectively, and ±0.3 m/s for the relative accuracy of both horizontal and vertical components of the wind.

The factors that limit the accuracy of present day measurement systems are the following:

1. The largest source of measurement error is the uncertainty in measuring the aircraft attitude angles, especially heading and pitch. These errors are exacerbated at higher velocities and altitudes.

2. The second largest uncertainty is the error caused by distortion of the airflow by the aircraft structure.

3. There are some scientific problems where sufficient statistics cannot be obtained from the measurements (this is discussed by Lenschow and Stankov, 1986).

4. The response time of sensors used in the air motion measurement systems are inadequate at normal aircraft speeds to resolve small scale and intermittent structures.

5. The techniques used to calibrate the measurement systems have inherent limitations that affect the subsequent accuracy of the measurements. A variety of methods are used by the different flight facilities to calibrate their systems, but there is no consensus as to which methods are best for each measurement system.

6. Measurement techniques that utilize a inertial reference (IRS) or inertial navigation system (INS) suffer from offset biases that vary with time in both horizontal and vertical components of the measured aircraft acceleration.
7. Additional errors arise during the analysis of measurements because of the approximations and assumptions that are made when the data is processed.

Part of the problem of providing the users of aircraft data with information concerning data quality is that there is not a commonly accepted method for determining the quality of a set of measurements, and an adequate error analysis of the measurement systems has yet to be conducted.

An additional problem is the lack of too little communication between facilities and too little publication in the open literature of studies that address the problems listed above.

3.2 Possible Solutions

A number of possible solutions to the problems listed above were discussed by the workshop participants. Specifically:

1. There is at present no system that can measure aircraft attitude angles with the accuracies needed, i.e., < .05 degrees. However, W.A. Cooper suggested the possibility of mounting Global positioning system (GPS) antennas on the nose, tail, and wingtips of the aircraft and use the subsequent position measurements to derive the aircraft attitude angles. Attitude angles with an accuracy of 0.006 degrees could be measured since the GPS measures aircraft position with an accuracy of approximately 1 cm.

2. The problem of air flow distortion could be circumvented if techniques are developed to remotely sense the air motion at a point outside the influence of the aircraft body. This technique is already in use by the British Meteorological Office for measuring true air speed. A three-beam laser system or rotating laser would be necessary to measure all three-wind components.

3. Better sampling statistics for flux measurements can be made over a smaller area if multiple aircraft are used; however, a scanning remote sensor will provide a method of covering similar area but with only a single aircraft.

4. Commercial pressure sensors have a response time of approximately 10 ms. This limits air motion measurements to approximately one meter at typical airs speeds of 100 m/s. One half meter scale structures can be measured with slow flying aircraft such as motorgliders; however, remote sensing techniques may be required to detect intermittent events that could be significant at even smaller length scales.
5. In situ measurement systems require in-flight maneuvers of the aircraft (Lenschow, 1986; Bögel and Baumann, 1990) to calibrate their response to changes in aircraft attitude angle and to correct for effects such as the location sensitivity of static pressure sensors, pressure line time lags, and lags in the IRS. However, these calibration techniques have inherent limitations because of background turbulence and uncertainties in the measurements from the other sensors from which the calibrations are derived. Some of the calibration factors for the IRS can be obtained in a laboratory set-up such as used by the NASA (Ames) group who use a special swing mechanism to measure the accuracy of their INS systems. Another possibility is to use numerical flow models to establish sensitivity factors for gustprobe systems. This latter technique is not simple to implement but would be a powerful tool if the model sufficiently represented the flow of air around the aircraft.

The participants agreed that some type of standardized calibration technique should be used by all the facilities when appropriate. This would be especially helpful in multiple aircraft projects when data sets must be shared and compared.

6. The problem of offset biases in INS’s and IRS’s is being solved through techniques that integrate the information from multiple systems, i.e., Loran-C, GPS, multiple DME’s, doppler radars, or Omega systems (e.g., see the summaries in this workshop report of Baumann et al, Friederici, and Haverland). GPS systems provide enough information to measure aircraft position with an accuracy of approximately a centimeter. The only remaining problem is to obtain satellite coverage that will allow 24-hour-a-day operation over all parts of the world. All satellites are expected to be in operation by 1992.

B. Leach (NAE) described a portable DME system that could be set up during field operations. The multiple distance information can be used to locate the aircraft quite accurately when several DME transmitters are located around the operations area.

7. The fundamental equations that are used to derive the wind components from the basic measurements are well known. However, some facilities use approximations to the equations after assuming that some of the components have negligible effect on the derived winds. The effect of these approximations have not been thoroughly investigated, but rough estimates have shown that the error introduced by these assumptions may not be
negligible under some conditions. This question is being investigated further, and an upcoming report will discuss this and evaluate the possible magnitude of these errors.

A poll of the participants also indicated that not all of the facilities implement all the corrections that are necessary to account for position errors of static pressure sensors, attitude sensitivities, or pressure line and INS time lags in the system.

Several methods for assessing data quality were discussed by R. Friesen in an earlier session of the workshop. Information of this type can be obtained by examining the power spectra of the horizontal and vertical components of the wind. The slope of the variance should follow a $-5/3$ trend in the inertial subrange if the measurements are of good quality. Likewise, the ratio of the covariances also should have a certain constant value if there are no biases in the measurements. Other tests may be possible that use the known behavior of the atmosphere to evaluate the relative quality of the data.

The workshop participants agreed on the need for a better evaluation of measurement uncertainties and a common format for reporting these uncertainties.

A great deal of discussion covered the topic of communication of results, sharing resources, and other communication issues. The possibility of using an electronic bulletin board was suggested, and it was recognized that results should be reported on both informal and formal levels. The easiest mechanism for reporting preliminary results seemed to be, at the present, to publish a brief summary in the *Airborne Geoscience Newsletter* (published by NASA, Airborne Science Program Office, 400 Virginia Avenue, SW, Suite 810, Washington, DC 20024). More formal results should be submitted to publications such as the AMS *Journal of Atmospheric and Oceanic Technology* (JTech).

### 3.3 Remaining Problems

The effect that air flow distortion has on in situ measurements will probably limit the usefulness of these measurements when centimeter accuracies are required. Remote sensing systems will be required to meet many scientific needs.

The question of how to measure turbulent intermittency was never adequately addressed. More research and development is needed in this area of study.

Aircraft facilities are generally lacking adequate resources for research and development efforts that improve measurement capabilities. This lack is usually in both personnel as well as financial support.
4. RECOMMENDATIONS

The participants were given the responsibility for compiling a list of recommended actions to be taken in the near future that would address the specific problems discussed during the workshop. These recommendations would be for the purpose of guidance for future research that would improve present measurements of air motion and position from an airborne platform. The actions that are recommended follow:

1. A collaborative effort should be organized to develop a laser-based gust sensing system.

2. Special sensor calibration equipment should be developed and shared among facilities.

3. A guidebook should be developed for describing how to install and calibrate a radome system on an aircraft.

4. A collaborative effort should be organized to study the effects of airflow distortion.

5. The participants advocated the development of a fast response instrument to measure water vapor mixing ratio.

6. A major effort should be made to evaluate measurement uncertainties.

7. More attention should be given to the development of techniques for measuring intermittent turbulence.

8. Alternative methods for difficult-to-measure parameters such as mean vertical velocity, divergence, and vorticity should be explored.

9. Aircraft facilities are encouraged to furnish their users with sufficient information about instrument performance so that these users can adequately assess the quality of their data. The recommendation was also made that facilities educate their users on the need for frequent flight maneuvers and their usefulness in improving data quality.
10. A special issue of the *Journal of Atmospheric and Oceanic Technology* that focuses on air motion and position measurements should be prepared. All participants who made presentations at this workshop were encouraged to submit papers for this special issue. A tutorial on fundamental measurements, calibration procedures and optimum flight maneuvers was strongly recommended for this special issue.

11. More effort is needed to find ways to share resources among facilities. Mechanisms for exchanging both people and equipment must be explored and put in place to expedite this process.

In addition to recommended actions, the following actions were taken immediately:

1. A review committee chaired by B. Leach (NAE) was formed to exchange information on INS coupling and updating methods.

2. A committee was formed to investigate methods for reporting measurement errors. The co-chairpersons of this committee are D. Baumgardner and W.A. Cooper (NCAR). The primary objective of this committee is to suggest a common format for aircraft facilities to report measurement uncertainties.

3. A committee, chaired by R. Friesen (NCAR) was formed to assess hardware filtering needs, delays in INS data, and other characteristics of the hardware.
5. REFERENCES

Bögel, W., and R. Baumann, 1990: Test and calibration of the DLR Falcon wind measuring system by maneuvers. Submitted to *Journal of Atmospheric and Oceanic Technology*.


APPENDIX A--WORKSHOP AGENDA

Wednesday, July 26:

09:00 - 09:45 Registration

09:45 - 10:00 Welcome by M.E. Reinhardt, Director at the DLR Institute of Atmospheric Physics.

10:00 - 10:50 D.L. Lenschow:
Workshop Keynote: Air Motion Measurement in Past and Future.

Session 1: Fundamental Problems.

Chairperson: H.P. Fimpel, DLR Oberpfaffenhofen.

11:10 - 11:35 D. Baumgardner:
Air Motion Uncertainties: Their Impact on Atmospheric Studies.

11:35 - 11:55 J. C. Wyngaard (presented by W.A. Cooper):
(Extended abstract not available)

11:55 - 12:20 W. A. Cooper:
Quantitative Assessment of the Errors in Scalar Fluxes caused by Airflow Distortion. (The paper will be published in JTech)

Session 2: Measuring Systems.

Chairperson: W.B. Johnson, NCAR, Boulder Co.
J.H. Seymour, MRF, Farnborough.

13:40 - 14:00 J.M. Hacker:
The F.I.A.M.S. Research Aircraft or 'Small is beautiful'.

14:00 - 14:20 M. Andre, M.P. Le Pipec:
Technical Presentation of the MERLIN's Radome Calibration and Data Processing.
14:20 - 14:40 M. Tjemstroem:
On the Use of Pressure Fluctuations on the Radome of a Sabreliner Aircraft for Air Motion Sensing in Boundary Layer Research or What to do when you can’t afford your own Research Aircraft? (The paper will be published in JTech)

14:40 - 15:00 R. Baumann, H.G. Christner, H.P. Fimpel, G. Wilke:
The Improvement of the Installation of the DLR Research Aircraft Falcon: Description and First Results.

15:00 - 15:20 K.R. Chan, S.W. Bowen, S.G. Scott, T.B. Bui:
The NASA ER-2 Meteorological Measurement System: Instrumentation, Calibration and Intercomparison Results.

15:20 - 15:40 G.K. Lemonis:
Fast Response Gust Measurement Device.

16:00 - 16:20 B. Friederici (presented by P. Voersmann):
METEOPOD, a Helicopter and Aircraft System for Real-Time Wind and Turbulence Measurements. (Extended abstract not available)

16:20 - 16:40 M. Haverland:
The Use of Array-Processors for Real-Time, High Frequency Turbulence Measurements.

16:40 - 17:00 B. Neininger:
Omega-Navigation and Radar Tracking Techniques used by LAPETH for Meteorological Measuring Flights with Motorgliders.

17:00 - 17:20 M. von Koenigsloew:
The Use of Doppler Radar for Navigation and Wind Determination for Airborne Atmospheric Research. (Extended abstract not available)

17:20 - 17:40 W.B. Johnson:
Preliminary Plans for Upgrading Positioning Systems on NCAR Aircraft. (Extended abstract not available)
Thursday, July 27:

Session 3: Analysis Techniques.

Chairperson: A. Druilhet, Universite Paul Sabatier Toulouse

08:30 - 08:50 P. Voersmann:
Algorithms for Real-time Airborne Measurements of Wind, Turbulence and Position. (Extended abstract not available)

08:50 - 09:10 B.W. Leach and J.I. MacPherson:
Application of Kalman Filtering to Airborne Wind Measurement. (The paper will be published in JTech)

09:10 - 09:30 Ph. Nacass:
Numerical Modelisation of Airflow on the Nose of the French Research Aircraft MERLIN IV for Measuring Air Motion.

09:30 - 09:50 W. Boegel and R. Baumann:
System Test of the DLR Falcon Wind Measuring System by Maneuvers. (The paper will be published in JTech)

Session 4: Applications and Measurements.

Chairperson: J.M. Hacker, F.I.A.M.S. Bedford Park

10:10 - 10:30 R. Friesen:
Turbulence Measurements in the Inertial Subrange on NCAR Aircraft. (The paper will be published in JTech)

10:30 - 10:50 W.J. Shaw:
NCAR Electra Measurements on FASINEX. (Extended abstract not available)

10:50 - 11:10 P. Durand, L. de Sa, A. Druilhet and F. Said:
Aircraft Measurement of Heat and Momentum Fluxes by Inertial Dissipation Method. (The paper will be published in JTech)

11:10 - 11:30 A. Druilhet:
Wind Field Aircraft Measurements over Inhomogeneous Surfaces (Sea-Land Experiments). (The paper will be published in JTech)
11:30 - 11:50 A.M. Jochum:
Turbulence Profiling in the Atmospheric Boundary Layer using three Powered
Gliders.

Chairpersons: W.A. Cooper, NCAR Boulder, Co.
P. Mascart, LAMP Clermond Ferrand

15:50 - 18:00 Working Session II: Software Aspects.
Chairpersons: D. Baumgardner, NCAR Boulder, Co.
A.M. Jochum, DLR Oberpfaffenhofen

Friday, July 28:

08:30 - 09:30 Visit of DLR Aircraft or Preparation of Reports by the Session Leaders.

09:30 - 10:30 Reports of the Session and Working Group Leaders.
Chairperson: M.E. Reinhardt, DLR Oberpfaffenhofen

10:50 - 12:20 Final Discussion and Formulation of Recommendations.
Chairpersons: D. Lenschow, NCAR Boulder, Co.
B.L. Leach, NAE Ottawa
INTRODUCTION

Airborne air motion measurements play a vital role in a variety of atmospheric research studies, from turbulence flux and dissipation measurements to synoptic-scale measurements of mean horizontal winds, and from the surface layer to the stratosphere. The prime advantage of aircraft is their mobility. They can reach remote locations and take measurements in time intervals that are small compared to synoptic variations. This led to early consideration of aircraft for air motion measurement.

On the other hand, their mobility and response to turbulence adds to the difficulty in obtaining accurate air motion measurements. In almost all situations, the measurements required to resolve air motions must include measurement of both the airplane motion with respect to the earth and the air velocity with respect to the airplane. The only exception is fine-scale turbulence measurements at frequencies higher than the aircraft’s response to turbulence (≥ 10Hz). Since the airplane horizontal velocity is typically five to ten times the air velocity, calculation of the air velocity involves computing a small difference between two large numbers. Aircraft are also free to rotate, which means that for many applications, the angular orientation of the aircraft must also be precisely measured. As a result, for many years accurate air motion measurements from aircraft were not possible. This did not preclude obtaining useful information from aircraft going back at least fifty years ago, but it did limit (and indeed still limits) application for aircraft measurements.

HISTORICAL SURVEY

Airplanes have always been useful as qualitative indicators of atmospheric motions—both on the scale of the mean horizontal wind and on the turbulence scale. Even today pilot reports are important sources of information for both mean and turbulent flow. More quantitative information on turbulence became available in the 1940’s with the use of VGH [airspeed (V), vertical acceleration (G), and altitude (H)] recorders on aircraft, mainly for flight testing and for studying aircraft response to turbulence. The emphasis at this time was to determine the aircraft response to a discrete gust. During the 1950’s, C.B. Notess and collaborators at Cornell Aeronautical Laboratories, Buffalo, NY, (e.g., Notess and Eakin, 1954) developed a system to measure all three components of turbulent air velocity by removing the effects of...
airplane motion from the measured velocity components. They also recognized the broad frequency range of turbulence and the value of spectral techniques in dealing with the recorded measurement.

The first airborne eddy-flux measurements were apparently obtained by Bunker (1955) using an amphibious PBY-6A, mostly over the North Atlantic Ocean. He measured aircraft pitch angle and vertical acceleration, and combined this with aircraft response characteristics to obtain vertical and longitudinal air velocity component fluctuations. Combining this with temperature measurements, he estimated eddy fluxes of temperature and momentum. Telford and Warner (1962) developed a more accurate air motion sensing system that used a Norden bomb sight as a vertically-stabilized platform for measuring vertical acceleration, and combined this with pitch and attack angle measurements so that vertical air velocity could be obtained independent of aircraft response. They used this system to measure temperature and water vapor fluxes in the boundary layer, as well as cloud updrafts and downdrafts.

One of the first uses of inertially-stabilized platforms for measuring airplane accelerations and attitude angles in the inertial frame of reference was reported by Axford (1968). He also derived the complete equations for calculating turbulent air velocity components and gave examples of pitching and yawing maneuvers that were used to check the accuracy of the system. Starting about this time, several research groups began acquiring inertial navigation systems (INS) that were used to provide both mean horizontal wind measurements and all three components of turbulent velocity fluctuations. Air motion sensing systems based on INS subsequently became generally available to the scientific community.

MEASUREMENT TECHNIQUES

The transverse components (lateral and vertical) of air velocity with respect to the aircraft has been measured by a variety of techniques over the years. The earliest systems used either vanes which were free to align themselves with the flow direction, or pressure sensing probes which used pressure differences across sets of ports at different angles to obtain flow angles. It is a testament to the usefulness and practicality of these techniques that they are still used today. One modification of the pressure sensing probe approach is the use of the airplane nose itself as the pressure probe (radome technique). A variation on the rotating vane technique is to constrain the vane from rotation, and measure the force on the vane, which is a function of air flow angle and dynamic pressure. Sonic anemometers have also been used for measuring the vertical component of air velocity (Miyake, et al., 1970). All these in-situ techniques are limited in accuracy by the requirement for in-flight calibration. This limits the accuracy to probably ±0.3 ms⁻¹.
The velocity of the airplane is obtained from an inertial navigation system (INS). With the current systems, the long-term drift in measurement of the horizontal airplane velocity without external positional information is \(0.5t \text{ ms}^{-1} \text{ hour}^{-1}\), where \(t\) is the number of hours from INS alignment. Loran-C and VOR/DME radio navigation systems are now also available which offer the possibility of more accurate long-term horizontal positional information than from INS, but coverage is not world-wide. In the vertical, the INS velocity must be combined with other measurements to obtain a stable vertical velocity. Normally, pressure altitude is used (although geometric altitude could also be used). Therefore, the accuracy depends upon the accuracy of the pressure measurement, and on the horizontal variability of the pressure field. Neglecting the latter, the limits on accuracy for vertical velocity are determined by the accuracy of the airflow angle measurement.

These accuracies are sufficient for a wide range of meteorological problems. In the convective boundary layer, turbulence fluxes of temperature, humidity and momentum, as well as second- and higher-order moment statistics of the three air velocity components, temperature, humidity and other fast-response scalars (e.g., ozone) can now be obtained with current aircraft systems. In stably-stratified situations, however, it is not always possible to completely resolve the high-frequency part of the flux; furthermore, turbulent mixing processes tend to be intermittent, so that sampling requirements are difficult to estimate.

The mean horizontal air velocity components are now measured with sufficient accuracy to resolve the mean wind field for standard synoptic analyses. However, quantities such as horizontal divergence or vorticity cannot be obtained routinely. Only in special circumstances, with careful calibration and radio navigation updating of position, it is possible to measure these quantities. Because of its small magnitude (A few centimeters per second or less), it is not, in general, possible to directly measure the mean vertical air velocity. In fact, it is standard practice to use the mean vertical velocity measured on a flight leg in a quiescent region of the atmosphere as a reference.

NEEDS

Based on the current status of aircraft instrumentation and the limits discussed above, I summarize below the needs for improved air motion sensing capabilities. First, in order to make routine measurements of divergence and vorticity, the mean horizontal velocity components need to be measured to a few centimeters per second, which is about an order of magnitude improvement in current capability. This should also significantly improve the aircraft’s ability to resolve small-scale circulations such as land and sea breezes, wind differences with height both within and above the boundary layer, and flow patterns around obstacles. More accurate mean wind measurements should lead to more accurate evaluation of the mean horizontal momentum equations in the boundary layer and of the aerodynamic transfer coefficients over the ocean.
Absolute vertical velocity measurements to a few centimeters per second would permit direct evaluation of mean vertical velocity associated with a large number of mesoscale and large scale atmospheric phenomena. Some examples include vertical motions associated with fronts and sea breeze circulations, perturbations in the flow field induced by convection, flow over irregular terrain, and secondary flow patterns in the boundary layer such as mesoscale cellular convection.

Another limitation in air motion measurement is the effect of flow distortion due to the aircraft on air motion measurements. It may not be possible to reach accuracies of a few centimeters per second with in situ flow sensors, if flow distortion effects are determined solely from flight tests. Furthermore, as discussed by Wyngaard, et al. (1985), effects of flow distortion on stress measurements can be particularly detrimental. This points to the need for remote sensors, or for more accurate determination of flow distortion effects—perhaps through numerical modeling. Related to this is the effect of flow distortion on scalar flux measurement; again, Wyngaard (1988) has shown that serious errors in trace constituent flux measurements can result if density is measured instead of mixing ratio.

Lenschow and Stankov (1986) have shown that stress measurements in the convective boundary layer are also hampered by sampling problems. In a typical case, a flight leg of more than a thousand kilometers would be required to achieve 10% accuracy in stress measurement in a convective boundary layer. This is a basic limitation of measurement along a line; an area-averaged measurement of stress may be a suitable alternative.

The basic parameter that describes the tendency of the stably-stratified atmosphere to become or remain turbulent is the Richardson number, which is proportional to the ratio of the vertical temperature gradient to the square of the wind shear. Therefore, in studies of turbulence in a stably-stratified boundary layer of the free troposphere, or in the interfacial layer between the convective boundary layer and the free troposphere, a measure of the Richardson number would be very useful. The appropriate vertical length scale for this measurement is typically on the order of tens of hundreds of meters.

NEW TECHNOLOGY

There are a variety of possible technological solutions to the needs listed above. First, the system of the future for updating INS position and velocity measurements is the Global Positioning System (GPS), a satellite-based radio navigation system that is now starting to be developed. Eventually (within 4 years?), continuous world-wide coverage is planned which will make possible three-dimensional positional accuracy of <20m and velocity accuracy of <0.1 ms\(^{-1}\) at frequencies of several hertz more than ten meters in front of the aircraft. Since the measured quantity is Doppler shift, the velocity measurement is absolute. All-weather performance, as well as operation in clouds, seem feasible. Combining this with
GPS (or other radio navigation systems) provides the opportunity for possibly a factor of five improvement in air motion sensing accuracy.

Combining laser measurements of vertical velocity above or below the aircraft with laser measurements of trace atmospheric constituents that can also be detected with laser techniques, such as ozone (e.g., Browell, 1989) or water vapor, would open up the possibility of remote measurement of trace species fluxes. Measurements of flux profiles throughout the boundary layer while flying at one level would then be possible.

Laser air motion sensing also offers the possibility of direct wind-shear measurement (Kristensen and Lenschow, 1987). Combining this with remote temperature gradient measurement provides a means for direct measure of Richardson number at the same time that the aircraft is measuring in situ turbulence. Gary (1984) has developed and demonstrated a scanning microwave (56.0GHz) radiometer that measures vertical temperature gradients.

Numerical flow simulation has now advanced to the point that it is a useful tool for studying flow around the aircraft. This can provide estimates of errors and correction factors for both air motion sensors and scalar flux measurement, and provide guidance for location of sensors on the aircraft.

REFERENCES


B.2 Air Motion Measurement Uncertainties: Their Impact on Atmospheric Studies (Darrel Baumgardner)

INTRODUCTION

Aircraft measurements of air motion are an important element for understanding atmospheric processes. However, there are uncertainties in these measurements that are a result of the inherent limitations of the instrumentation. These uncertainties place an upper limit on the information that can be extracted from the measurements and affect the interpretation and analysis of the data. A proper analysis of these uncertainties provides the scientist with a tool that can be used in designing experiments and interpreting subsequent measurements.

The effect of the uncertainties in the measurement of primary quantities (e.g., pressure, temperature, etc.) on the secondary quantities that are derived from them must be evaluated by propagating these uncertainties from the equations that relate the primary and secondary quantities. The remainder of this abstract describes this process for the derivation of errors in wind measurement and illustrates the possible magnitudes of the error.

ERROR PROPAGATION

There are numerous tests that discuss the theory of error propagation. In brief, using a Taylor series expansion on a variable, \( y = f(u, v) \), small deviations, \( \sigma_y^2 \), about the mean can be expressed as

\[
\sigma_y^2 = \left[ \sigma_{du} \frac{dy}{du} \right]^2 + \left[ \sigma_{dv} \frac{dy}{dv} \right]^2 + 2 \sigma_{uv} \frac{dy}{du} \frac{dy}{dv}
\]

(1)

where \( u, v \) represent independent variables, \( \sigma_u, \sigma_v \) their respective uncertainties, and \( \sigma_{uv} \) the covariance between the variables. This formulation can be extended to any number of independent variables.

The derivatives of the function, \( y \), with respect to the independent variables (i.e., \( \frac{dy}{du} \), etc.) provide a means of assessing the significance of the uncertainty in each independent variable on the total error. These derivatives are what Merceret (1982) termed the "sensitivity coefficients" and are useful in assessing where more accuracy is either needed or would provide little improvement.

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\(^1\)On scientific leave from the National Center for Atmospheric Research.
A brief digression at this point is necessary to define the term "uncertainty." A more extensive tutorial on this subject may be found in the tutorial by Abernathy, et al. (1973).

The uncertainty of a measurement is the maximum error (where error is the difference between the measured and absolute value) which might reasonably be expected and is a measure of the closeness of the measurement to the true value. The total uncertainty is a combination of random and bias errors. The random error is the error that can be minimized but not eliminated by repeated measurements. The bias error is a systematic error that is the same throughout repeated measurements and could be nearly eliminated through comparison with a standard instrument, if such existed.

The distinction between these two types of error is important when applying error analysis to the measurements since in some cases, both errors must be included in the analysis, while in others, the bias error can be neglected. Thus, error values should have random and bias components expressed separately. The total error is defined as the square root of the sum of squares of the two components, often referred to as the "root sum square" (RSS).

DERIVATION OF WIND VELOCITY UNCERTAINTIES

The wind velocity is calculated as the vector sum of the velocity of the aircraft with respect to the earth and the velocity of the air with respect to the aircraft. The derivation of the complete air motion equations is discussed by Lenschow (1986) but can be simplified with a few approximations that introduce negligible additional error. Following the discussion of Lenschow (1986), the three components of the wind are expressed as

\[ u = -V \sin(\psi + \beta) + u_p \]  
\[ v = -V \cos(\psi + \beta) + v_p \]  
\[ w = -V \sin(\theta - \alpha) + w_p \]

where \( V \) is the true airspeed, \( \psi \) is the aircraft true heading, \( \beta \) is the sideslip angle, \( \theta \) is the pitch angle, \( \alpha \) is the attack angle, and \( u_p, v_p, \) and \( w_p \) are the longitudinal, transverse, and vertical motions of the aircraft.

The measurement uncertainty of \( u, v, \) and \( w \) can then be expressed as

\[ \sigma_u^2 = [\sigma_{du} / dV]^2 + [\sigma_{du} / d\psi]^2 + [\sigma_{dp} / d\beta]^2 + [\sigma_{dw} / du_p]^2 \]

\[ \sigma_v^2 = [\sigma_{dv} / dV]^2 + [\sigma_{dv} / d\psi]^2 + [\sigma_{dp} / d\beta]^2 + [\sigma_{dw} / dv_p]^2 \]

\[ \sigma_w^2 = [\sigma_{dw} / dV]^2 + [\sigma_{dw} / d\psi]^2 + [\sigma_{dp} / d\beta]^2 + [\sigma_{dw} / dw_p]^2 \]
\[ \sigma_v^2 = \left( \sigma_{dv} \frac{dv}{dV} \right)^2 + \left( \sigma_{\psi} \frac{dv}{d\psi} \right)^2 + \left( \sigma_{\beta} \frac{dv}{d\beta} \right)^2 + \left( \sigma_{\sigma} \frac{dv}{d\sigma} \right)^2 \] (6)

\[ \sigma_w^2 = \left( \sigma_{dw} \frac{dw}{dV} \right)^2 + \left( \sigma_{\psi} \frac{dw}{d\psi} \right)^2 + \left( \sigma_{\alpha} \frac{dw}{d\alpha} \right)^2 + \left( \sigma_{\omega} \frac{dw}{d\omega} \right)^2 \] (7)

and the sensitivity coefficients are

\[ \frac{du}{dV} = -\sin(\psi + \beta) ; \quad \frac{dv}{dV} = -\cos(\psi + \beta) ; \quad \frac{dw}{dV} = -\sin(\theta - \alpha) \] (8)-(10)

\[ \frac{du}{d\psi} = \frac{du}{d\beta} = -V \cos(\psi + \beta) ; \quad \frac{dv}{d\psi} = \frac{dv}{d\beta} = V \sin(\psi + \beta) \] (11)-(12)

\[ \frac{dw}{d\theta} = \frac{dw}{d\alpha} = -V \cos(\theta - \alpha) ; \quad \frac{du}{du_p} = \frac{dv}{dv_p} = \frac{dw}{dw_p} = 1 \] (13)-(14)

Equations (5)-(7) can be evaluated after similar expressions are derived for \( \sigma_v, \sigma_w, \) and \( \sigma_\omega, \) since these uncertainties are all dependent upon the measured static, dynamic, attack, and sideslip pressures as well as the temperature.

RESULTS

The estimated uncertainties in the measured variables are listed in Table I. The values listed are the combined bias and random errors but the random component is also listed in parentheses. When equations (8)-(13) are substituted into (5)-(7), the uncertainties from Table I are used to evaluate the relative magnitude of each of the error components.
<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Estimated Uncertainty</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static Pressure</td>
<td>0.24 (0.16) mb</td>
<td>Brown, 1988</td>
</tr>
<tr>
<td>Dynamic Pressure</td>
<td>0.24 (0.16) mb</td>
<td>Brown, 1988</td>
</tr>
<tr>
<td>Temperature</td>
<td>0.26° (0.16°)</td>
<td>Cooper, 1987</td>
</tr>
<tr>
<td>Attack Angle</td>
<td>0.24° (0.12°)</td>
<td>Brown, Pers. Comm.</td>
</tr>
<tr>
<td>Sideslip Angle</td>
<td>0.16° (0.08°)</td>
<td>Brown, Pers. Comm.</td>
</tr>
<tr>
<td>Heading Angle</td>
<td>0.4°</td>
<td>Litton</td>
</tr>
<tr>
<td>Pitch Angle</td>
<td>0.1°</td>
<td></td>
</tr>
<tr>
<td>True Airspeed</td>
<td>0.4 - 0.7 ms(^{-1})</td>
<td></td>
</tr>
<tr>
<td>Horizontal Wind</td>
<td>0.5 - 0.8 ms(^{-1})</td>
<td></td>
</tr>
<tr>
<td>Vertical Wind</td>
<td>0.4 - 1.1 ms(^{-1})</td>
<td></td>
</tr>
</tbody>
</table>

\[
\sigma_u^2 = [\sin^2(\psi + \beta)\sigma_v^2 + V^2\cos^2(\psi + \beta)][\sigma_v^2 + \sigma_\beta^2] + \sigma_{\alpha p}^2
\]

(0.0 - 0.5) \hspace{1cm} (0.0 - 2) \hspace{1cm} (0.0 - 0.2)

\[
\sigma_v^2 = [\cos^2(\psi + \beta)\sigma_v^2 + V^2\sin^2(\psi + \beta)][\sigma_v^2 + \sigma_\beta^2] + \sigma_{\alpha p}^2
\]

(0.0 - 0.6) \hspace{1cm} (0.0 - 2) \hspace{1cm} (0.0 - 0.2)

\[
\sigma_w^2 = [\sin^2(\theta - \alpha)\sigma_v^2 + V^2\cos^2(\theta + \alpha)][\sigma_v^2 + \sigma_\beta^2] + \sigma_{\alpha p}^2
\]

(0.0 - 0.6) \hspace{1cm} (0.0 - 2) \hspace{1cm} (0.0 - 0.2)

The values listed below each term on the right hand side of the equations show the range of uncertainties contributed by each component of error. The second term in each equation is seen to have the greatest effect on the total error because of the influence of the true airspeed on the uncertainties in \(\alpha\), \(\beta\), and \(\psi\). These equations show that the uncertainties in the calculated winds are not constant, but vary with environmental conditions. This dependency is demonstrated in Figures 1 and 2 where the uncertainty in the lateral and vertical components of the wind is shown as a function of true airspeed for three different altitudes. The solid lines show the total error while the dashed lines represent the random component only. These figures indicate that the most accurate wind measurements will be made at lower altitudes and slower speeds.
To summarize, error propagation techniques provide a means of assessing the quality of measurements and guidance in data interpretation. The results from this study show that the accuracy in calculated winds would be improved by making only small improvements in the measurement of attack, sideslip, and heading angles.

REFERENCES


Figure 1

Figure 2
The atmospheric boundary layer and the processes which control its structure have long been one of the major fields of research interest at the Flinders Institute for Atmospheric and Marine Sciences (F.I.A.M.S.). Through a generous donation, the Institute was able to purchase and equip a small research aircraft for use in boundary layer research projects in 1984. As the author had successfully used motor-gliders for research projects similar to those envisaged by F.I.A.M.S., it was decided that a GROB G109B motor-glider would fulfill all essential operational requirements and still leave sufficient funds to allow for the installation of comprehensive scientific instrumentation.

As the main field of research was the continuing investigation of the planetary boundary layer, it was required to be able to measure the basic meteorological parameters such as air temperature, humidity, atmospheric pressure, and wind with a high degree of accuracy. To monitor vertical energy fluxes using the eddy-correlation method, sensors with a fast response time had to be selected to yield the desired resolution. The sensors and scientific subsystems fitted to the aircraft are:

* high-res static pressure transducer
* PA and IAS transducer
* 3 fast temperature sensors
* relative humidity sensor
* 2 Lyman-alpha humidity sensors
* dew-point mirror system
* infrared radiometer for surface temperature
* 2 spectral short-wave radiometers
* radar altimeter
* 5-hole probe for angle of attack and sideslip
* 2 diff. press. transd. for 5-hole probe
* attitude and heading reference system
  > aircraft attitude angles (pitch, roll, heading),
  > 3-dim. body accelerations and rates
* OMEGA/VLF navigation system
* GPS navigation receiver
* video-system

Rosemount 1201F1
Rosemount 1241M & 1221D
Pt100 in reverse flow & fast resp. housing
Vaisala Humicap
AIR LA-1A & ERC BLR
Meteolab TP-3S
Heimann KT-15
FIAMS
King KRA-10A
DLR
Rosemount 1221F2VL
Rockwell-Collins AHS 85
Litton LTN 3000
Trimble TANS
National
The on-board data system, designed and build at F.I.A.M.S., was especially tailored to give the users of the aircraft a reliable and easy to use means to sample, preprocess, display and log the measured parameters in flight and on the ground. The system enables the pilot and/or mission scientist to view raw as well as processed parameters on a 7" graphics monitor online in the aircraft. For a complete evaluation of the data in the field, a combination of a powerful laptop computer fitted with an array processor is part of the standard ground equipment. A detailed description of the aircraft, its capabilities and instrumentation is given in Hacker and Schwerdtfeger, 1988.

Since becoming operational in late 1985, the aircraft was used in a wide variety of research projects all over Australia. As typical examples, some results from two observational studies will be presented.

THE FINE STRUCTURE OF A SEA-BREEZE FRONT

Initiated by a visiting scientist from Germany (Prof. Helmut Kraus, University on Bonn), numerous traverses were flown through a number of strong sea-breezes in the Coorong area in South Australia. Although the final processing of the data is still in progress, it is already clear that the data sets will yield very detailed information about the small scale structure of the fronts. Figure 1 shows traverses through the front at two different altitudes.

As the fronts were moving at a steady rate, it was possible to assemble composite cross-sections through the front. Figure 2 shows composites of the field of potential temperature and specific humidity from 21 traverses over a time interval of approximately five hours. Cross-sections of the wind components are depicted in Figure 3. The horizontal wind components u (perpendicular to the front) and v (front-parallel) were computed using a combination of GPS data and data from the integrated accelerations from the attitude and heading reference system. All series were averaged over 200m and then interpolated onto a regular grid with 100x20 grid points (30x10 grid points for the wind components). In the u-w-field, the circulation around the head of the front at about 400m AGL can clearly be seen, as well as the change from sough-westerly winds in the shallow sea-breeze air to the synoptic-scale south-easterly winds.

VERTICAL ENERGY FLUXES OVER A DESERT LAKE AREA

South Australia is often referred to as the "driest state in the driest continent" and so the investigation of all possible sources of fresh water should be of paramount importance here. It is therefore surprising that the second largest surface water resource in the state, the Cooper Creek and the Coongie Lakes system in the Far North, has been barely investigated in the 140 years since its discovery. The Coongie Lakes are a group of very shallow lakes (average depth 2m) at the fringes of the Simpson Desert. Despite the very hot and dry conditions during summer there, these lakes have not dried out during the past 150 years, although
Cooper Creek flows only about every two to five years supplying the lakes with fresh water. The hydrology of these lakes has never been studied, probably mainly due to the remoteness of the area and the associated logistic difficulties.

By using the aircraft and with generous support from the local mining companies, the Flinders research team was able to overcome most of the logistic problems and was able to explore the meteorological and hydrological peculiarities around the Coongie Lakes. In May and in December 1987, as well as in December 1988, three one-week studies were carried out. Whereas the impact of both thunder- and sandstorms made the December 1987 study technically and logistically difficult, definitive results from the May 1987 study have already been published (Hacker, 1988). The December 1988 study enjoyed very favorable weather conditions, thus yielding a much more comprehensive data set. Apart from repeating the flight patterns of the first expedition, an extensive pattern was flown across one of the lakes (Lake Toontoowaranie) to investigate 'leading edge' phenomena and the horizontal and vertical structure of the vertical energy fluxes and other parameters. An example of the results is shown in Figures 4 and 5, the vertical cross-sections of the latent heat flux for different atmospheric conditions. The measurements depicted in Figure 4 took place in the morning, where remnants of a strong nocturnal inversion were still present between 200m and 300m AGL. Underneath this inversion moderate easterly winds prevailed. As can be seen, this led to a pronounced 'evaporation plume' downwind of the lake. Due to the stabilizing effect of the relatively cool water, the turbulent flux of water vapour could not reach beyond about 50m AGL over the lake itself; only after reaching the downwind edge of the open water, the convective processes were able to penetrate to higher levels due to the much higher surface temperature of the dry land and thus the formation of a superadiabatic layer there.

The data of Figure 5 was sampled around midday where the convective layer reached to a height of about 3000m AGL. Although the plume-like structure is still visible, it is much more confined to the immediate lake area. The cross sections shown in Figures 4 and 5 were computed as composites of numerous traverses (dotted lines). Fluxes were computed for running 2km sections and interpolated onto a regular grid with 128x32 grid points. The gridded data was then smoothed to eliminate the signature from 'individual events.'

Although the small research team which operates the G109B at F.I.A.M.S. had to overcome many financial, technical, operational, bureaucratic obstacles during the last four years, the research seen as a whole has proven to be very valuable and, for the members of the group, most of the time quite enjoyable. The research team has proven that it is possible to achieve high quality data sets and scientific findings at a very moderate level of funding. The aircraft itself has proven to be a very reliable and extremely economical vehicle and its small size has
only in a very few cases been a serious restriction. The instrumentation has proven its high quality by comparing the measurements with independent observations as well as its ruggedness under hazardous conditions.

REFERENCES


Figure 1--Traverses through a sea-breeze front on 13 January 1989 at two altitudes: 35m AGL (top), 350 AGL (bottom). The series shown from bottom to top are: topography as measured from the aircraft; specific humidity; potential temperature; vertical wind (w); wind components perpendicular (v) and parallel to the front (u); horizontal wind vector. The coast is at 0km, the front is moving from left to right.
Figure 2--Cross-sections through a shallow sea-breeze on 24 January 1989 showing the fields of potential temperature (top) and specific humidity (bottom). The dotted lines in the lower diagram indicate the individual aircraft traverses. For further details, see text. Note that the abscissa is different from the one in Figure 1.
Figure 3--As Figure 2, but for wind components. Top: vertical component perpendicular to the front; bottom: horizontal components. The dots show the regular grid onto which the original data was interpolated. For further details, see text.
Figure 4--Vertical cross-section of the latent heat flux during the morning of 2 December 1988 over Lake Toontoowaranie. The two series at the bottom show the surface temperature and topography of the underlying surface as measured from the aircraft. For further details, see text.

Figure 5--As Figure 4, but for midday of 1 December 1988.
B.4 Technical Presentation of the Merlin's Radome: Calibration and Data Processing (M. André and M.P. LePipec)

Mr. André first introduces Meteorological Aviation Center, part of the French Meteorological Research Center. M.A.C. consists of 8 people working for aircraft management, data acquiring and data quality check.

This presentation is a "status" of our work on dynamic data.

The Merlin IV is used for meteorological measurements since the end of 1987. Figure 1 shows different dynamic measurement points on the aircraft: radome, boom, INS, and Doppler radar.

Figure 1

RADOME DATA

Spectral analysis made by Mr. Guillemet from Clermont shows good signal for angle of attack and sideslip. Information seems to be available until 10Hz. (See Figure 2)
INERTIAL DATA

Angle Data Coding:

We first met a resolution problem for pitch, roll, heading which are codes on 12 bits and acquired at 25Hz. The resolution (0.043) is obviously insufficient. (See detail of roll data below).
With our Inertial System, manufactured by SAGEM, model ULISS 45M, spectral analysis shows we can expect information for pitch and roll until 1Hz only, which is inconsistent with 10Hz of dynamic data. (See Figure 3)

![Figure 3](image)

**Figure 3**—(Mr. Guillemet - LAMP - Clermont Ferrand)

We made another flight with INS model ULISS 45I (which will be soon mounted on FOKKER 27 of INSU). On this new model, data are acquired at 50Hz and angles codes on 16 bits.

Mr. Allet from Paris (INSU) ran spectral analysis program on these new data and output seems to be better. We gain one decade though the signal is very noisy. (See Figure 4)

![Figure 4](image)

**Figure 4**—Inertial data from INS UNI 45 I--Mr. Allet - INSU - Paris
Meteorological Research Department took decision to make modification on Merlin's INS from model 45M to 45I, and we expect to fly with this new model within one year.

**Pendular Movement of the INS**

Independently of this problem, when trying to compute wind components, we met the pendular movement problem for INS.

On an average, correlation between Doppler and inertial data is very good (more than 0.95), but if we look at the data at a higher frequency, it decreases.

We made a calibration flight and flew 1h30 at same level and heading. Unfortunately there is a gap of data during 9 minutes, but on X-Axis ground speed component we notice an offset from -1 to 2kts between Doppler and INS data. (See Figure 5)

![Figure 5](image)

For a ferry flight (for which level and heading varied a lot) the difference increases up to 4kts (see figure 6).
CONCLUSION

We think that it's necessary to couple INS with a reference which may be:
- Doppler Radar, though it's noisy
- or better: G.P.S. (Ground Positioning System) which should be available within a few years. The Merlin's INS is already equipped with a GPS output, so it could be rapidly done.
B.5 The Improvement of the Installation of the DLR Research Aircraft Falcon: Description and First Results (R. Baumann, H.G. Christner, H.P. Fimpel, G. Wilke)

INTRODUCTION

A systems upgrade of the DLR’s multi-purpose measuring platform Falcon E was carried out in winter 1988 by installing both a new Data Acquisition System as well as a modern Electronic Flight Information System (EFIS). The application of the Falcon spans from boundary layer research to high altitude missions up to 12 km as a carrier of various meteorological sensors, a turbulence measuring system, micro-physical instruments and optionally installed special equipment for remote sensing and other purposes (Institut für Physik, 1985). The upgrade should improve versatility and performance of the data recording and online monitoring, provide additional flight data to the experimentator and assist the pilots in their manifold tasks, e.g. to fly according to user requested flight patterns.

AVIONICS RETROFIT

Central source of information for the EFIS is - besides the Inertial Reference System (IRS) and the Weather Radar - a Flight Management Computer (FMC) manufactured by Global (GNS-X). It controls most of the avionic systems and processes the data to create powerful displays for the pilots. Flight track patterns can be visualized with this and up to 200 waypoints can be stored in constant memory for repeated use. Many of the calculated parameters are available also on a ARINC 429 Bus which is connected to the Data Acquisition System. The advantage of the system is that the GNS-X uses all available information from the peripheral systems to compute best-fit-values for such parameters that are supplied by more than one sub-system, especially for the position data. The so-called ‘blended position’ results from a combination of the data of the IRS, VLF/Omega and a VPU (VORTAC Positioning Unit, combination of VOR and TACAN), weighted by an actual error estimation of the individual sources, which is affected e.g. by the receiving signal strength. Optionally it is also possible to exclude one or more sources manually from this calculation. In future also a GPS-Receiver can be integrated into this system.

The formerly used platform based Inertial Navigation System LTN-72 (Litton) was replaced by a strapdown based IRS manufactured by Honeywell (YG 1779 LAS-EREF IRS). The advantages of this Laser-Gyro-System are mainly the higher data-rate (up to 50 Hz), accuracy and reliability. Table 1 shows first results of comparing the accuracy of the LTN-72, the YG 1779 and the GNS-X by some statistical moments of the post-landing position error. Data base for this are the last flights with the old and the first flights with the new system with a flight duration between 1 and 3 hours each. Note, that the errors of the YG 1779 were
significantly less than that of the LTN-72 and that the error of the 'blended position' of the GNS-X is in essential not dependent on the duration of flight, so that the long-time drift is zero. Therefore, it can be expected that an overall navigation accuracy of around ±0.25 nm can be achieved for research flights in the middle European area with sufficient coverage of VOR-, DME-, and TACAN-Stations. For the future it is planned to combine this integrated navigation system with its low long-time errors and the IRS with its high dynamic response by a Kalman filter or a complementary filter algorithm to gain more accurate ground speed data for wind calculations.

Table 2 shows some of the characteristics of the new IRS as they were determined through a ground test with fixed and balanced aircraft in the hangar. Although this test cannot represent the actual behavior under flight conditions, it might act as a hint to what could be expected in best case i.e. straight level flight.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LTN-72</th>
<th>YG 177</th>
<th>GNS-X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of flights</td>
<td>28</td>
<td>34</td>
<td>21</td>
</tr>
<tr>
<td>(\bar{x}) (nm)</td>
<td>-0.63</td>
<td>-0.20</td>
<td>-0.02</td>
</tr>
<tr>
<td>(\bar{y}) (nm)</td>
<td>0.73</td>
<td>-0.38</td>
<td>0.00</td>
</tr>
<tr>
<td>(S_x) (nm)</td>
<td>0.76</td>
<td>0.38</td>
<td>0.22</td>
</tr>
<tr>
<td>(S_y) (nm)</td>
<td>0.94</td>
<td>0.86</td>
<td>0.16</td>
</tr>
<tr>
<td>(\sqrt{x^2 + y^2}) (nm)</td>
<td>1.53</td>
<td>1.02</td>
<td>0.27</td>
</tr>
<tr>
<td>Mean drift (\dot{D_m}) (nm/h)</td>
<td>0.7</td>
<td>0.5</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Table 1--Statistics of position errors after landing (x=Δ-LON, y=Δ-LAT)
Table 2--Ground test performance of the YG 1779 IRS

DATA ACQUISITION SYSTEM

The old Data Acquisition System with separate low-speed and high-speed PCM recording was replaced by a new conception with more flexibility (Wilke, et al, 1988). It consists of two independent subsystems linked together with a high speed DMA-Interface. The first is a modular Data Processor that handles the sampling, formatting and recording of all meteorological sensor and avionics data. The second one is a LSI-11/73-based Quicklook System that performs only the online monitoring of individual sensors and meteorological parameters. This separation guarantees the maximal reliability on continuous recording without influence through possible errors in operating the Quicklook System.

The Data Processor consists of an analog part with 14-Bit A/D-Converter and 6 microprocessor controlled receivers for the digital data streams of several avionic systems. Special requirements of experimentators with own, additional sensors or extensions for the future can be handled through spare channels, easy replaceable Signal Conditioning Units and filters, and with programmable data formatter. The experimentator can also take over the digital output of the Data Processor and the analog signals into his own equipment. Two independent Streamer-Cassette-Drives record the data in parallel, so that easy distribution of the data to different experimentators is possible immediate after the landing.

The Quicklook System allows real-time monitoring of primary sensor data and computed or corrected parameters in alphanumeric or graphic format on two Plasma-Screens. Hardcopies are available through a graphical printer on board. By user-written Software-Modules and predefined Menu-Tables it is possible to adapt the supported functions of this system to special requirements of a certain flight mission.
CONCLUSION

In an act of modernizing, the DLR Falcon has been equipped with a new EFIS/FMC in order to increase the efficiency of flight management and improve the accuracy of navigation data. The higher accuracy of the new IRS will immediately influence the quality of wind and turbulence measurements. The new Data Acquisition System allows more flexibility and speeds up the post-mission data processing. A versatile and expandable On-Board-Quicklook provides both online quality control of all sensors as well as important information for the mission scientist needed to control his experiment or modify flight plans.

REFERENCES


B.6 The NASA ER-2 Meteorological Measurement System: Instrumentation, Calibration and Intercomparison Results (K. Roland Chan\textsuperscript{1}, Stuart W. Bowen\textsuperscript{2}, Stan G. Scott\textsuperscript{1}, and T. Paul Bui\textsuperscript{2})

ABSTRACT

The NASA ER-2 Aircraft is used as a platform for high-altitude atmospheric missions. The Meteorological Measurement System (MMS) was designed specifically for atmospheric research to provide accurate, fast-response, in situ measurements of pressure ($\pm 0.3$ mb), temperature ($\pm 0.3^\circ$C), and the 3-dimensional wind vector ($\pm 1$ m s$^{-1}$). Developed over a period of years and operational since early 1986, the MMS has participated in three major scientific expeditions: the Stratospheric-Tropospheric Exchange Project (STEP) based in Darwin, Australia in January and February of 1987, the Airborne Antarctic Ozone Experiment (AAOE) based in Punta Arenas, Chile in August and September of 1987, and the Airborne Arctic Stratospheric Expedition (AASE) based in Stavanger, Norway in January and February of 1989.

The MMS consists of three subsystems: (1) an air motion sensing system to measure the velocity of the air with respect to the aircraft, (2) a high-resolution inertial navigation system (INS) to measure the velocity of the aircraft with respect to the earth, and (3) a data acquisition system to sample, process and record the measured quantities. The location of the MMS instrumentation is shown in Fig. 1. Detailed discussion of the instrumentation is reported by Scott et al. (1989).

(1) The air motion sensing system consists of sensors which measure pressures, temperature and airflow angles (angle of attack and angle of sideslip). Static and total pressure measurements are obtained from precision pressure transducers, using existing aircraft pressure ports and plumbing. Total air temperature is obtained from two total temperature probes with matching signal conditioners installed on the lower hatch of the equipment bay. A radome differential pressure system, similar to the one developed for a NASA Convair-990 aircraft (Chaussee et al., 1983; Bowen et al., 1985) is installed in the ER-2 aircraft to measure the airflow angles.

(2) The inertial navigation system normally used by the ER-2 aircraft is a Litton LTN-72 INS. While this INS is satisfactory for aircraft navigation, it does not meet the stringent requirements of data rate and accuracy for MMS measurement. With a standard INS, the accuracy of wind computation is adversely affected by the internal digital filters of the INS.
and the resolution is limited by the INS data bus update rate of only 3 s\(^{-1}\). A high-resolution Litton LTN-72RH INS, configured for scientific applications, was selected for the MMS because of its compatibility (with the aircraft installation), higher altitude specification (usable up to cabin pressure altitude of 26,000 ft.), precision (no digital filters), time resolution (data update rate of 25 s\(^{-1}\)), and special provisions for MMS measurements (vertical velocity and inertial altitude with internal baro-inertial loop). This INS is installed in the aircraft upper equipment bay, which is maintained at \(-28,000\)-ft pressure altitude when the aircraft is at 65,000 ft. Temperature in the equipment bay with a full complement of operating equipment is typically 5 to 25\(\circ\)C.

(3) The data acquisition system (DAS) samples 45 independent variables at a rate of 5 s\(^{-1}\) (maximum: 10 s\(^{-1}\)), accommodates various modes of data (analog and digital, serial and parallel, synchronous and asynchronous), stores the data on two media (disc and tape), and meets aircraft constraints of compactness, light weight and safety. Commercially available board products were utilized where possible. The DAS is installed in the upper equipment bay of the aircraft, next to the inertial navigation unit. Major components of the DAS consist of a single-board computer, mass data storage systems, a communication and memory board, an INS receiver, clock and terminal interfaces, analog-to-digital (A/D) interfaces, input/output (I/O) interfaces, and power supplies.

The data acquisition software is highly customized and modularized to meet the following requirements: flexibility in modifying the data frame and sampling rate (1 to 10 s\(^{-1}\)); redundancy of mass data storage (tape and disc); simultaneity of sampling 45 variables (<0.01 s between the first sampled variable and the last); asynchronous interface with INS digital data streams; control of disc turn-on and turn-off during landing and takeoff to avoid possible damage to the disc drive; handling of read/write errors to minimize data loss; handling of data logging in case of temporary power malfunction; and special utility and diagnostic programs for preflight checkout and postflight command. Software is a key element of the MMS; it was written in the MC68000 microprocessor assembly language for compactness and speed. The data acquisition software code size is 34 Kbytes.

The DAS has two operating modes: stand-alone (flight mode) and interactive (ground mode). In the flight mode the DAS runs the acquisition routing at power turn-on and logs data continuously. Pilot interaction is limited to a power on-off switch in response to a fail-light indicator. In the interactive mode the user can execute any of the modular routines, including flight-mode acquisition, through an external terminal. Postflight data can be downloaded from the DAS to a ground system in two ways: through a heavily shielded and terminated parallel cable and through a pair of communication boards. The second method has a fast transfer rate of \(-100\) kBaud. For an 8-hour flight, MMS raw data (\(-15\) Mbytes) can be downloaded to the ground station in 15-20 min. The MMS ground station consists of several portable and desktop computer. Our current research effort has been primarily in the development and improvement of the data analysis software.
The calibration of the MMS instrumentation consists of (1) sensor calibration, (2) system and transducer response tests, (3) inflight calibration, and (4) laboratory INS calibration. First, pressure and temperature sensors, signal conditioners, transducers are individually and periodically calibrated either in-house or by the manufacturer. Second, the frequency response of the radome differential pressure system was measured and determined to be satisfactory even at high altitudes in the range of interest up to 10 Hz. The dynamic response of the radome system, including the short feeder tubing, has been measured in the laboratory. Third, inflight calibration requires the pilot to fly the aircraft in square patterns and to induce yaw and angle-of-attack maneuvers at several altitudes. These inflight maneuvers are used to establish the calibration constants of the differential pressure system which measures the airflow angles and to determine the angular offset between the differential pressure system and the INS. The calibration constants are Mach-number (0.35 - 0.72) dependent. Finally, the calibration of the INS is conducted on a physical pendulum of ≈ 2 m in length. The pendulum is tilted and positioned in such a way that pitch, roll, heading, N-S velocity, E-W velocity, and vertical acceleration can all be measured in each swing. Various time delays are introduced in the data processing, and Lissajous diagrams for each INS variable are plotted. This calibration procedures can determine the time delay of each INS output variable to the nearest 0.01 s. For the Litton LTN-72RH INS, the is ≈ 0.045 s time delay for the heading signal, ≈ 0.39 s for the vertical accelerometer output, ≈ 0.08 s for N-S and E-W velocities, and none for the pitch and roll signals. Time delays, caused by the INS internal electronics and/or the external antialiasing filters of the DAS, have been determined in the laboratory, and the appropriate time shift is applied to the data stream of each MMS measured variable during processing.

Intercomparison of MMS measurement, Vaisala radiosonde observation, and radar tracking data was conducted in April 1986 at the Crows Landing facility in California. Data were processed so that time and altitude of the three sets of data were properly matched. Measurements of pressure, temperature and the horizontal wind vector by the MMS, balloonsonde and radar were compared. The difference between the mean MMS and balloonsonde/radar measurements is within the specified accuracy of the instruments; the variability of these measurements is larger than the difference of the mean. The variability is primarily due to spatial and temporal difference between the aircraft and the balloons. This intercomparison indicates that the overall MMS accuracy is very good.

The vertical wind is the most difficult measurement of the MMS. As an illustration of the MMS response to a significant natural atmospheric phenomenon, the vertical wind measurement on September 22, 1987 during the AAOE mission is shown in Fig. 2. The ER-2 aircraft was stationed at Punta Arenas, Chile (53°S, 72°W), flew southward on an isentropic surface (≈420K), descended and ascended at the southern terminus (≈72°S) over Antarctica, and returned northward on the same isentropic surface. The vertical wind measurement over the 6-hour period is shown in Fig. 2a with time and corresponding latitude indicated on the bottom and top of the figure, respectively. For most of the flight the atmosphere was smooth,
and vertical winds generally average to zero over any section of the flight. However, large perturbations are observed on both the southbound and northbound legs at \(\sim 69^\circ S\) latitude. These perturbations have been noted as possible mountain lee waves over the Antarctic Palmer Peninsula (Chan et al., 1989; Gary, 1989). Two 20-min sections of the data in Fig. 2a are shown in Fig. 2b and 2c with the time scale expanded. In Fig. 2b (58,000 - 59,200 s) the amplitude of the vertical wind is very small and close to zero throughout this 20-min period. In Fig. 2c (58,000 - 59,200 s), the mountain lee wave signature is shown in more detail. Although the amplitude of the vertical wind data has large excursions during this 20 min period, the vertical wind measurement is well defined and returns to the mean value after the perturbation.

The MMS meets the science requirements for in situ airborne measurement of free-stream pressure, temperature and wind for atmospheric missions. The customized DAS provides the flexibility to adapt the MMS to changing scientific needs. Special attention has been given to sensor and system calibrations. Future development will involved spectral analyses of MMS variables to further reduce the aircraft motion feed-through in the wind measurement and computation.

REFERENCES


Figure 2--Location of the MMS instrumentation on the ER-2 aircraft.
Figure 2a--Vertical wind results on September 22, 1987 during the Airborne Arctic Ozone Experiment (AAOE) mission.
Figure 2b--Expanded section (52,000 - 53,200 s) of Fig. 2a.
Figure 2c--Expanded section (58,000 - 59,200 s) of Fig. 2a.
INTRODUCTION

DA-Bremen has been working in the field of parameter identification of large and small aircraft on the civil and military sector for many years, the need to have an exact knowledge of the gusts occurring during the identification flight becoming evident straightaway. Based on this philosophy, a high-precision turbulence measurement system was developed in cooperation with DLR-OP which satisfies not only this first objective but also requirements in other fields of application, with particular importance attached to the performance of on-line measurements from the aircraft.

SYSTEM DESCRIPTION

Based on previous studies, a gust measurement system which is to fulfill the following requirements was developed on the principle shown in Figure 1:

1. High accuracy for determination of angle of attack $\alpha$, angle of sideslip $\beta$, impact pressure $q$ and static pressure $p_s$ in the frequency domain $0 - 10$ Hz.
2. Connection possibility to an on-line data acquisition system.
3. Insensitivity to environmental influences.

In addition, the transfer function of the system is to permit the application of accurate correction methods at high frequencies.

Five Hole Probe

A five hole probe of Rosemount with anti-icing was selected as air data sensor with a view to the performance of measurements at great altitudes and unfavorable weather conditions. Developments without an efficient anti-icing system were not considered.

Pressure Transducers

The piezo-resistive miniature pressure transducer type was selected for pressure sensing in view of the compact design. The transducers were connected to the five hole probe tubes by extremely short pneumatic lines.
In order to minimize the thermal zero and sensitivity drift, the transducers have been installed into a temperature controlled chamber. The expected error due to thermal effects in flight amounts max. 0.4% FSO/BFSL.

The combined error from non-linearity, hysteresis and nonrepeatability (NL/H/NR) reaches typical values of 0.25% FSO/BFSL.

A Rosemount precision absolute pressure transducer can also be connected to the static pressure line of the system (Fig. 2).

**Transfer Functions of Pneumatic Lines**

Figure 3 shows the transfer functions of the pneumatic lines $\alpha_1$, $\alpha_2$, $\beta_1$, $\beta_2$, and $q$ of the sensor, computed according to the method of Bergh/Tidjemann. It is remarkable that:

1. In the low frequency range the amplitude and phase errors are very small (amplitude ratio of 1.0024 and phase lag of -0.56° at 10 Hz).
2. The response characteristics of several pressure lines are identical for a wide frequency range.
3. The important frequency range for wind measurement is free of resonance effects.

**FLIGHT TEST RESULTS**

The equipment was tested in flight in March 1989 at DLR-Oberpfaffenhofen up to a level of 37000 ft and Mach number 0.73. The greatest difference during flight between the miniature pressure transducer and the Rosemount pressure transducer measured static pressure amounts 0.4% FSO/BFSL (i.e. 4 HPa).

The data evaluation is running this time at DA-Bremen, thus further results will be presented in a future report.

**CONCLUSION**

A fast response gust measurement device for on line wind and turbulence measurement from the aircraft is described. The gust sensor design bases on the connection of a Rosemount five hole probe to an isolated, temperature controlled pressure transducer unit by extremely short pneumatic lines. This arrangement results in an advantageous pneumatic frequency response of the system, with high resonance frequencies and negligible response errors in the low frequency range.
Figure 1--Gust Measurement Device

Figure 2--Gust Sensor Principle
Figure 3--Dynamic Response of Pneumatic Lines
For the real time computation of the components of the wind velocity there is a need for fast arithmetic coprocessors. This paper presents a solution to do this task within a few milliseconds.

On board of an aircraft wind can not be measured directly. The wind is calculated from the vector difference of the inertial velocity of the aircraft and the aircraft movement relative to the air (true airspeed, TAS). For example, the true airspeed is calculated from the pressures, measured with a five hole probe, within the air data computer (Fig. 1). Typically, the ground speed of the aircraft is measured with an inertial reference system (INS). To get the vertical component of the wind, the vertical speed of the aircraft has to be determined very accurate. This can be done with a Luenberger observer.

Before carrying out the vector difference, the true airspeed is transformed into the inertial coordinate system by a set of trigonometric functions. These are depending on the aircraft’s attitude angles and the angles of attack and sideslip.

Figure 1--Calculation of Wind Velocity
Several publications have demonstrated the advantage of the combination of an INS with baro-inertial altitude measurement. There are two well known methods to get a precise estimation of an aircraft's inertial vertical speed.

- The first one is a complementary filter, which combines the good characteristics of both sensors (Fig. 2). From the barometric altimeter the vertical speed can be obtained by differentiation. From the INS the vertical speed can be determined by integration of the vertical acceleration. The signal derived from the altimeter has a good long time stability, but a bad dynamic with respect to the resolution of the signal. On the other hand, the vertical acceleration as an output of the INS provides a good short time characteristic. Both signals are combined within a complementary filter, which delivers in the ideal case an exact differentiation of the altitude. However, the use of a complementary filter does not eliminate the typical bias error of the accelerometer.

- The second method, the use of a Luenberger observer, gives a precise estimation of the vertical speed and compensates the accelerometer bias. The Luenberger observer is a special case of the well known Kalman filter applied to the deterministic signals. It consists of two integrators; they are estimating the vertical speed and the altitude. The estimated altitude is compared with the altitude measured with the barometric altitude and the low pass filtered difference is fed back to the input of the filter. In the ideal case, this filter gives an exact reconstruction of the vertical speed. If there is an accelerometer bias, the observer is compensating this error with respect to the estimated vertical speed. Therefore the Luenberger observer is used for the determination of vertical speed in the METEOPOD software package.

Figure 2--Estimation of Vertical Speed
The data system is divided into two subsystems, the data acquisition system located in the METEOPOD, and the data processing and monitoring system located in the cabin of the aircraft. They are connected via a serial link, data are transmitted in a PCM-standard format. All analogue and digital outputs of the sensors are fed to the data preprocessor. The data processing system in the aircraft consists of a frame synchronizer, a ruggedized airworthy computer, a plasma display and a hardcopy printer.

According to the application, the main computer has to be equipped with different interfaces and mass storage units, for example two disk drives, a floppy drive and a streamer for data recording purposes. The computer operates directly from the 28 VDC supply of the aircraft. In addition to the CPU, memory and mass storage controllers there is an ARINC 429-receiver, a real time clock and an array processor. This array processor is plugged into the computer. It is equipped with a flexible external I/O-interface and replaces the DMA -couple for the preprocessor.

The block diagram of the array processor depicts the flexibility of this unit (Fig 3). There is a standard Q-Bus-interface, which can be operated in a DMA-mode, and there is an external interface, which consists of two 32-bit lines and several control lines. Even the sequencer is a very flexible unit, because it’s a signal processor unit (TMS 32020). It has control of the instruction bus and can directly access the data bus. Floating point computations are carried out with the Weitek WTL 3132 floating point unit. Data from the 32 bit wide data memory are directly transmitted to the floating point unit with a transfer rate of 20 MByte/sec. An important part of the array processor is the flexible addressing unit of the data memory. It consists of two sets of 16-bit address registers, address increment or decrement is done via a hardware adder. The on-board program and data memory allows stand-alone operation of the array processor, after the executable program has been loaded from the host processor.

Besides the application software for the meteorological computations, there is a need for a standard package to operate the array processor. This package consists of development tools, a library and interfacing software to exchange data with the host computer. At present a microcode assembler, a linker, a pascal compiler and a debugger can be used for program development of the array processor. For example, array and matrix operations, trigonometric functions, exponential functions, and so on, are part of the library. User subroutines can be added to the library in a simple manner and can be called by the pascal compiler. The simple interfacing of the array processor to the user program in the host computer is achieved by high level language interface subroutines in the host.
Figure 3--Block Diagram of the Array Processor
Besides the application software for the meteorological computations, there is a need for a standard package to operate the array processor. This package consists of development tools, a library and interfacing software to exchange data with the host computer. At present a microcode assembler, a linker, a pascal compiler and a debugger can be used for program development of the array processor. For example, array and matrix operations, trigonometric functions, exponential functions, and so on, are part of the library. User subroutines can be added to the library in a simple manner and can be called by the pascal compiler. The simple interfacing of the array processor to the user program in the host computer is achieved by high level language interface subroutines in the host.

Which functions are performed by the array processor within the METEOPOD application? It is not only the computation of the wind vector, but also other important functions:

1. **Data input from the preprocessor**

   In the METEOPOD application, the preprocessor is directly connected to the array processor. Therefore the bus of the host computer is not affected by the data input. About 120 data words are transmitted from the preprocessor in a period of 0.53 milliseconds.

2. **Data unpacking and scaling**

   The data, transmitted by the preprocessor, are packed and have to be unpacked and scaled by the array processor. From the rough data out of the preprocessor this subroutine calculates a vector of physical data. This task is finished in 0.75 milliseconds.

3. **Air data computer**

   The airdata computer subroutine calculates - in 0.44 milliseconds - the true airspeed, temperatures, altitude and some humidity data.

4. **Humidity, measured by Lyman alpha sensor**

   The METEOPOD sensor package includes a very fast Lyman Alpha humidity sensor. Because of the bad long term characteristics the output data of this element are complementary filtered with the standard humidity sensor of the METEOPOD. Because of the complicated algorithm this subroutine lasts 0.45 msec.

5. **Calculation of wind vector**

   The calculation of the three dimensional wind vector including the Luenberger observer for the vertical speed can be done very fast (0.79 msec), because most of the algorithm consists of standard library functions.
6. Transfer of results to the host computer

The last step of the array processor program is the transfer of the results to the host computer. Because of the low data transfer speed of the Q-Bus, this subroutine lasts 1.74 msec.

Nearly the complete program, running on the array processor, is written in Pascal. Hence, the implementation of the existing program could be done in a few weeks. Only the data transfer routines and the standard library functions are not written in a high level language. Therefore this program can be changed easily by the use of the array processor. On the other hand, a complete execution time of 4.7 milliseconds is sufficient for this application, and further optimization of the program would be wasted time! With the use of an array processor the processing of wind and turbulence data can be performed 100 times a second. This is the maximum frequency, which is convenient for the METEOPOD application.

REFERENCES


B.9 Summary of Aircraft Measuring Activities at LAPETH (Bruno Neininger and Hans Richner)

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Two completely different types and sizes of aircraft were in use for atmospheric research at LAPETH: Instrumented motorgliders on one side of the spectrum and wide bodied airlines with their "Aircraft Integrated Monitoring Systems" (AIMS) on the other.

SPECIALLY EQUIPPED AIRCRAFT

The instrumentation for dedicated research flights consists of five portable (and therefore transferable) sets of sensors (dewpoint mirrors, copper-constantane-thermocouples, Rosemount pressure sensors), control units and data storage devices (tape recorders), allowing the simultaneous operation of several aircraft. Meteorological data is stored time multiplexed (0.5 s), frequency coded (0..10 kHz). Comments and/or FSK modem signals from navigational equipment is stored on the second track of the tape. Turbulence or other more sophisticated parameters were not measured until now.

The post-flight software includes conversion of raw data into physical parameters, plausibility checking, merging of position data from different sources (omega, radar, or visual) with the meteorological data, quick looks, and calculations for special applications (e.g. refractive index field interpolation, light- and microwave-paths).

As measuring platforms, several aircraft were in use: Motorgliders "ASK-16" and "Valentin Taifun 17E", single engined aircraft "Piper Cub" and "Robin Remorqueur", as well as the IFR operated twin engined turbo-prop aircraft "Gulfstream I G-159" HB-LDT of the Swiss Federal Aviation Administration.

The following missions have been flown and data has been evaluated:

1981-83: p-T-u-soundings in the Upper Rhone Valley (Budgets of sensible and latent heat, no horizontal navigation).

1985: p-T-u + Omega-wind in and near the Kali Gandaki Valley in the Nepalese Himalayas.

1983-now: Refractive index soundings along distance measuring beams (laser, microwaves) for geodetic research (terrestrial and GPS), navigation was visually, by tracking radar, or by Omega.
AIMS EQUIPPED AIRCRAFT IN AIRLINE SERVICES

During ALPEX, copies of some data recorded by the AIMS (Aircraft Integrated Monitoring System) of Swissair's DC-10 fleet were obtained. Special algorithms were subsequently developed which allow the computation of vertical winds and turbulence with a time resolution of up to 2 seconds. Intercomparisons of turbulence spectra with those obtained about simultaneously by the research aircraft Electra of NCAR show good agreement. When comparing temperature and horizontal wind data with balloon derived data, standard deviations for temperature is about 2 K, for wind speed about 1.5 m/s.

Aims data have also been used to determine the representativity of meteorological data in time and space. For this purpose, differences between aircraft data and balloon data were analyzed as functions of geographical separation and time lag.

AIMS data is continuously being collected by practically all commercial jet aircraft. However, on cruise level, the time interval is normally too long for making the data useful for meteorological purposes. The sampling can, however, be manually switched to a higher rate. While all data is available for computing temperature and air motion, humidity cannot be obtained from commercial aircraft.

OUTLOOK

In cooperation with PSI (Paul Scherrer Institute [formerly EIR] of ETH), we are evaluating a new dedicated measuring platform consisting of a motorglider equipped with fixed instrumentation, including airborne chemical probes and/or sampling capabilities.

REFERENCES


Gutermann, Th., 1989: The variability of wind and temperature over the eastern Alps (Innsbruck-Klagenfurt) derived from AIMS data during the ALPEX field experiment. Proc. of INt. Conf. on Mountain Meteorology and ALPEX, Garmisch-Partenkirch, FRG, June 1989, 40-42.
B.10 Numerical Modelisation of Airflow on the Nose of the French Research Aircraft Merlin-IV for Measuring Air Motion (Philippe L. Nacass)

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AIRCRAFT AND INSTRUMENTATION

At the end of 1986, the french Direction de la Météorologie acquired a Fairchild Merlin-IV-A airplane for the atmospheric research. It has been instrumented, early in the year 1987, by the Centre d’Aviation Météorologique (EERN/CAM) that was in the possession of two smaller research aircrafts (one Cessna-206-TU since 1967 and one twin-engine Piper-PA-23-Aztec since 1979).

The Merlin-IV is powered by two 1,000 horsepower turboprop engines. Its main performance and limitations data are:

- Transit speed: 260 kt.
- Operating speed: between 155 and 250 kt.
- Operating ceiling: 30,000 ft.
- Endurance: 5.5 h.
- Weight for takeoff: 14,000 lb.

This aircraft is first instrumented for state parameters and air motion measurements. The principal sensors external to the airframe (Temperatures, Humidity and Static Pressure) are placed around the nose of the aircraft itself. This nose is a Five Hole Differential-Pressure Flow-Angle Sensing Probe, copy of the King-Air Radome developed in USA by the National Center for Atmospheric Research (NCAR). The Weather Radar and the Inertial Navigation System are inside this nose. The end of the right wind is fitted with a Flow Angle sensor at the tip of a 1 meter boom. Additionally the Radar Altimeter, the Radar Doppler and Radiometer provide data relative to the ground.

Other sensors are also installed for cloud physics and upward and downward radiation measurements. Four Particle Measuring System pods are mounted, under the aircraft body, just after the nose and are equipped with FSSP and AOP. Pyranometers and Pyrgeometers are positioned on top and bottom of the fuselage.

The Merlin was ready in October 1987 at the beginning of Fronts 1987 and Toscane-2 International Experiments. A total of more than 60 flying hours, till May 1988, were also test flights on airborne instrumentation.

Since the beginning of 1989, the aircraft is configured, not full-time, for air pollution research. A pylon to accommodate two Cloudwater and Precipitation Collectors is mounted...
on the fore part of the roof. One Air-Intake is on the rear part.

The Data Acquisition and Recording Systems are inboard.

NON SPECIAL FLIGHT TESTS

In this paper, static pressure errors are supposed well known; they are determined, for the radome and sensor boom-tip from tower flybys. The velocity of the airplane with respect to the earth was obtained on the time-series of the Radiometric Surface Temperature; signal of the grass ends of the runway is a good measurement.

With data recorded during whole flights (from take-off to landing), we try to calibrate and evaluate the performance of the radome.

From measurement of the surface pressure distribution on the radome of the aircraft, without angle calibration, these data can be obtained:

- **Dynamic pressure** (the difference between the Total Central Pressure hole and the Static Pressure ports surrounding the cylindrical part of the radome).
- **Differential Attack Pressure** on both holes in the plane of symmetry of the aircraft.
- **Differential Sideslip Pressure** on both holes in the plane perpendicular to the plane of symmetry.

From accelerometers of the Inertial Navigation System (INS) the three attitude angles of the airplane (**Pitch**, **Roll**, and **Yaw**) can be obtained with respect to the earth.

Then, flights in a calm atmosphere with long straight (lever, climb and descent) are chosen and small-angle approximations are used. Variations of the dynamic pressure, the differential attack pressure and the ratio of these two pressures are shown as a function of pitch angle.

THEORY OF PRESSURE MEASUREMENT

Relations which govern the motion of one body in an inviscid fluid are not recalled in this paper. The fluid is regarded as incompressible and its density is uniform. The velocity is irrotational.

The velocity (overspeed) in the flow around a three-dimensional body and just outside the boundary layer may be found from the pressure distribution by using Bernoulli’s theorem.

The fuselage of the Merlin, forward the pilot’s canopy, is an axisymmetric body. It is a semi-infinite body of revolution in an uniform stream: a 12 inch radius half-sphere fixed on a 21 inch long cylindrical portion fitted to a slender body of revolution (the tangent to the meridian curve of this part of the fuselage is inclined at a small angle to the axis).
The two angle of attack holes form 35° angles with the central hold. Pressure distribution around a sphere or around a semi-infinite body may be used.

**MERLIN-IV FLIGHT ENVELOPE**

The Airplane Flight Manual provides current information applicable to operation of the Merlin-IV. During a whole flight, from take-off to landing, the airplane must be operated in compliance with the operating limitations. Theoretical studies of the flight dynamics show the flight envelope between two lines: the minimum operating speed and maximum rate of climb.

**RESULTS**

Modelisation of pressure distribution on the holes of the radome with the magnitude of the velocity vector and the attack angle is the first step in this process.

Variations of the dynamic pressure, the differential attack pressure and the ratio of these two pressures as a function of pitch angles are plotted, in a second step, for a lot of flights in calm atmosphere.

Parametrisation of the curve of modelisation in respect with the airborne measurements give the aerodynamical response of the radome. Limits of the transducer ranges, flight envelope and variation of sideslip angle are computed (figures 1 and 2).

A new modelisation with roll and yaw angels, size of the pressure holes and pressure variation on the static holes around the cylindrical part of the radome is developed and must be a better dynamic tool.

**CONCLUSIONS**

Three dimensional flow distortions on the nose of the Merlin-IV must be better known to understand the potential effect on the pressure radome, on the ring of sensors around it and about the four particle measuring system pods under the fuselage. Since the beginning of 1989, a code of numerical flow pattern circulation around three dimensional bodies is developed. First results are the pressure distribution on the fuselage of the Merlin-IV (figure 3).
Dynamic Pressure (hPa) = f(\text{Pitch Angle} (\text{deg)})

Parametrization of the radome

\[ \text{Dynamic Pressure (hPa)} = \text{f(Attack Angle (deg))} \]

Figure 1
Figure 2
Figure 3

PRESSURE DISTRIBUTIONS ON THE FUSELAGE

Static Holes

Kp

0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25

L (m) x L (m)
B.11 Turbulence Profiling in the Atmospheric Boundary Layer using Three Powered Gliders (Anne M. Jochum)

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OBJECTIVE

The Institute of Atmospheric Physics at DLR (German Aerospace Research Establishment) is operating three instrumented ASK 17 powered gliders as meteorological research aircraft. A low flight speed enabling the resolution of very small scales and a high degree of flexibility makes them the ideal research platform even for complex terrain studies. Due to their limited altitude range and payload they are primarily used in the atmospheric boundary layer. The investigation of the atmospheric boundary layer requires high spacetime resolution, and this is achieved by the utilization of three identically equipped aircraft.

The main objectives in developing such a system, and thus its basic advantages, can be summarized as follows:

- The use of multiple identical aircraft helps to overcome the sampling problem associated with airborne flux measurement (Lenschow and Stankov, 1986). Flying either side by side or repeated line averages reduces the required sampling length by at least a factor of three.

- The low flight speed (33 m/s) allows for increased spatial resolution, and thus - with fast sensors - for turbulence measurement at very small scales. On the other hand, it is easier to achieve good wind measurement accuracies with lower airspeed (as shown by Baumgardner in this volume).

- The fleet of light aircraft provides a very valuable tool for flexible and low cost use in small projects, they can be flown at low altitudes even over very complex terrain.

INSTRUMENTATION

The main characteristics of the basic measurement system are presented by Jochum et al. (1987), where more detailed references are given. A description of major ongoing modifications is given by Jochum (1988b). The powered gliders possess identical instrumentation. Table 1 provides a list of equipment available in the old configuration and of major modifications that are currently being implemented.

The sensors for temperature, humidity and pressure are installed in and on the wind instrument pod. A pitot static tube protruding forward from the point of the pod is being replaced with a differential pressure probe mounted in the same place. The distance between
the pressure apertures and the wing leading edge is sufficient to allow undisturbed pressure measurements. The humidity sensors are located in a channel in the pod. This channel is also fitted with a Pt100 for monitoring internal temperature. The sensor for external temperature is mounted in a case underneath the pod.

The attitude and heading reference system (AHRS) - a strapdown system manufactured by LITEF (Litton Europe) - is mounted in close vicinity of the center of gravity. A miniaturized high accuracy airborne GPS receiver is being developed by the Institute of Navigation at Stuttgart University. Kalman filter techniques are currently implemented to process signals from the AHRS and the GPS received in a complementary way in order to increase the accuracy primarily of wind measurements.

<table>
<thead>
<tr>
<th>Temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>○ reverse flow temperature probe (Pt 100 manufactured in-house)</td>
</tr>
<tr>
<td>○ Pt 100 in humidity channel manufactured in-house)</td>
</tr>
<tr>
<td>○ Barnes PRT-5 radiation thermometer (one aircraft)</td>
</tr>
<tr>
<td>• fast response probe (manufactured in-house)</td>
</tr>
<tr>
<td>• Heimann KT 17 radiation thermometer</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>○ ERC Lyman-alpha hygrometer</td>
</tr>
<tr>
<td>○ Vaisälä humicap relative humidity sensor</td>
</tr>
<tr>
<td>• dew point mirror (Swiss Meteolab)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pressure and air motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>○ Rosemount static and dynamic transducers for pitot static tube</td>
</tr>
<tr>
<td>• differential pressure probe (manufactured in-house) with Rosemount static, dynamic and differential transducers</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Aircraft motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>○ 2 Sundstrand accelerometers</td>
</tr>
<tr>
<td>○ SFENA vertical gyro (pitch and roll angle)</td>
</tr>
<tr>
<td>○ AIM directional gyro (heading)</td>
</tr>
<tr>
<td>• attitude and heading reference system LITEF LTR-81 and magnetic flux valve</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Aircraft position</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Japan Aviation radar altimeter</td>
</tr>
<tr>
<td>• GPS (Global Positioning System) receiver with additional ground based receiver for differential operating mode</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Video</th>
</tr>
</thead>
<tbody>
<tr>
<td>camera(s) looking forward and/or downward (optional)</td>
</tr>
</tbody>
</table>

**Table 1**--Instrumentation - old and new configuration:

○ being replaced, • being retained, © new.
Recently, a new very fast response, light weight ozone sensor developed by the Institute of Physical Chemistry, University of Bonn, has been added to the instrumentation. Tests and first field observations have demonstrated the capability of the system to measure turbulent fluxes of ozone.

QUALITY OF MEASUREMENTS

An uncertainty analysis reported by Hacker (1985) gives the following estimates of relative accuracies: temperature ±.07 K, specific humidity ±.05 g/kg, vertical wind speed ±.2 m/s (only errors of sensors, not of method).

As a further independent test of data quality with respect to flux measurements, intercomparison flights with the DLR Falcon (see Baumann et al., this volume) were performed (Willeke, 1985). Table 2 shows the results of one such low level flight along straight horizontal legs of 20-30 km length flown repeatedly. The sensible heat flux measurements agree remarkably well between the four aircraft. For latent heat flux the scatter is generally larger, and the difference between the motor gliders and the Falcon is almost 30%.

Another example of intercomparison flux measurements is shown in Figure 1. The data were taken during a field experiment in South Germany (Jochum, 1988a) where the three motorgliders and the Falcon were flying at various different altitudes along the same horizontal leg of 30 km length. The data from the motorgliders were assembled and interpolated to the multiples of .1z (z = atmospheric boundary layer depth). The thick line represents these data. The flux values measured by the Falcon are indicated separately by asterisks. The agreement appears to be well within the scatter of the individual measurements.

REFERENCES


Table 2--Results from intercomparison flights between three powered gliders (D-KMES, D-KMIF, K-KEIK) and the DLR Falcon (D-CMET).

H: sensible heat flux, λE: latent heat flux.

<table>
<thead>
<tr>
<th>flux, Wm$^{-2}$</th>
<th>D-KMES</th>
<th>D-KMIF</th>
<th>D-KEIK</th>
<th>D-CMET</th>
</tr>
</thead>
<tbody>
<tr>
<td>H Leg 1 (20 km)</td>
<td>29</td>
<td>32</td>
<td>27</td>
<td>28</td>
</tr>
<tr>
<td>H Leg 2 (30 km)</td>
<td>28</td>
<td>32</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>λE Leg 2 (30 km)</td>
<td>74</td>
<td>88</td>
<td>85</td>
<td>58</td>
</tr>
</tbody>
</table>

Figure 1--Sensible (a) and latent (b) heat fluxes in the convective boundary layers as measured by the three gliders (thick line) and by the Falcon (*)
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