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PREFACE

From 19–21 October, 1988, a workshop was held at NCAR for the purpose of reviewing needs for airborne instrumentation and planning to meet those needs. The workshop was planned by a steering committee consisting mostly of NCAR representatives, and was focused on the NSF-supported community of atmospheric scientists who use research aircraft. The meeting was attended by about 45 scientists, who worked in joint sessions and in smaller working groups to prepare the assessments and conclusions contained in this report. Contributions from invited speakers are reproduced here, in most cases from recordings of their presentations. In the working groups, members of the RAF “Science” group served as reporters and wrote most of the summaries in this document. In addition, several ad hoc groups held additional meetings and, in some cases, prepared additional material that is appended to this report. It was our hope that this review could help focus attention on common needs for airborne instrumentation, and that the participants could begin to plan for the needed projects. The important step in this effort, and the step that will determine how successful the Workshop was, is now to develop specific plans for implementation of the recommendations in this report.

Al Cooper
Darrel Baumgardner
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ACKNOWLEDGMENTS

On behalf of the Steering Committee (consisting of Greg Kok, Ron Schwiesow, Jim Dye, Jack Winchester, Gabor Vali, and the authors), we thank those scientists who prepared position papers and led the working groups of this Workshop: Ron Smith, Don Lenschow, John Hallett, Tom Marshall, Ed Eloranta, John Bane, Russ Dickerson, and Barry Huebert. We also thank all the participants (listed in Appendix A) for the time they were willing to devote to this workshop and for their thoughts and perspectives on our field. Members of the NCAR/RAF Science Group served as note-takers and constructed sections of this report from those notes: We thank Ed Brown, Allen Schanot, Andy Weinheimer, Ron Schwiesow, Greg Kok, and Cindy Twohy for their participation and for their written contributions to this report. We also appreciated the encouragement and participation of representatives from the National Science Foundation. Finally, we thank Karen Bowie for assistance with all the arrangements for this workshop and particularly for assisting the participants with their travel plans and hotel accommodations.
ABSTRACT

Approximately 40-50 scientists met in October 1988 to review needs for airborne instruments and to plan for development of some of the needed instrumentation. The participants represented various disciplines within or related to atmospheric science, and were all experienced in observational studies using airborne instrumentation. The meeting started with the presentation of position papers that formed the basis for subsequent discussions in working groups, each focussed on needs and opportunities in a particular area. This report contains the position papers, the assessments of current instrumentation that came from those groups, and the consensus regarding needs for new instrumentation. A number of specific needs were identified where development projects are feasible, and where there was significant interest both on the part of the community at large and on the part of some individuals prepared to conduct the development project. The workshop participants also discussed strategies for planning and securing support for these projects.
1. Introduction

The group that organized this Workshop did so because it is their opinion that work toward developing airborne instrumentation could benefit from a review of current problems and needs, and from more systematic and cooperative efforts to address those needs. Our objectives were:

a. To provide an assessment of the strengths and weaknesses in present airborne instrumentation, and to highlight areas where inadequate instrumentation is hindering scientific studies;

b. To identify new techniques or promising ideas for development of new measurement capabilities; and

c. To plan for implementation of some of the developments identified as having high community interest.

A few comments are in order regarding what the instrumentation workshop was not intended to accomplish. We did not regard this as a planning workshop for NCAR/RAF development activities, although we will certainly use the results from the Workshop as guidance in planning those activities. Instead, we tried to focus on community needs, actions, and plans. We view this as a shared responsibility, and not only the responsibility of RAF. Second, this workshop was not intended as a planning session on how to spend new funds. On the contrary, the NSF budget this year is disappointing, and we have had no indication that new funds will be made available or identified for the purpose of conducting these projects. Certainly, the 1989 NCAR budget cannot support substantially increased efforts in this area. Instead, we hope that the workshop may help us use the funds available more wisely, and perhaps to organize some projects in ways that improve the likelihood of being funded.

The Workshop began with the presentation of position papers by representatives of different areas of atmospheric science. These papers established a point of departure for the discussions that followed, both in the working groups and in the general discussion. Those papers appear in this report, in some cases in transcribed form. We have used almost-verbatim versions in order to speed the production of this report.

The size of the workshop was intentionally limited to permit suitable group discussions and to keep the atmosphere one of a working meeting. We tried to maintain representation of different areas and different segments of the NSF-supported community, but failed to do this in several areas. Perhaps the most important was that scheduling conflicts kept most of those interested in measurements of radiation from attending the meeting.

The focus was intentionally on the NSF-supported community. There are other workshops better suited to discussion of the benefits and ways of establishing cooperation among different agencies and perhaps different countries. Instead, the focus was maintained on how to improve the instrumentation available to NSF-supported scientists. As an example of the consequences of this policy, the remote-sensing discussions focus on ways of
providing access to the instruments that have been developed elsewhere; in many regards the NSF-supported community is behind other groups in this area.

We urged the working groups and the entire workshop to approach these problems broadly, by addressing long-range problems as well as immediate needs, innovative approaches as well as routine developments, and specialized projects as well as those of general community interest. One area perhaps needing particular attention is how we collectively organize and support projects having broad need in the community. Some past projects in this category have been narrowly focused at the development stage, and so have been viewed by others in the field as in competition with them rather than of benefit to them. As a result, it has been hard to obtain support for such projects. We need to direct more attention to ways of addressing our collective needs, both in organizing projects and in obtaining support for them. As an example, if we can identify a need generally viewed as having high priority, and if we can organize a collaborative project to address that need in which perhaps university investigators take the lead in the development but organizations like NCAR/RAF maintain involvement to provide the link to community access and use of the new instrumentation, such a project would be strong technically, scientifically, and politically. We sought to identify such problems at this workshop, and to begin the work of planning for projects that address community needs.

The working groups in the workshop were charged with the goals listed at the start of this section and with proposing projects and strategies for developing the needed instruments. They all identified needed and feasible instrumentation projects, and proposed strategies that might improve how such projects are planned, funded, and conducted.

Despite the budget problems of the present, it still seemed timely to address the instrumentation needs of the community. It is encouraging that there is growing support, at least in words, for these needs. The apparent imbalance between observational and other aspects of our science has been recognized and highlighted in several recent community-supported studies, such as that of the Joint NSF-UCAR Long-Range Planning Committee. The just-completed meeting of Department Heads and Chairs passed a resolution in strong support of increasing the level of activity in this area. The following workshop report illustrates that there are numerous opportunities to apply modern technology to limitations in our observational capabilities. Therefore, it seems appropriate to address these concerns now and to plan for a hoped-for future when funding opportunities are better.

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2 included as Appendix D.
2. Reports on needs of specific research areas

a. Current perspective and priorities, NCAR/RAF – Al Cooper

Current priorities at RAF reflect our opinions regarding needs and opportunities. We are focussing on three areas (although not excluding other areas from lesser attention):

- Remote-sensing instruments capable of increasing the volume that is sensed from the aircraft;
- Improvements in basic measurements, including humidity, in-cloud temperature, and wind and turbulence sensing in cloud;
- Basic chemical instruments for, e.g., O$_3$, CO, or condensation nuclei, that can be provided for routine usage and that are reliable, calibrated, and standardized.

Most of us probably agree on the value of pursuing remote-sensing opportunities from aircraft, particularly those of us who have had to make broad generalizations from measurements collected along a single line through a cloud. Developments in other agencies have provided many advances, but we have been slow to take advantage of them. Instruments such as airborne lidar (e.g., Bilbro et al., 1984; Kopp et al., 1984; Carroll, 1986), short-wavelength radar (Llermitte, 1987; McIntosh et al., 1988), temperature and humidity profilers (e.g., Hogg et al., 1983; Westwater et al., 1985; Melfi and Whiteman, 1985), microwave radiometers (e.g., Warner and Drake, 1988), multichannel spectrometers and radiometers, etc., have been developed and demonstrated to be useful, but they are not readily available to the NSF-supported user community. Often, the size of these development projects is too large to be addressed easily by one group, and yet expertise often resides in small university groups. This is an area where collaborative efforts seem particularly important and suitable.

In regard to ”basic” measurements, we have seen many recent examples where standard instruments for measurement of temperature and humidity have been inadequate to address the needs of research programs. Projects to provide improvements in these areas tend to be perceived as unglamorous, and so they receive little attention despite their importance. Certainly, major improvements are still needed in the measurements of in-cloud temperature and of humidity (either at low humidities, where dew points are below $-50^\circ$C, or with fast response for flux measurements).

In the area of microphysical measurements, the PMS probes have provided the standard solution for more than 10 years, but the technology is also mostly ten years old. Some of us have made partial careers out of studying the deficiencies in those instruments, but they have provided the basis for so much progress and have made microphysical measurements so easy that there has been little impetus to improve upon them. However, current problems seem to point to a reconsideration of needs in this area. In particular, there is an important need for better measurements of ice or water hydrometeors with sizes of 10–100 µm (e.g., Stephens, 1988), for improved sample volume for rain, for improvements in electronic...
response times and minimization of coincidence effects (Baumgardner et al., 1986; Cooper, 1988), and for coupling of the measurements with other measurements such as of particle charge or mass. The measurement of cloud condensation nuclei or of ice nuclei remains a specialized undertaking, and those measurements are not generally or routinely available to the community. We continue to suffer from inability to measure ice mass or total water very well, and have difficulty extending the microphysical measurements to the small scales needed to study the fine-scale structures produced by mixing.

In the area of air motion sensing, there are significant opportunities to change the way we make some basic measurements of winds. Laser air motion sensing via optical gust probes is feasible (Keeler et al., 1987; Kristensen and Lenschow, 1987), and could displace the sensed volume away from the aircraft and hence avoid all problems associated with flow distortion induced by the aircraft. The advent of the Global Positioning System will provide opportunities to supplement and perhaps replace inertial navigation as the basic source of aircraft position and ground-speed. However, effects of airflow distortion on other measurements from the aircraft have only been studied rather incompletely to date, and it appears that substantially more work (following the lines of the work of Wyngaard et al., 1985, and Wyngaard, 1988) is needed to understand and possibly correct for these effects.

As a final example of an important need, multi-channel measurements of radiation fluxes are feasible and have been demonstrated with particular instruments (such as that of Stephens and Scott, 1985), but are not generally available to the community.

NCAR/RAF has a somewhat unique role in these problems, in that it is part of our charge to address community needs, but all observational scientists must be concerned with instrumentation and involved in its assessment and evaluation. NCAR can support development activities in many ways other than by assuming direct responsibility. An important one is via collaboration in testing and eventual transfer of new instrumentation to aircraft, where NCAR represents the community interest in new developments and seeks to make them widely available. NCAR can also provide general support, e.g., in aerodynamic consulting or as a source of reports on problems that other investigators are encountering with instrumentation.

There are some specific examples of projects that have been collaborative and that may provide models for future interactions. One is the acquisition of field mills for the NCAR King Air. The field mills were designed and built by Bill Winn of New Mexico Tech, and were installed and tested a year in advance of his research program that used the field mills. Their construction and testing was partially supported by NCAR, and at the end of the project NCAR retained possession of the field mills and has continued to operate them for other investigators. The result was that we acquired a high-quality instrument through exploitation of the expertise in a university group that planned to use our facilities.

Another example is the Ophir radiometric thermometer, which was originally supported by the Cloud Systems (now MMM) division of NCAR. The unit underwent extensive testing in various field programs, some designed for that purpose and others where opportunities were available. Ophir, NCAR (CSD and ATD), and the University of
Wyoming (Paul Lawson) all participated in those evaluations (Lawson, 1988; Cooper, 1987), and they have led to a better understanding of the problems that arise from wetting of immersion sensors as well as to improvements in the Ophir radiometric thermometer.

Some specific examples where this model might be followed could include collaboration with specialists in cloud condensation or ice nucleus detection to develop and make available such counters on NCAR aircraft, or collaboration with the chemistry community to develop an extended set of "standard" measurements that might provide an appropriate context for many of the chemistry experiments, or collaboration with appropriate expertise in the community to study the effects of airflow distortion on airborne instruments.

We have compiled a list of “needed instruments” from our own ideas and those advanced by others at the workshop. They are presented without prioritization in Appendix B in hopes that this will serve as a source of ideas.

b. State parameters

1) POSITION PAPER – Ronald Smith

(a) Scientific needs.

State variables in this presentation will include pressure, temperature, and humidity, but there are other measurements (covered by other working groups) that will be discussed as well, notably wind measurement and the measurement of chemical constituents. I'll begin by surveying the needed ranges, accuracies, and time responses for the different measurements.

Pressure measurements are used in various studies including studies of dynamic forcing (pressure perturbations), thermodynamics of the atmosphere and of clouds, cloud physics, chemistry (e.g. for mixing ratios when densities are measured), and measurements of heat and moisture fluxes. The use requiring the smallest tolerances on accuracy arise from attempts to measure horizontal pressure gradients from D-value variations along flight segments (as done for example by Shapiro and Kennedy 1981, 1982, and LeMone and Tarleton 1986); for these studies a resolution of better than 0.1 mb is needed (although lesser accuracy is acceptable). For most other measurements, 1 mb accuracy seems acceptable and available. Response times of about 0.01 s are needed for flux measurements, but 0.1 s response is adequate for most other uses.

Temperature measurements are needed in dry air (e.g., for boundary-layer flux studies), in rain, in warm and supercooled cloud, and in ice clouds. In all these studies, accuracy and resolution of about 0.1°C is needed, and time responses of 0.1 s (or, in the case of boundary-layer fluxes, 0.01 s) are needed. These requirements arise from uses in studies of the dynamics of clouds and other mesoscale phenomena, in cloud physics, in studies of
fine-scale structures in cloud, and in studies of boundary layer transport. On occasion, for
looking at fossil (decaying) turbulence, a resolution of 0.01°C would be useful.

Humidity requirements differ according to altitude. At high altitude, in-cloud
requirements exist for measurements to dew points of −70°C having an accuracy of 1°C and
response times of 0.1 s. In dry stratospheric air, there is a need to extend measurements to
−85°C for studies in air chemistry, radiation, and air-mass identification; here accuracies
of about 2°C and response times of 0.1 s would be useful.

At medium altitudes, such as those normally accessible to a turboprop aircraft like a
King Air, there are needs to measure dew points down to about −50°C with accuracies of
0.2°C and time response of 0.1 s, for studies of cloud microstructure and in cloud physics.
In dry air, a similar lower limit applies but accuracy of 1°C is probably adequate for most
studies of dynamics or radiation.

At low altitude, studies in cloud and in precipitation require measurement of dew points
down to about −30°C with accuracy of about 0.1°C and time response of 0.1 s, to support
studies in cloud physics. In dry air, 1°C accuracy and about 0.1 s response is probably
adequate for most studies of dynamic effects and of radiation, although resolution of better
than 0.1°C and about 0.01 s response time are needed for the measurement of moisture
fluxes.

(b) Other issues

Other significant measurements related to state variables, but discussed in some other
sections of the workshop, are those of position and air motion. There is also significant
overlap with the remote-sensing group, particularly in near-field sensing of temperature,
lapse rate, and humidity. There is also a close interface with cloud physics in the above
measurements and in the measurements of different phases of water. There are important
interfaces with chemistry through measurements of water vapor and because trace gases
have radiative effects and can serve as air-mass tracers and flux surrogates.

These many interactions and overlapping concerns suggest that the concept of a
“standard” instrumentation package (in the past, consisting primarily of the basic
measurements of state parameters) be expanded. We have tended to view the standard
complement as consisting of pressure, temperature, humidity, and winds; the rest is
specialized equipment. However, as other measurements such as of O₃ or condensation
nuclei become available, researchers will learn how to use them in interpretation of data.
Expansion of the standard set is valuable in ways that cannot be foreseen.

Finally, the problems associated with airflow distortion (Wyngaard et al., 1985;
Wyngaard, 1988) need attention. They affect our ability to measure fluxes of heat and
moisture, D-values, and fine-scale cloud structure.

The working group will present an assessment of how well we are meeting these needs,
but it is clear that in most cases there is need for considerable improvement. These
problems must not be neglected because they are perceived to be unglamorous.
2) WORKING GROUP DISCUSSIONS AND RECOMMENDATIONS

The group chairman focused the session discussions on the measurement of pressure, temperature, and humidity from both the standard aircraft mounted and expendable aircraft-delivered instrumentation packages. The group’s efforts included a review of the strengths and weaknesses of the current instrumentation, a definition of the scientific needs for specific accuracy limits, and recommendations for key developments.

(a) Pressure

The current absolute accuracy limit for airborne static pressure measurements was estimated to be about ±0.4 mb, although the resolution can be considerably better. These limits were recently established through a field program conducted by NCAR/RAF under the sponsorship of the FAA (Brown, 1988). Improvements in absolute accuracy are currently limited by: 1) uncertainties in the static defect correction needed to account for changes in aircraft speed and attitude; 2) current accuracy limits of the available calibration techniques; and 3) current accuracy limits (±0.5 m/s) on the measurement of the aircraft’s true airspeed. Expendable dropsonde accuracies are better than 1.0 mb.

The impact of these measurement limitations was discussed and it was argued that, for most applications, the resulting errors would not significantly hinder the science being conducted. Certain applications, such as flux and D-value analyses or geostrophic wind studies, could benefit from improvements in the accuracy and resolution of pressure measurements, and the latter two classes also need corresponding improvements in the measurement of altitude. A reduction in the absolute accuracy of measurements of pressure, to a value of about ±0.1 mb, was considered desirable.

The state parameter working group recommended a strong and accelerated effort in the analysis of flow distortion effects on all research aircraft. Such an effort would improve the static defect corrections being applied and aid in the interpretation of the fine scale fluctuations that appear in the data.

(b) Temperature

The discussion on temperature measurements was divided into the two different sampling regimes found in the atmosphere: the clear air (dry) environment; and the in-cloud or in-precipitation (wet) environment. This distinction is directly related to both the current status of the measurement technology as well as the future sampling needs of the atmospheric sciences community.

Measurements in dry air. The current absolute accuracy for airborne temperature measurements in dry air was estimated to be ±0.3–0.6°C and considered to be aircraft (airspeed) dependent. The resolution is about 0.01°C. Improvements in this area are currently limited by: 1) uncertainties in empirically derived recovery factors; 2) current accuracy limits of available calibration technology; 3) density effects of flow distortion
around the aircraft; and 4) current accuracy limits on the measurement of the aircraft’s true airspeed. Expendable dropsonde accuracies were estimated to be approximately $\pm 0.3^\circ C$.

While these measurement limitations will have only a minimal effect in most studies of flow fields or air chemistry, they become much more significant when combining measurements from the multiple sources involved in large field projects — particularly in the area of air/sea or surface/boundary-layer interactions. A reduction in the absolute accuracy limit to $\pm 0.1^\circ C$ would be useful in these latter applications.

The working group noted the ongoing efforts with near-field radiometric techniques and supported this development. They also recommended further study of flow distortion caused by the aircraft platform and the sensors themselves.

*Measurements in cloud or in rain.* The current absolute accuracy for airborne temperature measurements in a wet environment was estimated to be about 1.0–2.0$^\circ C$, depending upon the microphysical conditions encountered. Improvements in this area are limited by the same factors that limit the dry air sampling, but with the additional complications resulting from effects due to undetermined amounts of sensor wetting.

The relatively poor state of wet-environment temperature measurements currently available from airborne platforms has been a major problem in the study of cloud processes for many years. Work on thermodynamic forcing, entrainment mechanisms, and microphysical precipitation processes requires substantial improvements in this area. An improvement in the absolute accuracy to near the limits of current dry air sensors is needed, and a useful goal would be to achieve an accuracy of $\pm 0.1^\circ C$ in cloud.

The group recognized that work on new techniques had begun in this area. The use of near-field radiometric techniques shows promise in the wet environment, and preliminary tests supported accuracies comparable to those of immersion sensors in dry air (Cooper, 1987; Nicholls et al. 1988). Other improvements in in-cloud measurements of temperature could come from new wet-bulb sensors, new shielding techniques for current immersion sensing elements, or the use of humidity measurements to deduce temperature in cloud. The group supported ongoing efforts in all of these areas and recommended parallel development strategies along these lines as the best approach to this critical measurement problem.

*(c) Humidity*

The techniques used to measure humidity from aircraft vary for different applications. High-rate sampling in relatively moist conditions of the lower to middle troposphere requires a fast-responding instrument, while sensitivity is the more critical problem for present applications in the dry mid-troposphere or lower stratosphere. Because each type of measurement has its own set of problems and limitations, the group discussions covered each of these two measurement capabilities separately.
Measurements of very low humidity. Currently there are no operational sensors that allow aircraft to make routine measurements of humidity when the dew point \( T_d \) is \(-50\) to \(-80^\circ\text{C}\). Certain chilled mirror techniques extend into this range but suffer from significant time lag at large dew point depressions. Limiting factors include: 1) limited cooling ability; 2) current limits in calibration technology; and 3) interference from inlet off-gasing at the extremely low values \( T_d < -70^\circ\text{C} \). NOAA has a cryogenically cooled balloon-borne unit capable of operating in this range with absolute accuracies around \( \pm 1.0^\circ\text{C} \) (resolution about \( \pm 0.05^\circ\text{C} \)), and this instrument is being reconfigured at NCAR for airborne use. The group recognized this ongoing effort and noted preliminary test results that placed the detection limit for the aircraft system at \(-80^\circ\text{C}\) with an accuracy of \( 2.0^\circ\text{C} \) and a time response of 2–3 s. The group recommended rigorous testing of this new technology with concentrated effort on defining the calibration and operational (flight characteristic) influences on instrument performance.

The measurement of low humidities is needed in atmospheric chemistry, tropospheric-stratospheric exchange experiments, and studies of dynamics near the tropopause. Direct airborne measurements are needed as one component of a multifaceted analysis of trace gas behavior in the upper troposphere. The working group saw a clear need for the development of an instrument to detect dew points as low as \(-85^\circ\text{C}\), an accuracy of \( \pm 1.0^\circ\text{C}\) and a time response of \(< 10\) s.

Measurements of rapidly-fluctuating humidity. Flux measurements are usually made when the dew points are much greater than \(-50^\circ\text{C}\) and when the dew-point depression is \(<20^\circ\text{C}\), but for such measurements fast (0.1 s) time response is usually needed. Both high-rate and mean humidity measurements in this range are currently available on aircraft platforms from cooled-mirror and Lyman-alpha instruments. Absolute accuracy limits were estimated at roughly \( \pm 0.5^\circ\text{C} \) in dry air and \( \pm 1.0^\circ\text{C} \) in wet environments. The high-rate instruments currently in operational use are susceptible to wetting in cloud or rain. Factors affecting the accuracy of humidity instrumentation are: 1) instrument instability requiring baseline adjustment against a slower reference value; 2) current limits on the accuracy of available calibration technology; 3) insufficient shielding to allow high-rate ventilation while avoiding sensor wetting in cloud; and 4) uncertainties regarding the effects of aircraft-induced flow distortion at the sensor locations (especially for measurements of vapor densities).

The current problems with the high-rate measurement techniques continue to hinder studies of the boundary layer and of microphysical processes. The errors caused by flow distortion may contaminate measurements of boundary-layer moisture flux, and errors due to wetting prevent the examination of fine-scale sub- and supersaturations in clouds. Along with solutions to these basic operations problems, an improvement in the absolute accuracy of these measurements to about \( \pm 0.2^\circ\text{C} \) in dew point would be highly desirable.

An additional recommendation for these measurements is that significant efforts should be directed toward understanding the effects of flow distortion on the sensors and toward development of improved housings to allow for high-rate measurements in cloud.
(d) General discussion

In a final general discussion of related topics the state parameter working group identified some additional actions that would make significant contributions to airborne scientific investigations:

- Continue to expand the definition of ”standard instrument packages” at the various flight facilities to include such things as: pressure; temperature; humidity; position; 3-D winds; ozone; CN concentrations; and remote surface temperature.

- Configure more research aircraft for the release of dropsondes.

- Involve many more of the U.S. and international facilities in collaborative efforts in instrumentation development and accelerate the distribution of information on individual development projects.

c. Air-motion sensing

1) POSITION PAPER: – Donald H. Lenschow

(a) 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. In almost all of these applications, 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 that the aircraft’s response to turbulence ( \( \gtrsim 10 \) Hz). 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 the angular orientation of the aircraft must also be precisely measured. Therefore, on the one hand, aircraft offer great advantages for meteorological measurement because of their mobility; on the other hand, their mobility adds to the difficulty in obtaining accurate air motion measurements.

(b) Current status

At the present time, on NCAR aircraft the velocity of the air with respect to the aircraft is obtained by sensing pressure differences across sets of ports on the nose of the aircraft (radome technique). The longitudinal component (true airspeed) is obtained from
the difference between dynamic and static pressure ports and air density. The airflow angles are obtained from pressure difference measurements between ports on the radome at angles from the longitudinal airplane axis that give good sensitivity to attack (vertical) and sideslip (horizontal) flow angles (Brown, et al. 1983); the lateral and vertical air velocity components are then obtained from the airflow angles and the true airspeed. Since the radome technique is inherently airplane-specific, calibration of the measurements is obtained from flight tests (although numerical or wind tunnel simulation may also be possible). Therefore, their accuracy is limited by how well in-flight calibration can be accomplished. The limits here are probably $\sim \pm 0.3 \text{ m s}^{-1}$.

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 on RAF aircraft without external position information is $\sim 0.5t \text{ m s}^{-1}\text{hour}^{-1}$, where $t$ is the number of hours from INS alignment. Loran-C and VOR/DME radio navigation systems are now also available on NCAR aircraft, which offers the possibility of more accurate long-term horizontal position 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 user-supplied fast-response scalars (e.g., ozone) can be readily computed from variables that are routinely recorded on the aircraft data systems. In stably-stratified situations, however, it is not always possible to completely resolve the high-frequency part of the velocity-component spectra.

The mean horizontal air velocity components are 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, is it 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.

(c) 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 flow 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 or 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 to hundreds of meters. The most straightforward way to do this is by measurement of the gradients directly. Gary (1984) has developed and demonstrated a scanning microwave (56.0 GHz) radiometer that measures vertical temperature gradients. Combining this (or similar) capability with a remote wind shear measurement would make possible direct measurement of the Richardson number at the same time that the aircraft is measuring in situ turbulence.

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(d) 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 deployed. Eventually (within 4 years?), continuous world-wide coverage is planned which will make possible three-dimensional positional accuracy of < 20 m and velocity accuracy of < 0.1 m s\(^{-1}\). This does not obviate the need for INS, since attitude angles are still necessary, but the availability of GPS may permit the use of less accurate INS. Inertial systems using ring laser gyroscopes offer the possibility of improved reliability with less accuracy. For these reasons, as well as the age of currently-used INSs, this seems an appropriate time to also investigate the state-of-the-art in INS technology.

Flow distortion effects can be eliminated by using remote measurements of the air velocity components. As discussed by Keeler et al. (1987), laser air motion sensing appears to offer a solution to this problem. All three air velocity components should be measurable to < 0.1 m s\(^{-1}\) 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.

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 direct measure of Richardson number.

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 measurements, and provide guidance for location of sensors on the aircraft.

2) WORKING GROUP DISCUSSIONS AND RECOMMENDATIONS

(a) Current strengths and weaknesses

The group generally agreed with the current status as expressed in the position paper. During group discussions, there were opinions expressed that needs for accuracy in horizontal and vertical wind measurements are not being met by current systems, and order-of-magnitude improvements would have useful impacts on the scientific questions that can be addressed.

There was concern about the validity of past and present flux calculations, because of recent indications that the effects of flow distortion (as discussed by Wyngaard et al., 1985, and Wyngaard, 1988) may be 10–100% of measured fluxes. Airflow calculations and
experimental study are needed, and some instrument re-design may also be required. John Wyngaard (in written comments to the Workshop) suggested that the problem deserved fundamental study and that perhaps the measurement systems should be redesigned. The most serious problems appear to be in the measurements of scalars such as water vapor or other variable gases where the instruments generally measure vapor density. In these cases, variations in total air density at the location of the sensor may be caused solely by airflow variations, and the false signals that result can be comparable in magnitude to the real fluxes being measured. It may be appropriate to consider different measurement schemes (e.g., based on sensors that measure mixing ratios directly) to eliminate this problem.

The group discussed the usefulness of the current air-motion capabilities and advocated general improvement in the accuracy of these measurements. The desired targets for which scientific justifications were presented were 0.1 m/s for horizontal components and 0.01 m/s for vertical wind. These requirements were suggested in order to consider measurement of divergence, vorticity, pressure perturbations, pressure gradients, and studies of small-scale circulations.

An important problem in the measurement of vertical air motion is the gap between the broad weak vertical motions inferred by the methods of synoptic meteorology (e.g., kinematic method, $\omega$-equation, isentropic trajectories) and the aircraft-measured vertical velocities. These synoptic-scale motions are of order 1 cm/s. Current aircraft measurements, based on differential pressure sensing averaged over several minutes, are not capable of this degree of accuracy, due to instrument drift.

In the discussion of wind accuracies (and in some written comments received before the workshop) it was stressed that a good uncertainty analysis should be applied to the present wind-sensing systems. The accuracy of current measurements is a complicated function of averaging time, update technique, wind-sensing system, and aircraft, and needs better characterization.

A specific problem of wind measurement in the tops of thunderstorms under adverse conditions was addressed as a need, and the potential of short-wavelength radars to make this measurement was recognized; see the further discussion under section f.

(b) Needs and opportunities for new instruments

The Global Positioning System (GPS) was proposed as the likely best system to use for position accuracy and for updating INS-derived positions to determine winds with improved accuracy. In view of the reduced maintenance support being provided by Litton Industries for the LTN-51 (about 25 y old, but still the most widely used INS in research applications), there was support for replacement of the inertial systems. While a GPS-based instrument would provide improved position information, an INS is still needed for short-term changes in aircraft velocity and for high-quality measurement of attitude angles in the earth coordinate system. The GPS is expected to be available for global operation in 1992. It was recommended that NCAR and meteorological associations communicate and advocate their needs to those administering the Global Positioning System.
Improvement in wind measurement requires not only that the aircraft speed relative to the ground be improved (as would be possible with a GPS-INS system), but also that the measurement of airspeed relative to the aircraft be improved. To improve upon the standard pitot-static system, it was suggested that a forward-viewing laser system (such as the systems proposed by Keeler et al., 1987), be considered. The pitot-static system is limited by the need to obtain a very accurate measurement of static pressure and by the effects of flow distortion about the aircraft, and order-of-magnitude improvement in this system is thought to be difficult to achieve. A forward-viewing laser system could avoid both of these problems and may provide substantial improvement in the accuracy of the wind measurements.

d. Cloud physics

1) POSITION PAPER – John Hallett

There are two needs for progress: funds and scientific ideas. I can’t do very much about the former, therefore I’ll discuss the latter in relation to cloud physics and related topics. I’ll make no excuses; I’ll tread on other people’s toes here because I’m going into some other areas. I’ll show examples of factors that are driving, or should be driving, the instrumentation development that should be coming out of this meeting.

(a). Climate

First, there is a lot of talk about climate these days. We need to sort out the good from the bad here or we’ll be chasing problems which are non-existent. Cloud radiation climatology is essential. We need to look at a spread of wavelengths, positions, and clouds. In big numerical models, clouds are represented in empirical and parameterized ways, and it is difficult for people who are concerned with clouds to have an input into the way they are incorporated. In addition, the sensitivity of the models to what goes in is never very well spelled out. This points to the fact that people who measure things are going to have to measure radiative properties of clouds a lot better than we have been able to, and to parameterize these in ways that are meaningful. Cloud radiation will depend on the nature of the cloud: droplet sizes, hydrometeor composition, etc. We must do it right with respect to this particular application. There are instrumentation needs here we must worry about.

(b). Electrical activities

There is convincing evidence to link microphysical processes with electrical processes. We must look at instrumentation that will look specifically at these interrelationships. We know something about how thunderstorms behave and something about how particles behave; we must make the scale interaction here and develop the instrumentation that will give us this link between the large and small scales.
(c) **Low-concentration precipitation initiation**

Our aircraft measure thin pencils through the clouds. We get a collection of these, all separated in time, from aircraft measurements. We have an intrinsic limitation in the volume which we can measure. This means that we talk of particle concentrations in number per liter or number per tens of liters. However, when we are looking at the early stages of precipitation initiation, for example, the odd big drop or odd ice crystal that starts the process going, particularly if there is an active secondary ice production process, low concentrations of early particles are extremely important. Therefore, we must worry about techniques and ideas that give measurements of low concentrations of particles, when those concentrations are in the range of $1/m^3$ rather than $1/L$. We need an increase of orders of magnitude here in order to answer some questions of significance regarding where precipitation comes from.

(d) **Mixing physics**

Mixing physics involves many processes, from Kelvin-Helmholtz structures to the kinds of processes that occur in a cumulus cloud, and processes in downdrafts. We don’t really understand many of the processes that give rise to mixing on the scales that are important for cloud physical phenomena to occur, and this brings us to spatial and time resolution considerations in order to confirm or reject certain ideas of how mixing takes place. The typical numerical model will use an eddy diffusivity. An eddy diffusivity gives a Gaussian distribution, yet when you measure profiles you get top-hat shapes. Obviously our simplest ideas here are not right. If we are to get better ideas of how the mixing takes place then we must pay particular attention to the use of instruments in this context.

(e) **Heat-balance physics**

A melting layer influences the atmosphere thermodynamically. We need to be able to study the dynamical and other consequences of these processes, in melting layers, downbursts, etc. We need instrumentation that will give specific answers to these questions.

(f) **Individual particle characteristics**

We know some things about sizes and some about habits, drop sizes, etc. There are other areas where there are holes, in individual particle characteristics that will be needed to answer particular questions. For example, individual particle composition (chemistry) is very poorly understood. If we look at the relative portions of materials in CN, CCN, cloud droplets, or ice crystals, we still have rather inadequate knowledge of how those are distributed. We tend to collect buckets and do gross analyses. We need to study individual particles more systematically than we have.
(g) Radiation

In a cirrus cloud, we have problems of state variables. What is the temperature, and what is the ambient supersaturation or subsaturation. When you ask that question, you must ask: With respect to what? If there is a crystal in the cloud, and that crystal is in a radiation environment that causes it to cool, that crystal will have a temperature other than the ambient temperature. The relative humidity is influenced not only by the state parameters but also by the radiation environment. If we consider growth or evaporation, this is an important aspect of the particle’s environment. We must be concerned with a particle’s radiation temperature, and a different measurement is needed to determine this temperature.

The same applies to charge. We have some measurements of charges on individual particles; here again, if we are to make sense of the overall electrical structure that produces thunderstorms, we must worry about the individual particles. Each snow crystal starts from somewhere, and each Coulomb starts from individual collisions. These are individual contributions that are important.

(h) New measurements needed

- Low concentrations of precipitation and ice.
- Radiation, especially in regard to thin clouds.
- Interstitial measurement: temperature of precipitation, ice particle temperatures, etc. Graupel, rain, etc., will differ in temperature. In particular, there will be super- and subsaturations that it would be useful to measure.
- Particle charge.
- Water-ice discrimination: This problem is applicable to a number of areas. There has been attention recently from radar meteorologists directed toward coalescence-rain development of drops that are observed at $-10^\circ$ C. This phenomenon has been known from in situ observations for some time. There are large regions of convective clouds containing supercooled drops. These new data need to be combined with the knowledge gained from in situ observations. The instrumentation does a reasonable job here, but there are improvements needed for ice-water discrimination.
- Individual particle composition and characteristics.

(i) Old measurements that should be done better

- In-cloud temperature. There may not be a single “in-cloud temperature.” We must be able to interpret the temperature measured in terms of the different temperatures
present, of cloud droplets, precipitation, and air with temperature gradients on 10-µm scales. This applies to radiation temperatures, temperature averaged over distances of a few meters, etc. We need to answer the question of what temperature we need to measure.

- Ice nuclei. Ice nuclei have a checkered history. Several people have spent major parts of their careers studying ice nuclei, and the picture that has evolved is one that is extremely complicated. We know from laboratory studies that a given ice nucleus may act in different ways depending on how it enters the cloud. There is no system that can give a single measurement of an ice nucleus spectrum. The activity spectrum must be related to the processes that occur in the cloud. Is the time now right for a new approach to this problem? New technology is available, and we also know more about the problem.

- Interstitial particles. We have not paid much attention to what, besides droplets, is in the cloud. The aerosols in the clouds affect the radiation properties, esp. in the infrared. We need instrumentation to see what is inside the cloud.

- Radar diversity interpretation. New and rather specific information is now available, and we need to study and interact with radar meteorologists here.

\textit{(j) New places where measurements are needed}

- High-altitude convection.

- At low altitudes, between those accessible from the ground and those accessible from the aircraft. For example, in a winter storm with flow over a snow terrain, low-level turbulence may inject ice yet the process cannot be studied by an aircraft.

- For mid-ocean studies. We usually tend to fly reasonably close to land. There tend to be few studies of air-masses well separated from land.

DISCUSSION:

1. CCN measurements are also needed, and they need to be comprehensive and global (including mid-ocean).

2. Q: You did not emphasize very much the links to chemistry. A: I did in the discussion of the chemistry of individual particles. There are also other links.

3. Q: Is there a known link between chemistry and CCN? A: yes and no. Our knowledge of origins of CCN is still somewhat uncertain. We need a global budget of CCN, and we don’t have the information to construct one. An important observation is that most CCN, even over the ocean, are not sea-salt.

4. We should consider short-wavelength radars with high resolution.
5. In some situations, we can’t measure ice crystal concentrations to an order of magnitude because of problems at small sizes, and we can’t measure ice mass so it is impossible to consider a water budget for many clouds.

6. Often we cannot measure liquid water contents in the tropics because of inadequate sampling of big drops.

2) WORKING GROUP DISCUSSIONS AND RECOMMENDATIONS

(a) Strengths and weaknesses of present instruments

An analysis of the microphysical characteristics of clouds requires measurements of the standard state variables (i.e., the temperature, pressure, and humidity), air motion, water/ice mass content, and the size distributions, charge, and composition of hydrometeors (cloud droplets, ice crystals, and rain or ice-phase precipitation) and of aerosols active in hydrometeor formation (cloud condensation nuclei [CCN] and ice nuclei [IN]).

The measurement of in-cloud temperature by immersion sensors is affected by sensor wetting with subsequent errors on the order of 1–2°C. The reverse-flow sensor was designed to eliminate this problem; however, aircraft and wind tunnel studies indicate that this sensor also becomes wet at temperatures above freezing. There is also the question of measuring particle temperature instead of air temperature. There are no techniques capable of this measurement at present.

The water vapor density in clouds cannot be measured with any reasonable accuracy at this time. Chilled-mirror devices respond too slowly and are susceptible to wetting, and the drift of Lyman-alpha devices makes it impossible to measure the relatively small supersaturations that are present in the clouds.

The air motion sensing systems are adequate for many cloud physics studies. The primary limitation is the lack of capability for measuring very small vertical velocities (<1 m/s).

Liquid water content is usually measured with hot wire sensors whose accuracy is on the order of 0.1 g/m³ when droplets are smaller than approximately 50 µm. Droplets larger than this size will break up and evaporate only partially so that the liquid water content will be underestimated. Ice water content is only crudely estimated from measurements with the 2D probe because assumptions must be made concerning the bulk density of the ice particles. The uncertainties in the estimates of ice water content using this method are dependent upon the type of ice particle but probably exceed 50% in most cases.

Cloud particles are measured in a number of ways. CCN measurements are usually measured with thermal diffusion techniques that measure the total number of CCN without
Recent work by Jim Hudson at the Desert Research Institute has produced a CCN instrument that discriminates by size and can also possibly measure interstitial CCN in cloud. The accuracy and reliability of this instrument is uncertain because it is still in the early stages of development.

Accurate ice nucleus (IN) measurements are difficult to make because of the multiple nucleation modes that can occur. The number of IN in the atmosphere has been measured with a variety of instruments and over a variety of environments. When measurements taken in similar environments have been compared, the differences sometimes exceed two to three orders of magnitude. There is no commonly accepted measurement technique that is presently used in airborne measurements.

The accuracy with which cloud droplets are measured is strongly dependent upon whether the measurements are taken in a mixed phase environment, on the droplet concentration, and on how well calibrated and characterized the droplet spectrometer is. The most common droplet probe is the forward scattering spectrometer probe (FSSP) made by PMS Inc. The concentration of water droplets smaller than 50 \( \mu \text{m} \) can be measured with an accuracy on the order of 20\% and the size can be measured to a similar accuracy. However, these accuracies can only be attained when the measurements are made in an all-water cloud and when proper corrections are made to the measurements for coincidence and dead-time losses and for the optical and electronic limitations of this probe. Unpredictable results will result for measurements in mixed phase clouds and concentration and sizing accuracies degrade to greater than 50\% if appropriate corrections for coincidence, deadtime, and electronic response time are not made.

At normal aircraft speeds, the size distributions of ice crystals smaller than about 50 \( \mu \text{m} \) cannot be measured with any of the PMS probes because of limitations due to response times of the electronics. Replication techniques are possible but the tedious data reduction limits their usefulness and there are uncertainties associated with collection efficiencies and particle break-up. The major advantage of impactors is that drops and precipitation particles are collected together, and in situ chemical analyses (by treated substrate) can be performed. For larger particles, the PMS two-dimensional imaging probe provides shadow images of particles from which some information can be deduced about the habit, size, and concentration. The accuracy of these probes is limited by the relatively small sample volumes (approximately 5 L/s and 170 L/s for the cloud and precipitation probes, respectively, at 100 m/s flight speed) and by contamination by spurious particles generated from collisions with the arms of these probes. The absolute accuracy of concentration measurements with these instruments is usually on the order of 20–30\% once appropriate corrections are made to reject spurious images. The sizing accuracy is 10–20\% when a particle is entirely within the probe’s field of view, but can be much worse otherwise.

The problem of small sample volume affects the measurement of those large particles that occur in extremely small concentrations (\(< 1 \text{ m}^{-3}\)). With the PMS 2D-precipitation probe, flight segments of 10 km or more are needed to obtain statistically significant samples of those particles that are present in these small concentrations.
The 2D images can sometimes be used to discriminate between ice and water. However, because of the limited resolution of these probes, hydrometeor types such as snow pellets or graupel are sometimes indistinguishable from water drops. None of the *in situ* instruments (except perhaps the replication devices) are adequate for discriminating between water and ice particles.

The composition of cloud particles has been measured with impaction techniques, water collectors, and most recently with a counterflow virtual impaction technique. The impaction technique requires that droplets impinge upon a chemical substrate that reacts to the composition of the droplet. Very painstaking analysis is required with this technique. The water collectors provide samples for bulk chemical analysis but the sample is biased by drop size because of the aerodynamic characteristics of these collectors. One of the most promising instruments is the counterflow virtual impactor (CVI) that separates droplets aerodynamically and evaporates them in a heated air stream. The residual particle or gas can then be analyzed (e.g., with an optical particle counter or other detector). Problems with this technique include a limited sample volume, possible chemical changes resulting from evaporating the droplet, and depositional losses to the walls of the sample cavity.

The size distribution and composition of interstitial particles such as haze droplets, CCN and IN, or other aerosols have only been addressed in the case of CCN (the Hudson CCN counter). There is apparently no technique available at this time for making measurements of other types of interstitial particles.

(b) Needs and opportunities for new instruments

A number of interesting microphysical questions remain unanswered in large part because of limitations of airborne instrumentation. For example,

- What are the origins of ice crystals?
- How are particle charge and cloud electrification linked and how do electrical effects alter the evolution of precipitation?
- How are precipitation processes affected by the presence of very large aerosol particles?
- What is the nature of mixing processes in clouds?
- What is the nature of radiative transfer in clouds, and how do various cloud types affect radiative transfer and climate?
- How do individual particle characteristics alter cloud evolution, radiation, electrification, and chemical scavenging?

The radiative properties of cloud particles are a function of the particle size, phase, and chemical composition. The uncertainty associated with calculations of radiative energy can exceed 50% when the measured particle distributions are used. The largest contribution to
uncertainty is the lack of information about the concentration of ice particles smaller than 50 µm. The second source of uncertainty is the lack of ice/water discrimination. In situ measurements are needed to provide basic characterization of the hydrometeors and also to calibrate remote sensing techniques, which offer the potential for more extensive spatial and temporal coverage than can be provided by in situ sensors.

The origins of ice particles cannot be determined without new approaches to the measurement of IN and of very small ice crystals.

Some advances have been made in the determination of particle charge. However, there is evidence that particles carrying charges too small to measure with available instruments carry a significant fraction of the charge in electrified clouds.

Modeling studies have shown that low concentrations of large particles can initiate coalescence. Evidence for such particles is sparse at this time because of the relatively small volumes sampled by most aerosol probes.

The study of mixing processes requires fast and accurate measurements of temperature, humidity, and droplet size distributions. Laboratory studies indicate the possibility of filamentary mixing processes that could only be detected by an instrument having >10 Hz response, and at some scales the structure of the process would require measurements at > 100 Hz.

Melting and evaporative processes can be a major driving force in cloud dynamics, but estimates of these effects are difficult because of uncertainties in ice/water discrimination and in estimates of the bulk densities of ice particles.

Very little is known about scavenging processes in cloud, acid rain production, and the effect of non-aqueous particulates and gases on hydrometeor evolution. Measurements of interstitial particulates, gases, and the chemical composition of cloud particles are needed before fundamental questions in these areas can be addressed.

Some of the aforementioned measurement problems can be addressed with new measurement techniques that are presently in the development stages. In particular:

- The measurement of in-cloud temperature is possible using radiometric techniques (as in the Ophir radiometric thermometer or the 4.3 µm radiometer developed by the British Meteorological Office). The preliminary results are encouraging but additional analysis is required over a wider variety of conditions.

- Some new instruments might improve on measurements of humidity in clouds, if suitable housings can be devised. One instrument now being developed is a UV hygrometer that uses dual paths and dual wavelengths to avoid the problems of drift and contamination that affect current Lyman-alpha instruments. Another feasible technique is to measure the dry- and wet-bulb temperatures in cloud.
• The detection of small ice particles remains a serious problem; however, an upgrade of the electronic circuitry in the particle measurement probes could improve the time response of those probes. Another technique holding promise for measuring these sizes of particle and also for determining the phase of the particles is that of particle impaction, perhaps on a oil-coated, moving film. The film would transport the collected particles across the field of view of a miniature video camera. Although this technique requires automated image analysis if large amounts of data are to be handled, major advances have been made in pattern recognition that might be used. Holographic imaging has also been used with some success by the British Meteorological Office. This technique has also been limited by processing techniques which could possibly be improved with advanced pattern recognition schemes.

• Particle probes are needed with substantially (100–1000 times) larger sample volumes than currently available. Holographic imaging is one solution and there has been some preliminary work towards developing a sensor that measures particle mass through momentum transfer.

• The development of millimeter-wavelength radar offers a way of addressing a number of measurement problems. Polarization techniques provide a way of discriminating between water and ice. Relatively small-scale structures (<20 m) can be studied remotely with airborne radars in this range of wavelengths.

• An airborne microwave radiometer has been used to measure vertical profiles of the liquid water content using tomographic reconstruction techniques. The preliminary results are encouraging but questions remain concerning the accuracy of the reconstruction algorithms.

• Total water content has been measured by evaporators that measure the water vapor density after evaporation of the water and ice. These techniques are promising but have limited sample volumes and require large amounts of power to evaporate the particles. Another experimental technique has been to use the compressors on a jet aircraft to evaporate the particles and then to measure the water vapor content of the bleed air from the compressors. A modification of the CSIRO (King) hot-wire probe that measures the power needed to melt ice particles has also been tried (King and Turvey, 1986).

• More studies are needed on water collectors to improve their collection efficiencies and collection rates. The CVI is a promising candidate for furnishing information on cloud particle composition.
1) POSITION PAPER – Tom Marshall

Our principal scientific goal is to learn how storms become electrified, including both intense thunderstorms as well as storms that are less electrified. The more intense storms have traditionally drawn greater attention and are thus better known electrically, although modestly electrified clouds have also proven to be hazardous to rockets and aircraft, and so merit greater attention. Since remote sensing alone is inadequate for acquiring the necessary data, penetrating aircraft are absolutely essential to research into cloud electrification. For example, charges on individual particles and bulk charge densities cannot be sensed remotely, but these data are important in the evaluation of electrification mechanisms and may indeed be obtained by in situ measurements. We are also interested in the interplay between cloud electrification and each of cloud microphysics, cloud dynamics, and atmospheric chemistry. The roles of cloud microphysics and cloud dynamics in cloud electrification are undoubtedly important, while lightning may prove to be a significant source of nitric oxide in the atmosphere.

Among the specific questions to be addressed using data from airborne instruments are the following:

- Where are charges located in clouds? How much charge is in each region, and how do the regions evolve?

- Which types of particles carry the charge? How much charge do individual particles carry? What is the bulk charge density of the measured charges?

- Updrafts, downdrafts, horizontal winds, and certain temperature ranges may play a role in electrification. What is the position of each of these features relative to the regions of charge?

The first set of questions above is the one most studied, although much more remains to be done. The charge structure of clouds is important to the evaluation of charging mechanisms. For instance, one mechanism might predict the occurrence of one sign of charge in one temperature range, and the other sign elsewhere. On the other hand, another mechanism might predict charge of one sign to be predominantly associated with downward moving air, and another sign in the updraft. Thus a knowledge of a storm’s charge structure, especially when coupled with the storm’s kinematic, microphysical, and temperature structure, would be quite revealing. The measurements, or rather inferences, of charge structure have generally suffered from the nonuniqueness of the structure that is derived (using simplifying assumptions) from the available measurements of electric field. The nonuniqueness will always be with us, but the situation would be greatly improved through the use of simultaneous measurements of the electric field at more than one location within the cloud, that is, from several measurement platforms at once. The inferences would be more constrained by the more complete specification of the “boundary values.”
Also, the use of aircraft that can stay with a cloud over a significant fraction of its evolution would allow a thorough study of how the electrical evolution relates to the microphysical and dynamical evolution. There have been a reasonable number of studies relating charge structure to radar reflectivity structure, but especially lacking are studies relating electrical and kinematic structure.

Measurements of charges on individual particles (addressing the second set of questions above) have provided extremely valuable data, but such datasets are very difficult to obtain and hence are few in number. Such data may be used, for example, to assess a mechanism that predicts charges to be less than a certain size-dependent value, or to assess a mechanism that predicts charges of a specific sign and magnitude to occur on graupel particles, say. Also, the role of hydrometeors in the first place may be assessed by adding up the measured charges to see if they are commensurate with the measured electric field. The most recent data of this type have yielded the perplexing (for those advocating the role of hydrometeors) result that only a small fraction of millimeter-sized particles are charged. Nonetheless, significant amounts of charge are being found. As stated above, though, very little such data exist, and their representativeness may be questioned. Additional measurements are clearly needed.

As is evident from the above, a detailed knowledge of the microphysics (particle type and charge), while of some use by itself, is of far greater use if it can be combined with a knowledge of a storm’s kinematic structure, its temperature profile, and its large-scale charge structure. Thus the third set of questions above calls for the aircraft measurement of temperature and air motion. Such data are required in order to make full use of the microphysical data, and it bears repeating that there is a shortage of measurements relating data on charged volumes to data on winds. This is especially important since air motions are often larger than the terminal velocities of particles in storms. Such comparisons would find application to the evaluation of virtually all proposed charging mechanisms.

Thus the dataset to be acquired from aircraft for the evaluation of electrification mechanisms includes the following: (a) the electric field structure and the charge structure inferred therefrom, (b) the charges carried by individual particles and their identities (size, shape, and phase), and (c) the kinematic structure and temperature profile of the storm. These data could then be placed in the context provided by ground-based measurements such as radar reflectivity, Doppler wind field, and surface electric field.

In order to provide these data and to be useful for cloud electrification research, aircraft should therefore be equipped with the following instruments:

- Electric field mills for the measurement of the electric field vector, so that charge structures and magnitudes may be inferred.

- An instrument for the simultaneous measurement of the charge, size, and shape of individual particles.

- Conductivity sensors to be used in conjunction with field mills in the measurement of the substantial currents which flow to the tops of thunderstorms (from above).
Air motion sensors for the measurement of motions on small scales not well resolved by radars (100 m, and smaller), so that the motions of measured charges may be determined and for verification of Doppler-radar-derived wind fields.

Cloud microphysical instrumentation, including both the standard instrumentation and any possible improvement in the detection of small ice particles.

Position (to better than 100 m), so that the in situ data may be related to radar data as well as to data from other aircraft.

QUESTIONS AND DISCUSSION:

1. Vonnegut urged that attention be paid to air circulations in the clouds. We know that about 1 C s\(^{-1}\) of negative charge is deposited on the top of the thunderstorm, but inadequate knowledge of the circulations keep us from knowing what happens to this charge.

2. Serafin: what spatial and temporal scales are needed? Vonnegut: we lack the ability to resolve the details of what is happening. We need scales of 100 m or less. The air motion picture from radar is significantly different from that deduced from an aircraft pass, where there is considerable fine structure on 100 m or smaller scales and those structures don’t show up on the radar. With circular-polarized radar and chaff, this might be addressed.

3. Vin Lally: Balloons are difficult and aircraft are few; wouldn’t it be useful to consider dropsondes? One would need to develop the sonde and the instrumentation. We have most of that already, and have FAA permission for over-land use.

4. Russ Dickerson: There is an interface between chemistry and cloud physics in that lightning produces oxides of nitrogen. We need to know the global dissipation of energy in lightning strokes.

2) WORKING GROUP DISCUSSIONS AND RECOMMENDATIONS

(a) Current strengths and weaknesses of instrumentation

Six instrumentation needs were listed at the end of Tom Marshall’s position paper. The first three of these relate specifically to electrification research, and each will be discussed in turn. The last three, on the other hand, are of more general interest, and no additional requirements are imposed by our concerns over and above those imposed by other users, the only possible exception being in the area of small-ice detection. Since small, pristine crystals are postulated by some to play a major role in electrification, we strongly support the recommendation of the microphysics subgroup that that measurement capability be improved.

Electric field mills are necessary for the inference of the large-scale charge structure. Existing measurement techniques are adequate; however, great care must be taken in the
installation and calibration of a system of mills on the airframe. Individual mills may quite easily be used to measure the local field at the surface of the airframe (including the field due to aircraft charge), but it requires great care to use a set of six or so mills, together with the airframe, as a system to measure the ambient electric field—without interference from the charge on the aircraft, the charge on exhaust, and the charge due to corona. In spite of these difficulties, recognized techniques exist for the installation and calibration of a system of field mills. There has been a shortage, however, of publications on this topic, and it is recommended that the experts publish their techniques and results so that others can take advantage of them. Also, intercomparisons among different aircraft are encouraged as a means of verifying the reliability of the different systems. Technical details on specific needs and accuracies required of aircraft systems may be found in the proceedings of a recent NASA workshop.

Many of the proposed charging mechanisms involve hydrometeors, and measurements do indicate that hydrometeors carry substantial amounts of charge. Thus instruments designed to measure the charges on individual particles, while simultaneously imaging the particles, are of great value. The development of such instruments has been identified as a top priority by this subgroup. A few such instruments have been under development in recent years, but very little data have been obtained to date. The instruments appear to work, although no intercomparisons have yet been made. These instruments show great promise and merit further development. One improvement that would be extremely valuable is a substantial increase in sample volume, especially for the study of early electrification.

Although their role in cloud electrification is disputed, it is widely recognized that large (ohmic) currents flow to the tops of storms from cloud-free air. Whether these currents impede or enhance a storm’s electrification, their magnitude is so large that they cannot be neglected. When used in conjunction with a measurement of the electric field, a conductivity measurement may be used to obtain this current. Thus for an aircraft with the capability to fly over storms, a conductivity sensor would be a useful instrument. Such an instrument is a relatively simple one and would be a cost-effective addition to the complement of instruments on an aircraft. What is more, in view of their reliability and simplicity, conductivity sensors are strong candidates for inclusion in the “standard instrumentation package” discussed in this workshop. They may find use in airmass characterization, since the conductivity is sensitive to the aerosol loading, and such sensors have proven to be useful in smoke plume tracking in real-time. Thus, research projects aimed at the study of aerosols or air chemistry may wish to avail themselves of this instrument.

It is clear that the requisite instrumentation for addressing important aspects of the electrification question are almost at hand. Once the particle charge measurement is more fully developed, the strongest need will be for a coordinated field program, as opposed to new instrument development. This will require that existing aircraft be more fully instrumented for electrical measurements than has generally been done in the past. With the use of aircraft flying at more than one level inside a cloud, along with one above the cloud, improved inferences of charge structure will be possible. This, coupled with
in situ microphysical data, will enable the assessment of charging mechanisms involving hydrometeors. In addition, certain aspects of convective mechanisms may also be assessed. Although data from individual aircraft are useful, the best use of resources is to apply them all at once. Also, ground-based radar will be necessary to provide the larger-scale, three-dimensional context within which the finer-scale airborne measurements may be placed. This electrification subgroup is perhaps unique within this workshop in that it is more interested in the application of existing instruments than the development of new ones.

(b) Survey of needs and opportunities for new instruments

A miscellany of other instrument development projects was discussed. However, an absence of widespread support or good ideas has resulted in their not being emphasized in this report. An instrument to measure charge density directly would be of great use, because its results could be compared to those obtained by adding up all the charges on individual particles, as well as to the large-scale charge density obtained from electric field measurements. A good technique for doing this is unfortunately not known. It appears that the deployment of dropsondes may soon become a convenient operation. However, it may be a substantial development effort to instrument such a sonde for the reliable measurement of electric field or particle charge, although such an effort may prove to be quite worthwhile. An airborne interferometer (for the location of discharges) or an airborne field change meter (for the detection of lightning) would also be interesting developments. Such instruments have proved to be extremely useful when operated on the ground. The different perspective provided by an airborne platform might prove to be of interest, especially in conjunction with identical ground-based measurements.

(c) Recommendations

Even though the instruments mentioned above would be of great value, the principal development effort recommended by this subgroup is for an instrument to measure the charges on individual particles. At the same time, this device should image the particles so that their sizes may be measured and their types inferred. Such developments are underway and have already provided small amounts of useful data, although the instruments are not yet fully evaluated. In addition, it is recommended that certain electrical measurements be made on a more routine basis. The particle charge measurement is certainly a specialty measurement at this stage. A properly installed and calibrated system of field mills, on the other hand, could be used to obtain measurements on a routine basis. The biggest payoff from this would most likely be in data involving weakly electrified clouds, a subject generally slighted in electrification research. And to move a step even further in the direction of routine measurements, it is recommended that conductivity sensors be employed on a routine basis, perhaps as part of a “standard instrumentation package.” Such measurements are of use not only for cloud electrification research (above the cloud), but are also of potential value to those interested in a qualitative measure of the aerosol content of air. These simple devices could be used, for example, in the real-time tracking of aerosol-laden plumes.
Furthermore, it is recognized that significant progress may be made in this field by the concentration of resources on single storms. A group of airborne platforms could much better pin down the charge structure than a single one. In fact, a coordination of existing resources is a higher priority than the pursuit of new developments, a possible exception being the continued development of instrument for the measurement of particle charge coupled with particle imaging. Once this measurement is on more solid ground, a multi-platform experiment should be pursued.

Finally, although the emphasis of this subgroup is cloud electrification, and the principal scientific goal is understanding the electrification of storms, our ties with cloud microphysics, cloud dynamics, and atmospheric chemistry should not be overlooked. Because of these ties, any coordinated field project aimed at the electrification question provides opportunities for addressing questions in these other areas, and vice-versa. Specifically, any storm that is well-characterized electrically is a good one in which to search for the production (and transport) of chemical species produced by lightning or corona. Likewise, since detailed microphysical data are required for the assessment of electrification mechanisms, it would be a waste not to pursue other microphysical topics at the same time. Such opportunities should be sought.

f. Remote sensing

1) POSITION PAPER – Ed Eloranta

Do we need to put remote sensors on aircraft? Obviously, yes. We need to get where the action is, and many of the sensors have relatively short range. Optical remote sensors, lidars, mm-wavelength radars, etc., need mobile platforms so that it is not necessary to wait for the phenomena to get to the sensor. In addition to needing mobility, we also have a range of problems that we can’t do with ground-based remote sensors. We can look at daytime boundary layers in the Kansas prairie, but there are many regions we cannot examine except with an aircraft. For example, many forested and hilly terrains offer no suitable ground location for radars and lidars which require a clear line of sight to their targets.

There are also more fundamental reasons for using remote sensors on an aircraft. One of the most important has to do with sampling difficulties, as referred to earlier by Don Lenschow. We take an aircraft and fly through the atmosphere to get a single line sample, yet we know that the atmosphere is filled with entities having sizes of 1 km or larger, and if we try to measure those structures from an aircraft we encounter fundamental sampling difficulties. One of Lenschow’s papers (Lenschow and Stankov, 1986) dealt with the sample distances needed to achieve representative samples, and showed that for scalar fluxes in convective boundary layers we must fly distances of 50–400 $Z_i$, where $Z_i$ (the depth of the boundary layer) is of order 1 km. Therefore, 500–4000 s are typically required to measure to 10% accuracy. For momentum flux, even longer averaging times are needed. These
considerations indicate that we need better coverage to study fluxes in the atmosphere. Another strategy is needed.

An example of the advantage of volume sampling was obtained during FIFE. On one convective day, with \( w_* \) of about 1.5 m/s (so there were convective velocities of that order), the mean wind was very low, less than 1 m/s. We tried various ways of measuring the mean wind. From PAM stations at the surface, even with 30 min averages, there was so much scatter that it was difficult to deduce a mean wind. The radiosonde showed similar variability. The NOAA Doppler lidar made VAD scans to measure wind, and obtained smoother variations with height and a more consistent field. Still better results were obtained by observing the advection of aerosol inhomogeneities over a 50 km\(^2\) area at 10 different, independent heights. The profiles of these were much more reasonable, and were nearly independent of height as expected because of the strong vertical mixing. There was only a few cm/s scatter with height, even though all the measurements were independent. In regard to the wind direction, there was high scatter in the radiosonde and PAM measurements, but the VAD and lidar techniques showed much more consistency.

The point is that if a measurement can be made averaged over an area rather than over points or lines, one can improve the accuracy substantially. No improvement in airborne \textit{in situ} sensors will solve the sampling problem; this requires some other measurement technique that looks at a larger volume. For that fundamental reason, we need to consider incorporation of remote sensors on the aircraft. This is difficult now because of the size and power requirements of some of the systems, so some adaptation of remote sensors to the requirements of airborne platforms is required.

The next question is, what parameters can we measure? We have at some point made measurements from the ground of wind velocities, water vapor, temperature, pressure, ozone, \( \text{SO}_2 \), \( \text{NO}_2 \), Hg, \( \text{OH} \) radical, \textit{etc.} – all have some potential for doing the kind of volume averaging we want. Most of those systems barely fit in a van, and they take a team of PhDs and engineers tweaking all the knobs. The advantages of volume averaging are such that this is a direction we must go in the future, but the problem at the moment is one of selecting which techniques are ready to make the step to airborne use and deciding how we can finance and carry out that step.

Another reason for putting a remote sensor on the aircraft is: that is where the other instruments are. Many of the things we do with remote sensors benefit from having \textit{in situ} measurements alongside them. If you look the other way around, one of the major difficulties with current measurements on the aircraft is that, even if we know exactly where the aircraft is on the earth, we typically don’t know where it is with respect to the atmospheric structure it is flying through. Once we have pencils of measurements through the atmosphere made with current instruments, we at least need to know what part of the atmosphere we were looking at. The simplest application occurs when we fly an aircraft through the boundary layer to measure turbulence, chemistry, \textit{etc.}, in the boundary layer, and we need to know \( Z_i \). We could locate our measurements in the boundary layer with a simple lidar that detects the top of the boundary layer. It is not adequate to determine the
top of the boundary layer from a sounding, because the location of the top is so variable; you need to average over distance. This type of backscatter lidar is well within today’s technology. We could move to this immediately without the complexity of measurements of state variables, etc. The same problem occurs in cloud physics. You need to locate measurements within the cloud. Radars, esp. high frequency radars, would provide the location of cloud boundaries.

I was interested to hear Al Cooper suggest how we should go about improving aircraft instruments. I have been a sometimes-vocal critic of the interaction of NCAR with the universities. NCAR, because it has been so successful in providing measurements to the university community, has almost destroyed the university-community instrument-makers. Because of funding policies and because it is difficult to get students who want to build instruments, we’ve had problems even without NCAR. But because NCAR has been so successful in providing measurements, university investigators can write a proposal calling for a measurement and have the measurement platform and instruments appear to make those measurements. What we’ve done is we’ve produced a generation of atmospheric scientists who don’t understand the measurement process. It is particularly scary that it is not just the students but also the people running the instruments and the people who are planning the science. As a result, we don’t know how to make measurements. We don’t know how to deploy the instruments, we don’t understand the limitations of the instruments, and we don’t do a very good job of deciding what the next instrument should be. I think the structure of how we provide measurement support needs to change. We need to put the instrument developers, university faculty, and students back together. This activity is so expensive, and requires so much support, that we probably can’t do it in the traditional university setting either. We have to take the money that we spend to develop these complex instruments and the instruments that are developed and put them back where they are available to the larger community. So I think we need to devise a structure by which we put those two things together. We could perform instrument development in the universities, perhaps in close collaboration with NCAR, and then take the instruments back to NCAR or make them available at NCAR with a home with someone who is particularly interested in the TLC of the instrument. In this workshop, we can discuss remote sensors that might be ready for aircraft deployment.

QUESTIONS AND COMMENTS:

Stith: There are many universities that have instrumentation involvement, and a few with aircraft also, but putting instrumentation on aircraft involves a lot more than just strapping it down and plugging it in. It requires cutting holes and actually modifying the aircraft structure. That type of aircraft modification and approval through the FAA is sometimes a very expensive job that takes expertise that is not available to university groups. It would be very helpful if there were a place, like NCAR, that was set up to help universities in getting platforms and instruments modified and in getting FAA approval.

Telford: There is no substitute for deep involvement by the universities. Investigators need a full comprehension of what is involved in handling measurements. I’d like to endorse
the principle that the universities themselves should be involved in the whole range of these activities. Clearly, we need to have consortiums and groups, and NCAR may be a pivotal point, but substantial projects can be set up between groups of universities. NCAR may provide the processor, someone else the physics of pulse generation, etc.; this is preferable because it involves universities directly. It is not adequate to stand back and say, give it to the engineers, particularly in view of the way in which measurements are misinterpreted, and the way groups can get together and create an atmosphere in which the measurements are just ignored.

Serafin: I don’t think NCAR is responsible, but the community collectively has allowed us to fall into this condition. At NCAR we have replaced our computers on a 3–5 y cycle and we know that these largest computers are necessary in order to conduct one element of atmospheric science, yet we don’t have those kind of funds available at NCAR for replacement of the inventories we are talking about. In our division, we have only $360,000/y budgeted for new development. Some in this room were at a meeting of Department Heads and Chairs, where I chaired a panel on the subject of balance between numerical modeling and observations, observational methods, and instrumentation. Out of that panel session with some 50 university representatives came a resolution\textsuperscript{3} that said there is a serious problem. It is a problem at all levels, at university campuses where instrumentation is not being taught and is being de-emphasized, and at our national centers where we don’t have the funds to make progress in instrumentation and observations. We allowed that to happen, collectively. It is not NCAR’s or the universities’ fault, but rather our collective fault. There needs to be a greater emphasis on this part of atmospheric science, and that indeed means more money.

2) WORKING GROUP DISCUSSIONS AND RECOMMENDATIONS

At the outset, the group noted that it was defined by an instrumentation technology rather than an application area, as is the case for other working groups. Because of this emphasis on technology, the discussion ranged over a wide variety of instruments and research areas.

(a) Current strengths and weaknesses of instrumentation

The principal strength of remote sensing techniques is the ability to sample large regions of the atmosphere or ocean surface. This translates into reduced flight track lengths or times to achieve a reasonable measurement accuracy. In contrast to \textit{in situ} sensors, which provide data along a flight line, remote sensing instruments can provide:

- synoptic maps, either in the x-z or x-y planes;
- true area averages; and
- freedom from effects of aircraft-induced flow disturbances.

\textsuperscript{3} This resolution appears as Appendix D of this report
These advantages hold for some state variables, motions, and some fluxes.

The range information available from remote sensors allows the aircraft and its \textit{in situ} measurements to be located with respect to atmospheric structures of interest, such as the top of the mixed layer, the core of an updraft, or the precipitating region in a thunderstorm.

Aircraft are ideal platforms for remote sensing instruments because they allow sampling rapidly enough and with adequate spatial continuity so that space and time variations can be unscrambled. Cross sections of the atmosphere are easily available from a remote sensor on an aircraft. Spatial differences in remotely-sensed data yield gradients and budgets that are unavailable to \textit{in situ} sensors. In addition, remote sensing allows measurements from regions where aircraft operations are not safe, such as very near the ground, in rough terrain (\textit{e.g.}, orographic clouds), and in intense convection.

The principal weakness of available and near-term remote sensing systems is that they are applicable to only some state variables and scales of fluxes, depending on the availability of a suitable sensing radiation and physical interaction with the variable of interest. However, there are a wide variety of interactions already identified that await practical instrument development. In general, remote sensor systems are more complex and expensive than the corresponding \textit{in situ} instruments. The current Differential Absorption Lidar (DIAL) for ozone is an example of a system requiring a number of complex subsystems.

\textit{b) Survey of needs and opportunities for new instruments}

Measurement of water vapor profiles and motions of particles are general needs for remote sensing techniques. Techniques involved include multiple-wavelength radiometry, Doppler radar, and Doppler lidar.

Boundary layer studies need remote measurements from aircraft of the height of the mixed layer and momentum fluxes. A DIAL system for ozone would be useful for chemical studies.

Studies of fundamental cloud physics involve questions of liquid water and ice distribution, turbulent structure, entrainment, and transport. Within clouds, millimeter-wavelength radar would be appropriate, with lidar for the region outside the cloud boundary. Both convective and orographic clouds are candidates for such sensor applications.

Oceanic and air-sea interaction studies constitute another group of needs and opportunities for remote sensing techniques. Required measurements include ocean surface topography, temperature, and salinity. Near-surface wind and spray measurements are related to heat and mass transfer at the surface. Remote mapping of ocean currents is an important application of remote sensing.
(c) Development projects having general support

These projects fell into three groups, listed here without relative priority. In general, the developments were thought to be practical in the near term and of special utility to the NSF research community.

Millimeter-wavelength radar: This would be a Doppler radar in the region 35 – 215 GHz, with the frequency choice depending on available technology and specific applications. The general research field for such an instrument is cloud physics.

Passive radiometry: Four different applications at different spectral regions were mentioned. A 60 GHz radiometer could measure temperature and, with a range-height indicator (RHI) scan, give temperature profiles. In combination with a remote-sensing laser Doppler velocimeter for velocity gradients, such a radiometer would yield Richardson’s number.

Multiwavelength microwave radiometers can be used to provide smoothed temperature and humidity profiles via a spectral inversion. Another application of radiometry in this spectral region is tomography to map cloud liquid water in the x-z plane.

Fourier transform infrared (FTIR) spectrometry has been used from an aircraft platform to identify atmospheric constituents in solar absorption and may be useful with other sources and geometries for such identification.

Lidar: A simple backscatter lidar, preferably in the eye-safe region of the near infrared, would be useful for mapping the height of the mixed layer, for studying the structure of cirrus, and for determining the evolution of sea breeze structure, for example.

A Doppler lidar would allow measurement of winds in the cloud-free atmosphere to support studies in dynamics or boundary-layer transport processes.

(d) Working strategies

A lively interchange on the needs and technology in millimeter-wave radar prompted serious discussions on cooperation between the University of Massachusetts and the University of Nevada, which may lead to a proposal for joint research (cf. Appendix C3). This cooperation is an example of combining available technology with longstanding measurement needs in the cloud physics community. Another potential cooperation involves ATD and the University of Wisconsin on a practical, eye-safe backscatter lidar.

The strategy for development in remote sensing involves distributed projects, where technology and application centers work together on a chosen instrument from initial concept to field application. This is necessary because of the comparatively complex instrumentation required and the wealth of data potentially available from remotely sensed
variables. Benefits of the strategy were seen by the working group as:

- effective student training,
- cost-effective hardware,
- better user-developer interaction, and
- diffusion of interpretive capability.

Distributed projects involve three elements: the instrument specialist working on development, the principal investigator using the remote sensing system in observational meteorology, and the flight facility, which provides the platform and assures availability of the instrument to the wider community.

\[ g. \text{ Gas-phase chemistry} \]

1) POSITION PAPER – Russ Dickerson

RAF has recently started support of gas-phase chemistry experiments through the addition of an atmospheric chemist to the staff (Greg Kok). Greg has begun the task of adding instrumentation for chemistry, with the installation of ozone sensors on the aircraft that have sufficient sensitivity and response time for many applications. Greg plans a CO instrument soon that will have response time of about 10 s and sensitivity of 5–10 ppb, adequate for many studies also. Both of these species, ozone and CO, are very useful not just to chemists but also to dynamicists, cloud physicists, and people interested in fluxes. They are also important in the earth’s radiative balance, ozone in particular, because it is a greenhouse gas.

CO is a good example of, “You get what you pay for.” If you want to be very simple you can take an evacuated cylinder onto the aircraft, fill it, take it back to the lab, and get a single measurement. You can also use commercial instruments, but they are designed for air pollution studies and will not have the sensitivity needed for studies of remote, clean atmospheres. Or, as I have done, you can take a commercial instrument and change it into a hot-rod (Dickerson and Delany, 1988), and get 5–10 ppb with 50 s response time for about 45 lb. Greg is turning this hot-rod into a Maserati that will give about 10 s response time. If you want to really push this measurement, CO can be measured by a tunable diode laser system with response time of 0.1 s and high absolute accuracy, but that is a 1500 lb system and takes years and hundreds of thousands of dollars to develop.

RAF has also been working on new inlet systems for both gases and particles, and on engine-driven pumps for sampling, and Greg has been doing a lot of development of calibration standards for ozone and CO. This is very important because chemists are a doubting lot, who tend not to believe any instruments but their own, and if there are
instruments put on the NCAR aircraft we want to see some proof that they are generating accurate numbers, at least as accurate as we could produce ourselves.

That is what is going on, now and in the near future. The list of things that are not happening, but are feasible, is much longer. Chemical species that are not routinely measured at RAF, but for which someone has developed either a ground-based or airborne instrument, include NO, NO\textsubscript{x}, NO\textsubscript{y}, SO\textsubscript{2}, PAN, HNO\textsubscript{3}, H\textsubscript{2}SO\textsubscript{4}, DMS, CH\textsubscript{4}, H\textsubscript{2}CO, H\textsubscript{2}, OH, H\textsubscript{2}O\textsubscript{2}, \textit{etc}. The reason we care about these is that, for example, the oxides of nitrogen are involved in ozone production, and they are in fact a key component. If you have less than a certain amount, 10 ppt, of NO, photochemistry in the atmosphere will destroy ozone; more than about 10 ppt, you can generate ozone. Anthropogenic activities, burning of fossil fuels for example, produces lots of NO. If we had enough NO in the atmosphere the ozone concentration would go up quickly and this would have major impact on the greenhouse effect. The other nitrogen compounds are important for a variety of reasons, because they for example are reservoirs for NO and NO\textsubscript{2}; nitric acid is involved in acid rain. These species are also important nutrients.

The various sulfur species also are interesting. Over the oceans there are theories that cloud formation is limited by the number of condensation nuclei, and these nuclei come from the ocean first in the form of dimethyl-sulfide which can be oxidized to SO\textsubscript{2} and then on to sulfate, providing the important nuclei. You can, without changing the liquid water content, change the size number distribution and therefore the radiative properties of the clouds. That feeds back into climate, and maybe there is also a biological feedback. Thus these sulfur species are very important in global climate, and of course are involved in acid rain where sulfuric acid is about 2/3 of the total acid in the atmosphere.

We are very concerned about a variety of carbon-containing species including methane, carbon dioxide, and formaldehyde, because they have an active photochemistry, or they are greenhouse gases, or both. Molecular hydrogen can be measured relatively easily, but some of these hydrogen-containing radicals are extremely difficult to measure; there are enormous projects that have been working for many years and are just beginning to bear fruit. We are beginning to be able to measure OH on the ground, and would like to be able to measure it on an aircraft as well. H\textsubscript{2}O\textsubscript{2}, produced when two hydroperoxy radicals get together, is important in acid rain.

In addition to the species themselves, we would like to be able to measure the radiation that is important in atmospheric chemistry. Many of the reactions going on in the atmosphere are driven by sunlight.

We’d like to be able to do some remote sensing; ozone is already being done via DIAL in which ozone can be measured a few km away from the airplane (at NASA-Langley).

Halogen-containing compounds are important. It has been demonstrated that chlorine is the culprit in the Antarctic ozone hole, and we need to pay attention to the chlorine compounds in the atmosphere, their sources and sinks and budget.
There are a number of instruments that have responses fast enough to look at fluxes in the atmosphere. We have already heard about ozone, but there are techniques for measuring CO and CO\textsubscript{2} and a variety of other compounds that either now or in the near future will have a response of 1–10 Hz so we can start looking at fluxes.

It is difficult to talk about the needs because there are so many molecules we need to measure that we know so little about. The big problem is that you can buy instruments to measure say NO, SO\textsubscript{2}, or nearly any of the compounds we are talking about, but the commercial instruments are designed for use in urban areas so their sensitivity is not high enough. Most of the excitement in atmospheric chemistry is in the more remote areas of the atmosphere and the interaction between urban and remote atmospheres. If you put one of these commercial instruments on an aircraft you can’t fly it in the boundary layer low enough over an urban area. So the instruments don’t provide useable sensitivity, and instrument development is needed.

The atmospheric chemistry community needs continued improvement in the fast response winds, for example, and in fast and highly sensitive water measurements — dew points down to \(-85^\circ\text{C}\) — because we would like to look at stratospheric-tropospheric exchange. Water can be considered a useful tracer because there is much more in the troposphere than in the stratosphere. The mixing ratio in the stratosphere is about 5 ppm by volume, which makes it a trace gas and you have to be careful how you do your analytical chemistry on something that has a concentration that low.

The whole area of cloud chemistry is just beginning to be investigated. There are reactions strictly in the gas phase that are different inside clouds and outside clouds. There are reactions that are strictly aqueous phase, and there are reactions that are heterogeneous, going from the gas phase to the liquid phase; we need to investigate each of these different processes in much more detail. There is a great need for instrumentation, of many varieties. Brian Heikes has been working on these problems, and may talk about them later on.

The most important thing we need before we can do atmospheric chemistry better on any aircraft is, we have to have better aircraft. We need improved payload, range, maximum altitude, and internal volume over that currently available. The Electra is big enough but has range that is sometimes inadequate and payload that is sometimes limiting. The most important thing, in my personal opinion, is that in order to make progress on this kind of joint project between universities and NCAR we need more chemists and chemical technicians on the NCAR staff. Currently they have 1/2 a person, 1/2 of Greg Kok. If half of the atmospheric chemistry community starts to ask him for help he will be swamped.

In regard to planning, we need money to do this, and the FY89 NSF budget is bleak. University people can go directly to NSF, where there is some support for instrumentation, and I think we should consider other agencies such as EPA and DOE who have been given funds to help support experiments on climate and climate change and the effects of climate.
DISCUSSION AND COMMENTS:

Q: (Hallett) Is the need for improve sensitivity going to be met by manufacturers of the instruments, or will we in the atmospheric science community have to meet that need?

A: It is rare that you can buy an off-the-shelf instrument for use in remote atmospheres and get useful instruments. Ozone and, to a limited extent, CO, are the only exceptions. People like Brian Ridley are working on NO and have been for years.

Q: (Taylor) Of the three possible locations where instruments are developed, universities, industry, and government labs, how would you characterize chemistry instrumentation in terms of relative effort?

A: There are companies like Aerodyne (fast methane) and Thermo-Electron, but they don’t develop sensitive instruments on their own. Certainly NOAA and Brookhaven have been active, especially in cloud chemistry. A rough guess would be 45, 45, and 10% for university, government, and industry.

Q: (Smith) You focused heavily on RAF in your comments. It seems that this is an area where bringing together instruments from a variety of sources could produce a pool of chemical instrumentation. We won’t always work in the mode where each investigator brings his own instrument. That will be done in the initial phases, but there will be a phase where a single PI will be able to get several of these instruments after they have been developed further, and that is the phase we need some structure for. How do we get these instruments, after they have gone through their first years of development and the PI has gotten his primary payoff in terms of publications and research, merged into a stronger community effort?

A: That is certainly something that needs to be done, that is for chemists to turn over their instruments for people to use. It hasn’t happened very much so far. I think mostly because the most interesting compounds in the atmosphere are very difficult to measure. We’re moving in that direction, and that should be encouraged.

Q: (Delany) Industrial labs are quite prepared to make instruments like, for example, a 100 ppt nitrous oxide instrument, but they won’t unless the market is about $1M. There are several instruments in that category. The technology exists because university and agency scientists have worked them out, but there is no commercial market to justify commercial production. There is a need for, perhaps tens of instruments, while the commercial companies need markets of hundreds of instruments.

Q: (Grossman) To what degree do atmospheric chemistry departments interact with atmospheric science departments in development of these types of instruments? There may be a level of expertise there that can help.

A: A lot of that happens. Many of the atmospheric chemists are in chemistry departments, Alan Bandy for example. A problem is that it seems that a vast majority of the traditional meteorological effort is not directed toward observational work. “Data” is
what comes from balloons and sondes and they don’t really care about making observations. In chemistry, there is perhaps a tendency in the opposite direction.

2) WORKING GROUP DISCUSSIONS AND RECOMMENDATIONS

A comprehensive survey on atmospheric chemistry instrumentation capabilities and needs was published in 1984 by a panel on Global Tropospheric Chemistry representing the National Academy of Science and the National Research Council. This comprehensive review was thought to be sufficiently current that no discussion was undertaken on new instrument design needs.

A wide variety of analytical instruments are currently available from commercial manufacturers. With very few exceptions, these instruments are oriented toward pollution sampling, and have detection limits that are not suitable for measurements in rural or remote regions. Other analytical instrumentation and techniques have been developed in research laboratories that have sufficient detection limits for measurement in remote areas. As this instrumentation develops to the nearly routine operational capability it should be incorporated as part of the state parameter capability on aircraft. Examples of this type of species which could soon be measured on a routine basis are NO, NO\textsubscript{y}, and PAN.

Measurement instruments that have reached routine status and that would be useful from aircraft include O\textsubscript{3}, CO, C\textsubscript{1–C}\textsubscript{5} hydrocarbons and filter-pack sampling for HNO\textsubscript{3}, SO\textsubscript{2}, SO\textsubscript{4}\textsuperscript{2–}, and NO\textsubscript{3}–. This would provide a suite of basic measurements that would form the basis on which investigators could build a measurement program.

Inlet systems for the measurement of gas-phase species need more research. The inlet needs to be considered as an integral part of the analytical instrument. The development and characterization of inlet systems is an area where multidisciplinary collaboration would be helpful. In addition to the chemical measurements, considerable input is needed on flow dynamics.

Chemistry studies from aircraft have historically focussed on sampling for acid rain or photochemical-cycle experiments. These types of experiments will continue to be performed, however chemical experiments will move in the direction of chemical exchange studies from both the boundary layer region and from the stratosphere. This is going to require tracing the movement of species with both natural and injected tracer chemicals. Injected tracers have been heavily used by cloud physicists for a number of years. A major difficulty in working with any tracer measurement is that the speed of the measurement needs to be made at a rate commensurate with the process being studied. To study dynamics, measurements will need to be made at approximately 10 Hz.

A difficulty with the use of natural tracers, H\textsubscript{2}O, O\textsubscript{3}, CO and CO\textsubscript{2}, is that many of the analytical instruments do not have sufficient response time or resolution to detect

\footnote{Global Tropospheric Chemistry: A Plan for Action, NAS Press 1984.}
the small differences in concentration. Considerable use has been made of the fast \( \text{O}_3 \) measurement with an NO-chemiluminescence system and this unit can be considered reasonably routine. Potential exists for exploiting other chemiluminescent reactions to be used for fast measurements. A difficulty in the use of injected tracers is that tracer release dynamics can distort the results. The development of more instruments with a response time of 1–10 Hz will be of use to many in the atmospheric sciences community. The availability of more fast \( \text{O}_3 \) instruments was felt to have high priority.

The measurement of a true actinometric flux in the ultraviolet is reasonably easy. These measurements have been made for both \( \text{O}_3 \) and \( \text{NO}_2 \) from aircraft. More studies need to be done in cloud regions to help define radiative properties and photochemical potential of cloud systems. In cloud physics and radiative transfer the emphasis shifts to the visible and infrared portions of the spectrum where no chemical actinometers have been developed.

Only a limited number of chemical measurements have been made using remote sensing techniques. The UV-DIAL is the most successful chemical remote sensing instrument presently in use. The use of remote sensors will never replace the need for \textit{in situ} chemical measurements, but they can provide a broad spatial measurement for certain species of interest. An area of remote sensing which will be important to atmospheric chemists in the future is the remote measurement of surface vegetation and productivity. Emissions from grasslands, forests, and oceans all feed into gas-phase chemistry and will become increasingly important in the future. The development of remote surface productivity sensors should be a high priority as it will benefit several disciplines.

A cooperative effort on utilizing space available on research aircraft would be of significant use to atmospheric chemists. Frequently large aircraft are utilized as observational platforms and much of the cabin space is vacant. The use of this aircraft time for chemical measurements could prove useful for both the chemistry community and the investigators using the meteorological data. At this point there is no effective mechanism for sharing information on available aircraft space.

The gas-phase chemistry working group supported the recommendation of the 1987 RAF fleet planning workshop (Johnson and Cooper, 1988) for the acquisition of a mid-size jet aircraft.

The chemistry of the atmosphere is one of the newest and most rapidly growing areas of atmospheric science. The unique position occupied by the National Center for Atmospheric Research makes it particularly important for the Atmospheric Technology Division to enhance its scientific expertise in air chemistry by adding staff in this field.
h. Aerosols

1) POSITION PAPER – Barry Huebert

Only a small fraction of the atmospheric chemistry community worries about aerosols. Aerosols have traditionally been the fourth stepchild of atmospheric chemistry for a variety of reasons, among which is that you can measure good rate constants for gas-phase reactions but when you start involving surfaces everything gets much more difficult. Surfaces are hard to characterize and get contaminated easily, so heterogeneous chemistry has in general been much more difficult to study and to put into a form where you can make the same kind of predictions that you can for gas-phase chemistry. And yet there are a lot of problems that involve aerosols that need to be studied.

I thought I would start by mentioning a few of the directions where we need to make progress so we can then discuss what instrumentation might be useful.

The first is to learn something about the sources and sinks and chemistry of aerosols. Where do they come from, and where do they go? There are difficult problems to be studied in terms of the nucleation of new aerosol, similar to problems that cloud physicists may worry about. The growth of aerosols via gas-to-particle conversion turns out to be something that makes aerosol measurements very difficult. It is not only something you want to study but also something that is a continual problem because aerosols frequently are in equilibrium with the material in the gas phase and there are significant problems in trying to sample the liquid or solid phase material without evaporating some of it or permitting additional condensation. Those gas-to-particle conversion processes need a lot of study. Aerosols are scavenged from the atmosphere by a variety of wet and dry processes, and many of them are involved in the nucleation of cloud droplets and are ultimately removed from the atmosphere by scavenging of that type. The deposition of aerosols by wet and dry processes is something that is very poorly characterized. Dry deposition, for instance, is a strong function of the size of the aerosol and the nature of the receiving surfaces. None of these processes that are described here in this first section are very well understood. That may be part of the reason why chemists have tended to study the relatively simpler problems that involve only one phase.

It is important to study the aerosols, however, because they have effects on a variety of other processes. Aerosols are involved in the nucleation of cloud droplets, and those CCN have effects that are dependent on the chemical nature and size of the aerosols. In order to be able to make statements about how much the cloudiness might change if the DMS coming out of the ocean were decreased as a result of some calamity that killed off that particular phytoplankton, in order to understand processes like that and be able to make predictions we need to know a lot more about how the chemical composition of aerosols affects their ability to serve as CCN. They are also involved directly in the radiation balance of the earth, not only in their involvement in clouds and the reflectivity of clouds, but also because the aerosols themselves are able to scatter radiation. Finally, those aerosols can have various effects on nutrients and toxicity that affect ecosystems.
Many university chemists are studying how nutrients enter the open ocean. Iron, for instance, transported in the form of mineral aerosol in the atmosphere, may turn out to be a limiting nutrient. Those processes that involve the transport and deposition of aerosols can be very important in the study of biological processes of that type.

A third reason for wanting to look at aerosols is the value they have in studying source apportionment. Scientists collect a large sample of air, look at a large number of elements in that air, and from the elemental composition can identify the sources of the aerosols. Aerosols thus can provide an air-mass tracer. A good example is the use of Beryllium-7 in aerosols to identify air which has recently been in the stratosphere, or the use of stable lead isotopes to identify air masses which have come from the North American continent rather than the Asian continent. There are many situations where, by studying the aerosols, we can learn something about the history of the air mass.

I want to talk about several techniques that are needed, and I suggest we think about the relative importance of having NCAR/RAF handle certain tasks and outside investigators handle certain tasks. It is not a foregone conclusion that any technique that is brought to the pretty routine stage should therefore become the responsibility of the RAF to maintain. There are, for instance, inlet systems for which individual investigators are going to be fanatic about wanting Teflon coating, or not Teflon coating, or no more than a certain bend, or a certain diameter; there are systems like that for which the individual investigators will want to have their own specifications for those systems. They therefore should maintain them themselves, even though in determining the aerodynamics of those systems they could use help from, e.g., the RAF. There may be other systems such as the PMS probes for which it doesn't make sense for a large number of investigators to try to maintain them and keep them tweaked up properly and do the calibrations that are needed to make them really useful; in these cases a facility such as the RAF could really do the best job for the community in keeping those systems operational. So when I talk about what we need, I am not suggesting that all of those must be designed, built, and maintained by the RAF. Rather, we should discuss where the responsibility should lie.

One of the things we need to do is to be able to measure the size number distribution of aerosols – that’s the zero-order problem. There are several things that go into doing that. One is that the optical probes don’t do well when you get down to really small sizes, below a few tenths µm. It may be that you need to use electrodiffusion rather than optical systems for counting the number of aerosols in that size range. But those electrodiffusion instruments don’t work well at the larger sizes. So there needs to be a hybrid system available in which some combination of these techniques is used to get a good size distribution.

Often, simply knowing the size distribution is not enough. I was pleased this morning to hear a cloud physicist emphasize the need to know the chemical composition of aerosols. Sometimes you need to know what exactly are those particles. One very useful technique is the cascade impactor which will permit you to look at the mass and bring back samples for analysis in each of several size ranges. Cascade impactors have been around for a long time.
and yet it is very difficult to use those on an aircraft because there are serious sampling problems involved. If you are to do isokinetic sampling so that you don’t inertially exclude certain size ranges or enhance others, then for a cascade impactor having a 1–5 L/min sample rate you need to have an extremely small hole to let the air through. We need to develop some systems, decelerators or manifolds, or something, which will slow the outside air so that it can be sampled by cascade impactors and other low-flow measuring systems with a lesser probability of artifacts. There are serious problems with trying to plumb aerosols around and to measure from a platform moving at 100 m/s or more.

In March-April, we will fly a program in collaboration with the Aviation Facility to look at inlet systems for aerosols. A lot of people have gone up in an airplane with a curved pipe that goes from the outside of the airplane to the inside of the airplane and have put a filter at the end of that pipe and have brought back aerosols that they collected on that filter claiming to relate those to what is in the atmosphere. (I myself am guilty of that crime many times.) What we recently learned on the FIRE program is that most of the standard aerosol inlet systems that bring flow rates on the order of 250 L/min through a 1 inch pipe are likely to lose a large fraction of the aerosols in that pipe going around the corner. The unfortunate conclusion is that much of the data that many of us have published on aerosols is questionable. We are going out in March-April on the Electra to fly in both continental and maritime regimes, and look at a variety of geometries, some that have no curved tube ahead of them, some with a narrow tube, various radii of curvature, etc., to determine what is the best way to get an aerosol sample to the aircraft without changing that sample. This is the kind of problem that is an ideal one on which a university investigator can work with the RAF. It is appropriate for the RAF to be involved because, presumably, the results will be used by a large fraction of the community, those people who want to collect samples of aerosols. And yet the fact that the RAF is helping us to develop this knowledge base doesn’t mean that they should have a suite of inlet systems so that every person who comes to the facility can have just what he wants without having to make it himself.

This is a pretty plebian one, but: We need suction. Those people who study aerosols have traditionally been hated by those who install equipment on aircraft, because we require so much weight and power and create heat and unpleasant noises by the large pumps that we have to use to do those experiments. The RAF is installing an engine-driven venturi system which will help for some of our high-volume sampling applications. But there are a lot of other problems, particularly those that involve the elemental signatures, that people have never been able to attack from aircraft. Bill Zoller showed up for a NASA program with a pump that was very large, and they encouraged him to stay home. In order to do those experiments in which you are looking for elemental signatures or for particular signatures such as Beryllium-7 or Pb-210, those studies require extremely large samples of air, and traditionally we haven’t been able to do those from aircraft. If it is possible to develop some sort of engine-driven venturi system that will make it possible to collect 100 m$^3$ of air or more through a filter, that would be extremely valuable and is worth some attention.
Finally, again, dealing with the interface between atmospheric chemistry and cloud physics, there are many of us who study not only aerosols but also cloud droplets, and are at a loss for being able to determine exactly where it is that we can get a good sample. Where should we locate our sensors on the Electra, e.g., to avoid problems of shadowing or enhancement or other effects due to the presence of the aircraft? That is an area where the RAF can be extremely useful. I am grateful for the work that has been done to date in modeling airflow around the aircraft, but I would suggest that it would be valuable to go even further and make some measurements, e.g., of droplet distributions as a function of distance from the aircraft, so that we can gain some confidence that what we are measuring from the aircraft is really representative of what is present in the cloud. And that is an area where, I think, many of the chemists are totally at a loss. We don’t know how to approach the problem, except to realize that there is a problem. The expertise in aerodynamics at the Aviation Facility can be very helpful to us here.

DISCUSSION AND COMMENTS:

Q: (Vonnegut) I think it is worth mentioning the strong interaction between atmospheric aerosols and atmospheric electricity. We have seen changes of an order of magnitude in conductivity caused by heavy aerosol loading, so aerosols are of great concern to us in fair-weather atmospheric electricity measurements. I think that, in turn, measurements of atmospheric electricity can be of use to those studying aerosols, because one can make measurements of the electric field and the conductivity from an airplane in real time. At the meeting at Upsala on atmospheric electricity, there was a Dutch paper in which they showed how they were seeking out plumes for aerosol measurements by atmospheric electrical measurements. They were able to do this at night. A conductivity sensor is a simple device that should be of considerable use.

Q (Vali): It might be worth focusing on the collection of cloud and precipitation samples. This deserves considerable discussion.

A: Agreed. The RAF has been very helpful in our work to date in looking at slotted rods for cloud water collection. They have a student working there now on the CVI technique. I think that the problems of collecting cloud water, especially in size-sorted samples, needs considerable attention.

2) WORKING GROUP DISCUSSIONS AND RECOMMENDATIONS

Much of this group’s time was spent discussing the status of aerosol instrumentation currently in use at institutions with aircraft (primarily RAF), focusing on problems users had encountered and how they might be solved. Four major areas of discussion were inlet and sampling technology, airflow effects, particle size distributions, and chemical measurements. Several “high priority” needs for improvements which were perceived to be
universally beneficial were agreed upon by the group. Some strategies were then suggested for meeting these instrumentation needs in a cooperative manner.

(a) **Strengths and weaknesses of current instrumentation**

Regardless of the type of instrument which is used to actually analyze aerosol particles, the first task is to obtain a sample which is artifact-free and representative of the ambient atmosphere outside the aircraft. Aerosol impaction and diffusion in inlet lines, flow rate limitations which prevent isokinetic sampling, pressure differentials between the atmosphere and the cabin, and electrostatic and temperature effects all may distort the aerosol distribution before it is measured or analyzed. Ideally, to avoid misleading or meaningless results, inlets would be carefully designed and materials chosen for the specific needs and conditions of each experiment. Most of the group felt, however, they did not have enough expertise in inlet technology and/or enough time prior to an experiment to do this job consistently and properly. It was generally felt that it would be worthwhile and convenient if several inlets (or inlet designs) were routinely available for different sampling needs. A sampling system which would allow an investigator to obtain large sample volumes in a relatively short time period was another related need, especially for aerosol chemistry and tracer studies. Some progress in the high-volume capability has been made with the NCAR Electra’s new venturi sampling system, and inlet comparison studies are planned for early in 1989 on the Electra.

Another area in which progress was deemed necessary was in the assessment of the effects of the aircraft and/or its velocity on measurement results (for both aerosol particles and liquid water or ice). Questions regarding orientation of sampling inlets and external instruments (such as how far from the fuselage? in what direction? how far back?) are currently very difficult to answer since little is known about the airflow around most of the aircraft. In many cases, inertial and turbulent effects influence collection efficiency for certain particle sizes, and processes such as dynamic heating may affect other instrument characteristics. It was felt that both modeling and experimental studies are needed to gain the knowledge with which to attack these problems.

Although certain portions of the aerosol particle size spectrum are currently measured fairly accurately, it was felt that measurement in the lower size ranges (\(< 0.5 \mu m\) diameter) by aircraft is somewhat deficient. PMS instruments (specifically the ASASP) which measure some smaller particles are generally noisy in their lowest channels. In addition, particle distortion, loss, or chemical changes within the internal cavity may affect the apparent size distribution. It was felt that more effort to make the ASASP quantitatively reliable is certainly worthwhile, but that because of their limitations, PMS probes alone should not be relied upon to measure the entire spectrum of atmospheric particles. In most cases the majority of particles (by number) are actually smaller in size than the ones the ASASP can detect, and these smaller particles play important roles in cloud physics and chemistry. More aircraft experimentation with instruments such as CN and CCN counters, diffusion batteries, electrical mobility analyzers, and UV-diode lasers is needed to learn
more about the smaller aerosol particles. Inside clouds, the collection and measurement of interstitial aerosol particles is also worthy of investigation.

The chemistry of aerosol particles is important in a variety of areas, such as radiation and cloud chemistry, and therefore should be studied with the continually improving analytical techniques which are now available. Much interest was expressed in developing capabilities for in situ chemical analysis of single particles and in determining the chemical properties of both aerosol particles and cloud droplets as a function of their size. Techniques for these types of analyses do exist, although aircraft use of most of them presently is limited. Laser techniques for in situ chemical analysis, and particle size-segregation techniques, such as the cascade impactor for aerosol particles and the counterflow virtual impactor (CVI) for cloud droplets, were specifically discussed. The use of tracers such as Beryllium-7, the study of ice nuclei, new types of cloud water collectors, and a “grab sample” capability were also considered to be areas for potential instrumentation development.

(b) High-priority instrument development needs

Several high-priority items were identified by the group. First, inlet systems need to be improved in order to secure a representative sample for any further analysis. Inlets with a variety of designs and materials should be characterized, and the results of these studies (and possibly some of the inlets themselves) should be available to meet specific experimental needs. More effort also is needed to provide for efficient, higher volume sampling systems, using, for example, alternate vacuum sources and pressurized sampling manifolds.

Another area to pursue is the modeling and characterization of the airflow around each research aircraft. Although computer models will provide a good initial information base, it was strongly felt that experimental verification of models would also be required. An example of this type of experiment would be to examine the variation in response of a liquid water or PMS probe at different distances from and locations on the aircraft fuselage.

Calibration and improvement in the response of the optical probes, particularly the ASASP, is considered to be very important as a first step in improving our measurements of aerosol size distributions. Calibration techniques which utilize realistic aerosol particles (rather than only glass beads or latex spheres) and include number as well as size verification are hoped for. Appropriate instruments (such as those mentioned earlier) which measure in smaller particle size ranges should be added to current capabilities.

The final high priority development need is the ability to determine chemical composition as a function of size, for both aerosol particles and cloud droplets. This capability should ultimately provide important insight into cloud physics, cloud chemistry, and radiation as well as aerosol physics and chemistry. Instruments that separate by size are already available and experiments which test their suitability and usefulness on aircraft should be conducted.
(c) **Strategies**

We feel that collaborative projects will be the most useful in achieving progress in the above areas. Working together will not only pool our expertise and improve the overall quality of our work, but will assure that we utilize effort already expended in these areas and avoid working separately along parallel paths. One way suggested to promote collaboration was to hold workshops, perhaps coordinated by NCAR, in specific high priority areas to allow for the exchange of ideas, experiment planning, and instrumental comparisons. Another idea which might encourage collaboration would be to inform the interested scientific community of specific research projects in which they could effectively participate (e.g., if an aircraft was not being fully utilized by a principal investigator).

The aerosol group also feels that publishing the priorities set in this workshop and making them widely available to funding agencies should help to achieve our goals. Emphasis should be put on the fact that although experimental work is “high risk” in terms of money and time, the potential payoffs, in terms of scientific developments and achievements, are in fact, just as high.

(d) **Conclusions and recommendations**

In summary, the recommendations of this group are to improve aerosol measurement capabilities in the following ways:

**INLET AND SAMPLING TECHNOLOGY**

- Define and characterize a variety of inlet types (of different designs, sizes, and materials) which allow representative, artifact-free sampling of aerosols for specific needs (for example, certain particle sizes, particle compositions, or flow rates).

- Develop technology to obtain large samples efficiently, using, for example, engine-driven venturi systems like that on the NCAR Electra.

**AERODYNAMIC MODELING AND EXPERIMENTS**

- Use computer models to predict the airflow characteristics around each aircraft.

- Verify the results and further characterize airflow effects by conducting appropriate experiments.

**SIZE DISTRIBUTION MEASUREMENTS**

- Improve the response and accuracy of the ASASP, especially in the smaller size categories (<0.5 µm diameter). Develop improved calibration procedures.

- Investigate suitability of instruments which measure particles smaller than about 0.3 µm in diameter for aircraft. Suggestions include CN and CCN counters, diffusion batteries, and electrical mobility analyzers.
CHEMICAL COMPOSITION AS A FUNCTION OF PARTICLE SIZE

- Design experiments to determine the chemical composition of aerosol particles of different sizes. Utilize existing separation techniques (e.g., cascade impactor) and explore new possibilities for separation and analysis.

- Investigate composition of cloud droplets as a function of their size, using existing techniques (e.g., counterflow virtual impactor) and exploring new possibilities for separation and analysis.

Strategies which the group felt would be useful were to publish these priorities to provide leverage with funding agencies, and to convene small group workshops to plan projects in more detail.

i. Deployable sensors

1) POSITION PAPER – John Bane

I was asked to give a presentation on aircraft-deployable sensors for atmospheric and oceanic research, which I have reduced in scope to an emphasis on oceanic research. Vin Lally will represent dropsonde capabilities, esp. the new L²D² (Lightweight Loran Digital Dropwindsonde). The first major use of this new sonde will be in the ERICA project this winter.

In oceanic research, there are only a few researchers who use aircraft. One reason that there are so few is that there are few deployable sensors. My feeling is that if there were more readily-available deployable sensors then more oceanographers would use aircraft. The problem is a circular one in that, so long as oceanographers don’t use aircraft much, they don’t make a good case for development of the sensors they need.

Among existing instruments, the most widely used is the air-dropped expendable bathythermograph (AXBT), a very valuable instrument that still needs improvements. These instruments are manufactured primarily for military use, and there are some variations in capabilities of available sensors. The instrument is deployed from the aircraft in a sonobuoy A-size cannister, parachutes to the sea surface, the cannister floats to the sea surface and drops a probe which profiles through the water and measures the temperature profile in the upper several 100 m of the ocean. The standard probe profiles over 300 m, but there have been some built that extend to 750 m. It is often difficult to obtain the deeper-profiling probes. The temperature accuracy is 0.55°C, but can be easily improved to 0.2°C or better. The improved accuracy is needed, and the depth range needs to be extended to 750 m or more on a routine basis.

The next standard probe for use is oceanography is the Air-dropped Expendable Current Profiler (AXCP), developed primarily by Tom Sanford at the University of Washington. These probes have been used primarily in hurricane studies and studies
of ocean storms. The probe provides a measurement of velocity shear, and so does not provide a true profile but needs some reference value. It covers the upper 1500 m, and costs about $1500; it also provides a temperature profile with accuracy generally better than the AXBT. There was a problem initially with high failure rates upon deployment. The development was promoted by industry representatives, esp. oil companies, for use in hurricanes, and so the probes were dropping through high winds. There have been significant improvements, to 80% success rates in the Ocean Storms program and 90% in recent releases by the University of Wyoming in hurricanes. This probe has uses in oceanography, air-sea-interaction studies, ocean-atmosphere feedback processes, etc.

There are also sound velocity profilers (the AXSV), but they are rarely used in oceanography because it is difficult to obtain a density field from these measurements. They are commonly used for military purposes. There are also many types of current drifters for tracking surface current. The one that is planned for ERICA is manufactured now by a company that developed it in conjunction with a Navy lab. There are also A-size-cannister units that parachute from the plane to the ocean surface and float, measuring their position and atmospheric temperature and pressure and sea temperature. The probes are not very good current followers because they have flotation collars that cause them to extend above the surface. Some have probes that can measure temperature profiles, but this is a relatively new instrument. Other drifters are in use, but are less convenient to deploy from aircraft; an example is the drifter used in TOGA. These are probably better at following the current. Determining the drift is difficult; you need to know effects of waves, the profile over the depth of the probe, etc. The instruments are valuable for their other capabilities, even if the current following characteristics are poor. Data are telemetered, and for ERICA the real-time data handling is being addressed.

Needed instrumentation includes, at the top of the list, the need for an AXCTD (Air-deployed Expendable Conductivity-Temperature-Depth) probe, an instrument that has been under development with joint industry-Navy funding for several years. It is two years behind schedule, but is expected to reach completion about now. This is the most needed new sensor. Temperature and conductivity give salinity and consequently density vs depth in the upper 1200 m. The first time that these are combined with an altimeter on a GPS-equipped aircraft and someone maps an oceanic mesoscale feature synoptically in three dimensions to get surface dynamic topography, the density field and the current field all in one snapshot, everybody will want to do it. That may lead to a change in the way that oceanographers view the need for aircraft and aircraft-deployable instruments.

Other things that are desirable include subsurface light and color profilers that measure in ways that complement the satellite-measured surface features. More work is possible on surface and sub-surface tracked drifters, esp. using GPS for surface drifters and acoustic techniques for sub-surface drifters. One of the needs is for real-time data. Oceanographers are generally far behind the atmospheric science community in developing and using real-time data. The Gulfstream project now underway has been collecting data underwater for two years, and the data will not be retrieved until next summer. Air-deployed sensors provide real-time measurements and so are valuable for such uses. Another instrument
to look for later is air-deployable subsurface-moored instrumentation, which is a difficult engineering task but perhaps feasible. The effort in recovering a moored array by ships is substantial, and the main reason is to recover the data; the instruments may be expendable in this context. If it is possible to deploy expendable moored instrumentation, it will be very useful.

In addition to the need for money and ideas, there is a need for time in instrument development. I support the discussion of the NCAR-university collaborations in development of instrumentation. The problem with instrument development, at least in oceanography, is that you won’t succeed well at NSF in competition with science projects because you can’t guarantee you can perfect an instrument in 3–5 y, the normal science project time scale. It is difficult for an instrument developer to operate under those ground rules. For a university investigator to undertake development, there has to be some top-down influence on that so the funding agency recognizes the time needed to develop a new instrument.

QUESTIONS AND DISCUSSION:

Q: Is it conceivable to use tethered instruments from an aircraft, that is, dragged along?

A: This is an option for a very expensive instrument that can be lowered and raised, esp. from helicopters.

Q: Are there deployable biological sensors? Perhaps a light-sensitive device could be useful to biologists?

A: By measuring several wavelengths, generally in the visible range, you can get indications of biological activity.

Q: Why were aircraft-borne remote sensors not discussed?

A: That wasn’t the topic I was asked to talk about, but there are a set of useful instruments including scatterometers, etc.
3. Workshop summary, conclusions, and recommendations

a. Summary of needed measurements

Many measurement needs were identified and discussed in the preceding reports from the working groups, and in many cases there were duplications in expressed needs from different groups. This section of the report contains a compilation of needs that were supported by most of the participants. Where possible, specific plans discussed at the workshop are summarized.

1) There was strong support for continued and expanded exploitation of remote-sensing techniques now available or feasible for use on aircraft. Specific instruments discussed as having high potential for immediate development were millimeter-wavelength Doppler radar, passive radiometry for measurement of temperature profiles, and a simple backscatter lidar for studies of the height of the mixed layer, the structure of cirrus clouds, and other phenomena where backscattered intensity (perhaps in two polarizations) provides useful information. The scientific justification is based on the potential for improving the coverage or “dimensionality” of the measurements, which will lead to entirely new ways of conducting research using aircraft. The problem of representativeness of measurements for such uses as calculation of boundary-layer fluxes is a serious one that can only be addressed through fundamental changes in coverage of the measurements, because it arises from statistical considerations. Remote sensors are also needed to probe those regions that the aircraft cannot enter (because they are too low, or too near a mountain, or in locations too dangerous for the aircraft to penetrate).

1a). Millimeter-wavelength radar. There was strong interest in the development of a millimeter-wavelength radar for studies such as the fine-scale structure of clouds, the structure of turbulence, entrainment processes, first-ice formation, etc. This is an area where technology is available that is suitable for use on an aircraft of either Electra or King Air size. There is strong interest among the cloud physics community, and there are experienced specialists who can provide the engineering expertise. This development was one that appeared to provide the potential for a strong collaborative effort. Scientists from the Universities of Nevada, Wyoming, and Massachusetts and from NCAR are pursuing these plans.

1b). Aerosol-profiling lidar. There were several discussions of ways in which a simple backscatter lidar could be developed for use on NCAR aircraft. The technology for this instrument has been available for a decade, and such an instrument would have wide use. There are potential collaborations with universities or with other agencies that could be used to provide this capability for NSF-supported investigators.

2) There was general agreement that there is a need for improved measurement of horizontal and vertical wind, temperature (esp. in cloud), and humidity (at high levels, or in clouds, or in the boundary layer). Some expressed their needs for wind measurements having accuracies of 0.1 m/s (horizontal) and 0.01 m/s (vertical). It appeared that there is a possible route to achieving substantial improvement, through development of a new system
that would be based on the Global Positioning System (and an inertial navigation system) for aircraft motion and on a remote-sensing laser-based gust system for detection of air motion relative to the aircraft. Measurement of in-cloud temperature remains a need, and could be approached through more thorough exploration of the radiometric thermometers, design of better housings for in situ sensors, and development of an intentionally-wetted sensor for use in cloud. The need for improved measurements of humidity (at high altitudes, or in cloud, or in the boundary layer) was stressed; this is a limiting factor in current studies in many different fields. There was strong sentiment for an approach that features improvement in all the basic parameters, because they are all linked together in calculations of parameters of interest such as wind or equivalent potential temperature.

3) In regard to hydrometeor size distributions, substantial upgrades to the PMS probe capabilities are needed and are feasible. Among the improvements needed would be to improve the electronic response times of the circuits and to minimize the effects of the variations in beam intensity. Other methods (e.g., holography, or large-aperture probes for improved sample volume) would also be useful. Ice-water discrimination remains a problem at all sizes, but especially for hydrometeors smaller than about 100 \( \mu m \). There is a serious weakness in our ability to measure ice crystals smaller than about 50 \( \mu m \) from an aircraft. Because of the slow response times of the electronic circuitry, most of the PMS probes have only limited and hard-to-interpret ability to detect ice particles of these sizes. This is a problem of critical importance in studies that seek to determine ice origins, or that examine the effects of cirrus clouds on the earth’s radiation balance. There is need for improved accuracy in the measurement of all components contributing to the total water content of clouds. Evaporators should be investigated and developed as a partial solution to this problem, but there are also needs for more accurate measurements of cloud water content and for an instrument that can measure the mass in an ice pellet or other ice hydrometeor.

3a). \textit{Small-ice detection.} The weakness in our ability to detect small ice crystals is one that has several potential solutions, including impaction and video recording, use of replicators, improvements in optical array probes, and development of improved ice detectors based on polarized light. The importance of this problem indicates that one or more of these solutions should be pursued.

3b). \textit{Evaporators.} The evaporator technique for measurement of total water content is one that has not been fully explored in the NSF community, but evaporators are in use on other aircraft (e.g., in Australia and on the NOAA aircraft). This appears to be an instrument that should be investigated as a means of providing better measurement of the total mass of condensed water.

4) There was support for expansion of the set of “standard” instruments available routinely on research aircraft, and some measurements of chemical species were leading candidates (\( O_3 \), condensation nuclei, CO, radiometers, etc.). In addition, development and calibration of a set of standard instruments to support studies in atmospheric chemistry was favored, and candidates proposed (in addition to the above) were sensors for \( C_1-C_5 \) hydrocarbons, and filter pack capability. The need to measure the flux of chemical
species such as ozone was emphasized, and such measurements were considered valuable in many other studies where ozone may serve as a tracer. The workshop worried that the fast-response ozone sensor operated by Dick Pearson would become unavailable to the NSF community now that he has moved to NASA. This measurement was considered to be an example of capabilities that should be expanded, not lost; other candidates for high-rate measurements are CO$_2$, CO, and tracers like SF$_6$. There was also support for investigation of the potential for remote sensing of chemical species via DIAL or Raman techniques, although the level of interest did not appear to warrant a task-force approach but rather continued exploration of the feasibility and desirability of such systems.

5) The scientific importance of measurements of the radiation spectrum and of aerosols contained in clouds was stressed. The radiation measurements can be made with specialized equipment now available in the community.

6) Better characterization of inlet losses and design criteria for inlets are needed, as is knowledge of the airflow around the aircraft so that inlets and collectors of cloud or rainwater can be located appropriately.

7) To measure ice nuclei, a major scientific and instrument-development effort is needed. The problem of primary ice production remains one of the most important and poorest understood in cloud physics.

8) Airflow distortion has effects that may seriously compromise our ability to measure scalar fluxes such as moisture flux, and this problem needs attention at several levels: airflow modeling, experimental study, and instrument redesign.

9) There is a need to improve upon measurements of the size distribution of aerosols, and especially to determine composition as a function of size for aerosols and also for cloud droplets.

10) In regard to measurements of particle charge and electric field, it was thought that the most important steps are to make existing instruments available on more aircraft and to continue development and improvement of the 2D-charge probe. Conductivity sensors and sensors for measuring total space charge appear to be feasible for aircraft use (and, in the case of conductivity sensors, have been used on aircraft previously). These developments are relatively small-scale projects that could be undertaken now.

11) There are growing needs for aircraft in oceanography that are best met by capabilities to deploy expendable sensors, but there are also remote-sensing opportunities in oceanography.
12) Appendix B contains an unprioritized, comprehensive list of instruments that were discussed at the workshop. In addition, it seems worthwhile to list some ideas that, while perhaps not of universal or even wide interest, are clever and/or unique approaches:

- Dropsondes for measurements such as $O_3$, esp. for use in environments where research aircraft cannot penetrate as for example in severe storms. Other dropsonde measurements may be the best compromise between the need to enter the severe-storm environment and the need to avoid damage to the aircraft and crew.

- Upsondes released from aircraft, which could complete soundings to high altitude in ways that complement dropsondes, and which might also be used for measurements other than the conventional ones.

- Passive radiometry for temperature profiles, where the requirements are much less stringent than for ground-based profiles because the altitude range to be covered can be much less and still be useful.

- The need for a space-charge sensor that could be essentially a Faraday cage and a means of measuring the charge collected.

b. Models for projects, and strategies

It was an underlying theme of all the “strategy” discussions at the workshop that, in some way, these development projects need more involvement on the part of university scientists. Not only is it impractical for NCAR to undertake to do all of these or even more than a few, but also it is unwise for the future of the field. Students and university-based investigators need the close contact with instruments that comes from involvement in development projects such as these. The workshop participants frequently bemoaned the fact that the field seems to have moved too far from its observational base; corrections to that trend must come through the universities and through the students that they educate. Not only for practical reasons, but also for the future health of the field, these projects need to have a strong university connection and in most cases would be best if university-based.

The best projects should link together those with a scientific interest in the applications, those with hardware expertise, students, and representatives of the general community who are interested in making the new capabilities widely available. The flight facilities like NCAR/RAF can play an important role in these developments by providing the link to the broader community, so that development projects are not beneficial only to those conducting the project. Also, the facilities can help represent community needs by encouraging or participating in projects that address needs that the facilities cannot otherwise satisfy.

Some unsuccessful proposals for development projects in the past have been perceived by the community as too specialized to have general benefit, and so they competed poorly in relation to other proposals. There are examples of needed instruments being developed
by several groups simultaneously, in slight variations, where each was inadequately funded and understaffed to conduct a comprehensive project and each is likely to have only local benefit. If, instead, such projects could be conducted collaboratively, with the explicit goal of not only developing the instrument and using it in a scientific project but also of making it available to the community, it should be possible to devote more resources to it and to conduct the development properly. The community stake in the project would be not only in the initial development and use but also in the long-term benefit that would come from continued use and maintenance of the instrument.

The flight facilities should be able to play important roles in these projects, by providing the link to community access and by providing the means of maintenance and continued operation of the instruments after the developers have finished their project and perhaps lost interest. The involvement of the flight facilities in this way would also be an indication that they are offering a commitment to continued operation and that they view the development as being in their long-term interest. Their involvement also ensures that they will be better prepared to assume operation of the instrument when necessary. They can offer assistance through flight testing, aerodynamic consulting, and help in meeting the standards for an instrument that is to be installed on a research airplane. They can also help maintain contact with the developers of the instrument, and can encourage their continued involvement with the instrument.

A number of past projects fit this model. In the case of the electric field mills recently installed on the NCAR King Air, Bill Winn of New Mexico Tech designed and constructed the field mills, but NCAR helped support their construction and installed and tested them on the NCAR King Air. They were then used in a field program for Dr. Winn, after which NCAR retained possession of the mills and has continued to operate them in other programs (with occasional consultation from the developer). In this case, the expertise in a university group was used to form the basis for the development, but NCAR was involved in transferring that capability to the research airplanes where it could benefit the entire community. There are other examples, e.g., in the current joint efforts of NCAR (ACD, ATD, MMM), NASA, and PMS to improve the circuitry in one of the PMS optical scattering probes.

A number of projects discussed during the workshop could fit this model well. The following are some specific examples (not intended to exclude others):

- Studies of airflow distortion. Some preliminary studies of these phenomenon have been conducted at NCAR, but the project is an ideal project for a university graduate student (and his/her advisors) with some experience in aerodynamics. The needed studies can be conducted with airflow models that use potential-flow and other solutions for the airflow around an aircraft, but to apply them will require knowledge of the procedures used in making measurements of boundary-layer fluxes and other quantities that may be affected. Some experimental verification of the results is needed, and there will probably need to be redesign of some of the sensors to minimize the effects.
• Development of mm-wavelength radar for inclusion on research aircraft and for the study of cloud microstructure and turbulence. This is an area where engineering groups (e.g., at the University of Massachusetts and the University of Kansas) have developed operational systems, and where there is strong interest in the eventual use of the systems by cloud physicists.

• Development of a backscatter lidar for aerosol profiling. There is expertise in such systems at the University of Wisconsin (and at NASA and elsewhere) that could be the technological basis for development of a system for installation on NCAR or other aircraft, and there is lidar expertise at NCAR (that is presently committed to development of other lidar systems) to support continuing operation, maintenance, and upgrading.

• Development of a laser-based gust probe. Design and feasibility studies for this instrument have been performed at NCAR, and the project can move forward if there is strong scientific interest and involvement from others.

• In the area of electrification, it was learned during and after the workshop that the conductivity sensors developed for use on the NASA aircraft may be available for installation on NCAR aircraft. Also, the space-charge sensor seems to be an appropriate device for development now.

• There are a number of ideas for improvements in in-cloud temperature sensors that can be explored, and this would be a good project in which to have wide involvement so that several different alternatives can be pursued.

• Interest in a total-water evaporator and other instruments needed for improved microphysical observations is shared by a number of cloud-physics groups with strong observational backgrounds, and good collaborative projects could be designed to pursue some of these developments.

• Several university groups have developed experience and expertise in the use of tracer detectors, and those groups could provide the expertise needed to install and begin operating such devices on the NCAR aircraft.

• With the potential loss of the fast-ozone capability from the NSF-based research community, it may be desirable to find ways of preserving, duplicating, or replacing that capability.

• The needs for detectors of small ice crystals are shared by a number of groups having microphysical, radiation, or climate interests, so the various alternatives to approaching this problem could be the basis for other collaborative projects.

This list of possible collaborations is not meant to preclude, hinder, or inhibit the isolated, specialized project justified only for one goal or one planned use. However, mechanisms for those projects seem to be in place. The weakness in the present system seems to be the difficulty in planning and conducting the projects that are broader in
scope and that are designed to serve community needs and interests as well as meet specific scientific goals. If we can improve the methods by which we plan, organize, and conduct such projects, we also should be able to make a better case for them with the funding agencies. Such projects need to be viewed broadly by those who review and consider them, and there is a corresponding need to design them to meet broad needs and generally-accepted priorities. We have an opportunity to use some of the projects proposed in this workshop as examples of ways in which such broad projects can be approached.

During the workshop, it was suggested that perhaps what is needed is a “task-force” approach to the problem of instrumentation. Instead of proceeding with many independent projects each seeking to develop and justify the need for some new capability, it was suggested that we try to organize these efforts into a coherent program that represents a true initiative, a program that would seek to take a larger step toward advancing efforts in instrument development. Instead of many disjoint proposed projects, we could present a coherent set of programs to be viewed as a major initiative (on the scale, for example, of a moderate-size field program). If the program were organized so as to represent scientific needs and priorities in the field, to incorporate the needed university involvement and the involvement of those with technical expertise, and to provide for transfer of the new capabilities to the community, it would have to be viewed as a high priority for observational atmospheric science.

In developing plans to implement some of the ideas of this workshop, it seems appropriate to give serious consideration to this more ambitious approach and to see if the efforts of the community can fit this model. If so, there may be the basis for an initiative on the scale that is needed to correct for the neglect of these efforts in recent years.
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APPENDIX B: List of Proposed Instruments and Projects

1. Total water evaporator
2. Small-ice detector (e.g., collector with video recording)
3. cloud condensation nucleus counter
4. ice nucleus detectors
5. wet-bulb hygrometer
6. nephelometer
7. radiation spectrometer
8. Raman-scatter spectrometer for water and ice mass
9. tracer detection and perhaps release schemes
10. aerosol-profiling lidar
11. alternate measurements of liquid water content
12. 2D modifications to provide electrical charge
13. aerosol instrumentation to measure full size distribution (mobility analyzers, optical counters, diffusion batteries, etc.)
14. turbulent-structure probes (air motion, droplet spacing, etc.)
15. profiler techniques to provide temperature and perhaps humidity profiles away from the aircraft
16. short-wavelength radar detection of cloud fine structure and turbulence-scale air motions
17. laser air-motion sensing system using intersecting beams and Doppler shift from aerosol particles, and updated via GPS.
18. new housings for temperature probes to avoid wetting
19. upgrades to hydrometeor spectrometers to improve response and sample volume
20. ice-water discrimination and mass based on dielectric constant
21. actinometer (UV)
22. cooled-mirror using liquid nitrogen cooling
23. DIAL techniques for ozone and water profiles
24. C_{1}-C_{5} hydrocarbon monitors
25. filter-pack sampler for HNO_{3}, etc.
26. O_{3} dropsondes
27. biological sensors, *e.g.*, for chlorophyll
28. space-charge detector
29. liquid water content and spectrum from diffraction patterns
30. sensors for electrical conductivity, after Vonnegut.
31. dual-path dual-wavelength version of the Lyman-alpha probe
32. counterflow virtual impactor for study of the size-dependent composition of cloud droplets
33. microwave temperature sounder
34. microwave radiometers for liquid water content
35. holographic system for hydrometeor photography
36. modified dropsondes with new sensors
37. fine-wire probes for high-rate turbulence studies
38. DIAL-alexandrite for water vapor and pressure
39. differential GPS techniques
40. fast methane sensor
41. fast CO_{2} sensor
42. membrane filters for size-sorted collections (NUCLEOPORE)
43. 10.6 \mu m extinction for liquid water content
44. use of bomb-racks to mount special turbulence pod with short lines for high-rate turbulence gust probe
45. flux of heat and moisture remotely from remote sensing of temperature, moisture, and wind by lidar
46. profiling by scanning of a PRT-6 sensor.
47. cascade impactor
48. field-change meter
APPENDIX C: Special Reports

Appendix C1: Boundary Layer Group Report

As part of the NCAR RAF Workshop on Aircraft Instrumentation, a subgroup concerned with instrumentation particular to Boundary Layer (BL) problems met on 21 Oct 86. This subgroup consisted of Bob Grossman–Univ. Colorado (rapporteur), Don Lenschow–NCAR, Peggy LeMone–NCAR, Ed Eloranta–Univ. Wisconsin(Madison), Brian Heikes–Univ. of Rhode Island and Providence Plantations, and Sherman Fredrickson–NOAA/NSSL. In addition the written comments of John Wyngaard–NCAR, Carl Friehe–Univ. Calif. (Irvine), and Roland Stull–Univ. Wisconsin (Madison) were taken into account by the group.

The group was responding to a sense of the general meeting that a coordinated effort was needed within the atmospheric science community to secure proper funding for future aircraft instrumentation. The BL Subgroup felt that a position paper to NSF and other major funding agencies which outlined and prioritized instrumentation needs was necessary and that this would aid in guiding those PI’s interested in submitting proposals with specific needs as well as providing community backing to facilitate the funding of those proposals which obtain good peer reviews.

The group used some guiding principles in their deliberation:

1. It was felt that as we move into the 1990’s and beyond that aircraft would be used more and more to complement ground-based and satellite-based measurements. This integration of aircraft measurements would most likely be enhanced by the use of numerical models.

2. Two major problems face experimenters wishing to use aircraft to obtain atmospheric measurements:

   (a) Since most aircraft measurements are along a line of flight, there is a problem in relating those measurements to area and volume measurements necessary for model initialization and verification as well as aiding in the interpretation of ground-based and satellite-based remotely sensed measurements (which often encompass ground areas or atmospheric volumes). Aircraft experimenters in two recent USA experiments, FIFE and FIRE, are currently grappling with this problem. A related problem within this context was the finding by Lenschow and Stankov (1986) that measurement of BL fluxes may require very long flight legs (or multiple shorter flight legs) to overcome sampling errors. This may be avoided if line flux measurements could be related to area measurements or if the aircraft could be used as a platform for remotely sensed area and volume flux measurements.

   (b) The theoretical work of Wyngaard (1988) indicates that flow distortion around the aircraft may introduce substantial errors in the measurement of wind, scalar
variables, stress, and scalar fluxes if any of the instruments used measure near the skin of the aircraft.

3. Aircraft will be used more and more as platforms for remote sensors rather than for immersion instruments.

4. In a few years, the Global Positioning System (GPS) will be in place and available to update aircraft absolute position in three dimensions.

5. The group felt that instrument needs could be best identified in the context of important areas of research.

With this in mind the following summary will first list the area of research, then the instrumental need or specific problem for which instruments should be developed.

GENERAL (Some will be repeated in specific research areas):

1. Satellite imagery and synoptic maps available in aircraft during flight missions.

2. Telemetry to and from ground during missions (related to 1.), especially during complex experiments using several different types of instrument platforms (ships, radars, satellites, lidars) which are being monitored and controlled from an experiment operations center.

3. Improved airborne radar displays with hard copy capability.

4. Position of aircraft relative to cloud boundaries (base, top, or sides whether in or out of cloud), inversion height ($Z_i$), and ground. Terrain height mapping along aircraft track will be a spin off of this measurement.

5. Profiles of horizontal wind components, temperature, and moisture around aircraft, especially below aircraft when at minimum allowable altitude (nominally 30 to 60 m, depending on conditions).

FLOW DISTORTION PROBLEM: Suggestions for solution

1. Dedicated computational aerodynamics expert at major facilities to work on flow distortion, instrument placement, instrument design, and intake port design.

2. Use national experience in aircraft flow distortion and aircraft boundary layer research (NASA, private industry).

3. Dedicated time on aircraft for experimental investigation of problem.

4. Measurement of horizontal and vertical wind components, temperature, and moisture away from skin of aircraft.
5. Measurement of mixing ratio of scalars rather than absolute densities or concentrations.

**STABLE BOUNDARY LAYER**

1. Fluxes of temperature and momentum using at least 50 samples per second data.
2. Infra-red radiation flux profiles for improved radiation flux divergence measurements.
3. Temperature and moisture profiles near aircraft.
4. Improvement of absolute and relative accuracy of horizontal and vertical wind components, pressure, temperature, and moisture.

**CLOUDY BOUNDARY LAYER (where a cloud layer is considered part of the BL):**

1. Position of aircraft relative to cloud whether in cloud or out of cloud.
3. Improved measurement of liquid water content for liquid water fluxes.
   - measure entire particle size spectrum
   - improve measurement at low liquid water concentrations
4. Consider area or volume sampling of stress and temperature and moisture fluxes which would include several cloud spacings to either side of aircraft. This would improve statistical confidence in cloud flux measurement by including more clouds than those intersected along flight track.
5. Air temperature and total water inside cloud.

**AIR-SEA INTERACTION**

1. Profiles of horizontal wind components, temperature, and moisture above and below aircraft from ocean surface to just above inversion layer.
2. Sea surface characteristics (friction velocity \(u_*\), sea surface temperature, wave spectrum)
3. Characteristics of ocean mixed layer (temperature and salinity profiles to thermocline, surface and mixed layer currents). Need to be able to couple ocean heat budget to BL heat and moisture budgets.
4. Aerodynamic transfer coefficient estimates.
5. If present, characteristics of spray (how much per unit area, drop size distribution).
6. Position of aircraft relative to cloud base, surface, Z_i, inversion level.

7. Characteristics of surface biology (presence of oils or other surface layers, plankton, vegetation).

BOUNDARY LAYER OVER LIVING SURFACE

1. Vertical fluxes of sensible heat, stress, CO_2, HOH, CH_4, DMS, N_2O, and O_3.

2. Surface characteristics (Chlorophyll content, roughness, albedo, leaf area index, surface radiation budget).

BAROCLINIC BL AND BL IN VICINITY OF DISTURBED WEATHER

1. Mesoscale horizontal and vertical wind components, to 0.1 and 0.01 m s^{-1} accuracy, respectively.

2. Improved accuracy of D-values by improving pressure accuracy and resolution, and by improving altitude measurements, especially over land.

3. Aircraft position relative to phenomena (clouds, rain)

4. Vertical and horizontal gradients of wind components, temperature, and moisture along aircraft track.

BOUNDARY LAYER CHEMISTRY

1. Development of improved chemical sensors with higher sampling rate and resolution accuracy so that vertical flux profiles become feasible for budget computation.

2. Aerosol profiles to improve understanding of aerosol effects on chemical reactions.

This list is not intended to be complete or reflect a consensus of the Boundary Layer community but is intended to provide a point of departure for a realistic assessment of needs with the hope that consensus can be reached. Such a consensus will benefit all concerned (“It’s harder to hang us all than to hang us separately”). We hope that this summary of our meeting can be circulated through the BL community in order so that specific, high priority needs can be identified.
Subgroups continued to meet after the working groups to discuss measurements of ice nuclei and of particle charge. In regard to ice nuclei, the following comments are pertinent:

- Laboratory work has demonstrated that ice nuclei are present in the atmosphere in highly variable concentrations.

- Concentrations, in general, increase rapidly with decrease of temperature and increase of relative humidity, particularly near 100% over water.

- To provide realistic input to numerical models, the geographic variability of primary ice nucleation should be included.

- In uniform airmasses mean data taken by filter packs have some utility; limitations are present in these techniques because of lack of time resolution and because simultaneous capture of CCN on IN may alter their surface characteristics.

- Laboratory studies have clearly demonstrated that nucleus activity is influenced by the microphysical history of the nucleus (i.e., whether immersed in a drop prior to cooling, or directly exposed to an ambient supersaturation, or captured by a supercooled drop through Brownian motion), and these processes have a temperature and (to a lesser extent) a time dependence.

- Recent studies and current technology suggest that the time is ripe for a re-examination of the procedures for construction of an aircraft instrument for characterization of the nucleating ability of a given air parcel, bearing in mind that there are a number of different measurements to be made. Results would be applied to the aerosol as it is incorporated into a cloud in different ways.

- Several laboratory ice nucleus instruments have addressed the problem; an airborne CCN spectrometer has demonstrated that current technologies can be successfully applied to such a problem.

In regard to the measurement of particle charge:

- Current technology utilizes an induction ring to measure charge. Recording of this charge is triggered when the particle produces an image in the 2DC probe. These instruments are capable of measuring charge with an accuracy of about 2 pc on particles larger than a few 100 µm.

- Alternatively, charges can be measured in a bigger volume (larger by factors of 10–100), and with accuracies of about 0.1 pc, but must be associated statistically with particle size obtained in a simultaneous measurement but not linked uniquely.
to the particles producing the charge measurements. Real-time read-out, rejecting splashed particles in software, is possible.

- This measurement is important in assessing volume charge and fraction of particles with positive, negative, or “zero” charge. Each measurement is important in assessing any theory of how charge separation occurs, and also in assessing “rogue” lightning discharges that might occur unexpectedly.

Further development of instruments for the measurement of particle charge is given high priority in both cloud physics and atmospheric electricity.
Potential uses for a millimeter-wavelength radar include studies of:

- The structure of turbulent fields.
- Entrainment at cloud boundaries.
- Transport within clouds.
- Location of first ice in clouds.
- Ice advection and diffusion.
- Delineation of cloud boundaries.
- Spatial variability of drop scattering.
- Multi-wavelength mm radar: Possible relation to state parameters.
- Precipitation development.
- Location of precipitation development within cloud.
Appendix C4: Fast Airborne Measurements of Ozone
Tony Delany and Greg Kok

Fast (10-20 Hz) ozone measurements have found a great deal of utility in the disciplines of atmospheric chemistry, cloud physics and meteorology. Projects such as surface deposition fluxes, boundary layer entrainment, pollution dispersion, stratosphere-troposphere mixing, cloud entrainment and the atmospheric chemistry of ozone have all been studied to great advantage with fast ozone measurements. As the availability of this measurement technology increases the use of the measurement will also increase.

Presently the main technique for the fast measurement of ozone is the reaction with nitric oxide in the gas phase. Liquid-phase chemiluminescent reactions also show potential for use as a method to measure ozone with fast response. The technical level of development for the nitric oxide fast ozone technique is such that the instrument can be operated as a standard device on research aircraft.

The capability of the fast ozone measurement technique has been clearly demonstrated and the technology is advanced so that the measurements can be made routinely. Development should continue on new techniques to make this measurement and the existing instrumentation should become part of the normal complement of airborne sensors.
APPENDIX D: Resolution from Heads and Chairmen
REFERENCES


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