N84 27286

APPLICATIONS OF AIRBORNE REMOTE SENSING IN ATMOSPHERIC SCIENCES RESEARCH

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ABSTRACT

This paper explores the potential for airborne remote sensing for atmospheric sciences research. Passive and active techniques from the microwave to visible bands are discussed. It is concluded that technology has progressed sufficiently in several areas that the time is right to develop and operate new remote sensing instruments for use by the community of atmospheric scientists as general purpose tools. Promising candidates include Doppler radar and lidar, infrared short range radiometry, and microwave radiometry.

1. INTRODUCTION

Aircraft have been used profitably in atmospheric sciences research for several decades. The principal advantage of an airborne platform is clearly its mobility, which allows it to sample the atmosphere in regions in and near the weather and in geographical regions around the globe. It has been traditional for researchers to use aircraft to make very high resolution, in situ measurements of air motion, temperature, moisture, cloud particle size distribution, liquid water, hydrometeor phase, trace gases, and aerosols. In situ measurements, while very precise, suffer from at least two significant problems. First, is the fact that measurements made along a given aircraft flight track sample a very small volume of the atmosphere. For example, a particle spectrometer, flown through a cloud, will have a total sampling volume of less than a cubic meter per kilometer of path length. There are therefore significant concerns as to how representative such measurements are of precipitation processes in other regions of a cloud. Even small cumulus congestus encompass a total volume well in excess of 10 m. Secondly, in situ probes are adversely affected by icing and liquid water in clouds and may in certain circumstances become inoperative.

The first of these problems has tended to be mitigated in part by the extensive use of ground-based and satellite remote sensing techniques, which have provided information on the larger scale structures of clouds and precipitation, while the aircraft have concentrated on the microphysical and smaller scale measurements. Contamination of in situ probes by the cloud environment remains a problem.

*The National Center for Atmospheric Research is sponsored by the National Science Foundation.

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There exist several important reasons for incorporating remote sensing techniques to a greater degree on research aircraft. First, is the great emphasis now being placed on mesoscale meteorology as articulated in the documents prepared for a national Stormscale Operational and Research Meteorology (STORM) program in the United States. In order to conduct a true multi-scale investigation, that is, to examine in a definitive way the scale interactions from the meso-alpha to meso-gamma scales, it is essential that instrumental coverage be extended to areas of the size of one-third of the United States. The limited number of research, land-based remote sensors will dictate strongly that more remote sensing be added to research aircraft for adequate three-dimensional observations of the meso-beta and meso-gamma scales. In addition, the mesoscale programs of the future will place greater emphasis on coastal regions, requiring extensive measurement capabilities over the oceans where surface arrays of remote sensors are exceedingly difficult, if not impossible, to deploy.

In a similar vein, it is expected that there will be new thrusts in global and regional atmospheric chemistry and that combining chemistry with meteorological measurements will take on a greater importance than in the past. Global chemistry measurement programs will require long-range flights over the open oceans. In these flights it will be essential to define better the kinematic and thermodynamic properties of the atmosphere through the use of remote sensing. In regional studies related to acid rain, in situ microphysical and aqueous chemical measurements must be augmented by information on the structure and phase of precipitation as well as on the kinematic properties of clouds.

These scientific thrusts clearly point out the need for expanded use of remote sensors on research aircraft. If the potential of airborne remote sensing can be realized, it is possible to conceive of arrays of research aircraft used as highly mobile beta and gamma scale networks, approximating closely the capabilities of the more traditional, but fixed, surface research arrays.

2. STATUS

Appendix A provides a bibliography of papers describing remote sensing techniques that could be deployed from aircraft platforms. Appendix B is a list of remote sensing instruments, available within NASA, which have been constructed and tested to varying degrees. Neither appendix is exhaustive of the state of the art, rather each is illustrative of how much work has been accomplished in the field.

In light of the considerable history of ground-based remote sensing and of the considerable research and development that has been conducted, one can legitimately ask why remote sensing has been so sparsely used in research aircraft to date. The reasons for this are many. Perhaps most significant is the fact that at the present time airborne remote sensing remains in the developmental stage. Consequently, remote sensing tools tend to exist within the domain of specialists (scientists and engineers) whose interests lie primarily with the development and/or demonstration of observational techniques rather than with the interpretation of the data for atmospheric research. This situation is similar to that which existed 15 years ago in the field of Doppler radar meteorology. Doppler radar has now become a widespread research and operational tool for meteorology partly because of major technological advances which took place in the late 1960's and early 1970's. More important, however, was the technology transfer that took place between the radar meteorologists of the late 1960's and the broader community of users. This technology transfer has resulted in widespread acceptance of Doppler radar as a tool for meteorologists who know little or nothing about radar. A similar technology transfer must take place if other remote sensing techniques are to be effectively utilized.

A second reason for the sparse use of remote sensing techniques is the simple fact that most remote sensors have not delivered all of the potential that has been promised. The spatial resolution of passive techniques has been limited. For example, microwave radiometric techniques provide generally unacceptable resolution in the vertical for profiling of temperature and humidity. Aerosol backscattering cross sections have not always been adequate for reliable coherent lidar measurements at all altitudes in the troposphere. Doppler radar use on aircraft has been slow to develop because of uncertainties related to ground clutter contamination through antenna side lobes. The need for compensation for aircraft yaw, pitch, and roll adds complexity and attendant cost to coherent radar or lidar measurements from the airborne platform.

It is also true that many of the developmental remote sensing instruments have not been packaged well for airborne use in that they are heavier, larger, and consume more power than is desirable for many applications. Indeed, it is clear that smaller aircraft, of the class of the NCAR King Air, will be limited in their ability to accommodate many remote sensing instruments. Because of this, larger aircraft such as NASA's Convair 990, NOAA's P-3's, and high altitude aircraft such as the NASA U-2 have been the platforms of choice. The high costs of operating these aircraft have served as impediments to many who would wish to use advanced remote sensing systems for their airborne research. Aircraft have been used for testing these sensors but often times their general purpose use on aircraft platforms has been overlooked. In addition, much remote sensing development has been undertaken for eventual use from satellites.

Despite these impediments, however, the future now is bright for airborne remote sensing. There are many remote sensing techniques, both active and passive, which can contribute substantially to the scientific challenges of the future. Short range, rapid response measurements of temperature, water vapor, liquid water, winds and turbulence are all possible using infrared radiometry, microwave refractometry, and continuous wave Doppler lidar velocimetry. Pulsed Doppler radar systems will make measurements of hydrometeor and wind structure in precipitation. Polarimetric radar techniques will help to determine the three-dimensional structure of precipitation phase and its evolution. Pulsed Doppler lidar methods are needed for measurement of winds and turbulence in regions free of cloud and precipitation. For measurements of liquid water, research is now under way on microwave radiometric techniques for measurement of the three-dimensional structure of the liquid water fields in clouds.

3. SOME PROMISING CANDIDATES

3.1 Microwave Doppler Radar

It is our view that the earliest significant scientific payoff will come from airborne Doppler radar. Mueller and Hildebrand (1983) describe the capabilities of airborne Doppler radar for two- and three-dimensional measurements of air motion in precipitation. This work, a cooperative effort between NOAA and NCAR, has illustrated that properly processed airborne Doppler radar measurements differ only in small detail from those made by ground-based systems and moreover are as physically plausible as are those obtained from the surface radars. Before the end of this decade, we should see improved Doppler radars on both of the NOAA P-3 aircraft, on the NCAR Electra, and on the NCAR King Air. These radars should be designed with adaptability to other aircraft in mind. In particular, there is a great need for down-looking Doppler measurements from high altitude aircraft flying over convective storms. These vertically pointing measurements, when combined with horizontally scanned data from lower altitude aircraft, will permit accurate estimates of the vertical fluxes of mass and moisture in mesoscale convective systems and in tropical cyclones

Aircraft platforms will dictate that some compromises in system performance be made. Wavelengths at X or K band will probably be used which will provide acceptable spatial resolution but which will prohibit quantitative precipitation measurement in heavy rain. Such effects are however mitigated in part by the mobility of the platform. The initial implementation on research aircraft will be single wavelength systems. More sophisticated systems are likely to follow which will provide wavelength and polarization diversity capabilities for more quantitative determination of precipitation phase and evolution.

3.2 Doppler Lidar

Doppler lidar is also ready for deployment from aircraft. While pulsed systems still require development, CW Doppler lidar can be effectively utilized now. Cannel et al. (1983) describe a CW system which has been installed on the Royal Aircraft Establishment (RAE) HS-125 for studies of wind shear. The system has proven to be reliable, accurate, and easy to maintain. Keeler and Serafin (1983) have suggested that a scanning CW system, focused a few meters ahead of an aircraft can be used as a substitute for mechanical three-dimensional gust probes such as that described by Lenschow (1978). The feasibility of the lidar gust probe system is expected to be demonstrated further through test flights in the spring of 1984 in a collaborative effort between the British Royal Signals and Radar Establishment, the RAE, and NCAR. Successful tests will lead to the design and development of a scanning research system for the NCAR aircraft.

The great interest in wind measurements from space as described by Huffaker (1983) is resulting in substantial new development in pulsed CO_2 systems for air motion measurements. Bluectein et al. (1983) have reported on comparisons between wind field measurements obtained by airborne pulsed Doppler lidar and ground-based pulsed Doppler radar. Their results show good agreement between the radial velocity fields but poor correlation in the derived eddy fields. Considerably more research and development is necessary in order to make pulsed systems practical for general purpose use. However, the potential for vector wind field determination in the clear troposphere is so important scientifically that this work is certain to continue to its successful fruition.

3.3 Infrared Radiometric Measurement of In-cloud Temperature

Great difficulties are encountered with present in situ probes for accurate temperature measurements within clouds because of dynamic heating and wetting effects. Reverse flow housings have been designed to inertially separate air and cloud particles; however, these are as yet questionably effective and generate additional problems because of flow turbulence around the sensor element. With proper design, remote radiometric measurements can be obtained in the near-field of the aircraft without suffering these deleterious effects.

Radiometric measurements of temperature in and out of clouds have been made previously in the 15 μm infrared carbon-dioxide rotational band. Recently, Albrecht et al. (1979) have reported on a series of measurements using a moderately narrow band thermistor bolometer detector centered at 14.8 μm. The effective free-air sample path length was of the order of 100-200 meters at lower flight altitudes. Larger sized hydrometeors at nonequilibrium temperatures within the sample volume caused the measured temperature to be weighted in an unknown fashion by precipitation, while cloud particles caused significant sample volume variations for measurements made in clouds. Other errors originate because of temperature variations within the radiometer itself as a result of its exposure to the variable temperature environment of the aircraft at flight altitudes.

These problems at 15 μm wavelengths appear to be eliminated as a result of a 4.3 μm radiometer by Ophir Corporation, Denver, Colorado, being developed under NCAR contract. At 4.3 μm, sapphire optics can be used with negligible emission temperature error at all flight altitudes. A fast response sensitive lead selenide (PbSe) detector can be used, which more than compensates for the lower radiance at 4.3 μm as compared to 15 μm. The sample path length is such that two-thirds of the received energy originates within the first two meters and almost all the energy received is from the first ten meters of sample path. Because few hydrometeors of precipitation size will be present in this restricted sample volume, errors originating from precipitation are negligible. A prototype 4.3 μm radiometer has been flight tested from NCAR's Queen Air research aircraft. The results confirmed that the remote radiometric-measured air temperature is independent of speed (dynamic heating effects) and the presence of cloud (wetting). Construction of the first radiometer for airborne use is planned to occur early in 1984 with flight testing scheduled during September/October of that year. Design accuracies of 0.2°C and a frequency response of at least 10 Hz are expected to be achieved. The successful development of this device will pave the way for a differential absorption technique, in the same wavelength regime, for high frequency humidity measurements.

Two additional variations are worthy of note. First, through selection of different optical narrow-band filters, the radiometer can be shifted to nearby wavelengths which are either out-of-band or on the edge of the band. This provides a means for sensing other parameters. For example, a radiometer operated with a narrow band filter centered on 3.7 μm will operate in an "atmospheric window" and can be used for remote surface temperature measurements (of sea surface, clouds, land surfaces, etc.). This variation is planned for development concurrently with the in-cloud temperature radiometer. Similarly, for either lead selenide or thermistor bolometer detectors, it is possible to "de-tune" the radiometer center wavelength to the edge of the absorption band such that sample path lengths are greatly increased. This allows remote temperature measurements which can be weighted with respect to range. With appropriate scanning in elevation or wavelength, radiometers can therefore be used to obtain temperature profiles above and below the aircraft flight altitude. Such airborne application would be useful for boundary layer and inversion studies. Also, because the sampling range increases with decreasing air density, this application would be useful for studies of tropopause folding at higher flight altitudes. This concept has been used on NASA aircraft.

3.4 Tomographic Radiometric Measurement of Liquid Water in Clouds

A measurement of the emission from a spatial atmospheric distribution of particulates can be particularly useful for the detection and monitoring of parameters such as pollutants or naturally occurring atmospheric distributions, e.g., liquid water content in clouds. If a large number of such measurements along a series of intersecting rays can be utilized, then it is possible to compute the distribution through the use of tomographic mathematical inversion procedures. Such procedures have been in use in geophysical exploration, in radio astronomy, and especially in medicine for over a decade. The technique is applicable for optical or microwave frequencies. Warner et al. (1984) describe a ground-based system.

Jack Warner (NCAR, Boulder, Colorado, USA) and Sean Twomey (University of Arizona, Tucson, Arizona, USA) are collaborating on the development of the tomographic technique using scanning microwave radiometers from aircraft for the remote sensing of liquid water content in clouds. The aircraft radiometers would be mounted to subtend a fixed fore-aft angle such that multiple rays would be provided as the aircraft flies beneath isolated, developing cumulus clouds. Simulations and a field test of ground-based scanning radiometers operating at a wavelength of near 1 cm (K-band) have been carried out, with the result that it appears possible using the tomographic inversion technique to measure the two-dimensional distribution of liquid water content in an isolated cloud to an accuracy of 0.1 gm^{-3} with a spatial resolution of a few hundred meters. In principle, similar results should be obtainable from the aircraft configuration. It should be noted that at the K-band wavelength, the presence of ice particles is nearly invisible because of a greatly reduced emissivity of ice as compared to liquid water. It is also important to note that the method is accurate for drop distributions without appreciable water content in drops greater than 1 mm diameter. Field flight tests are planned for 1985.

3.5 Temperature and Humidity Profiling

While coherent lidar and radar will provide accurate measurements of air motion in the clear air and in precipitation respectively, accurate and high resolution measurements of temperature and moisture remain difficult problems. Radiometric measurements in the oxygen and water vapor bands such as described by Hogg et al. (1983) provide estimates of the profiles of moisture and temperature but with poor resolution in the vertical. However, these techniques may be more useful from aircraft than from fixed surface locations because, although vertical resolution will not be improved, the mobile aircraft platform will permit measurements of the mesoscale variability of temperature and moisture in the horizontal with substantially higher resolution in the horizontal than is available from satellites. The result will be a set of measurements from satellite and aircraft that complement one another by providing both large aerial coverage and high horizontal resolution.

3.6 Incoherent Lidar

Pulsed incoherent lidar is also now suitable for aircraft use. Single wavelength systems can be inexpensive but tend not to be quantitative with respect to detailed properties of the aerosol or molecular backscattering medium. They do however provide important information on boundaries and structure. Single wavelength lidar will therefore be very useful for examining boundary layer height, structure, and evolution, and because of the airborne platform, the mesoscale variability of these properties can also be observed. In a similar vein, single wavelength lidar is suitable for making highly accurate measurements of cloud tops and cloud structure. Differential absorption lidar is more costly but offers more information. Profiles of gaseous constituents including water vapor should be possible in the troposphere.

4. THE NEXT STEPS

There is little doubt that the atmospheric sciences community can use airborne remote sensing very profitably. Indeed, scientific headway in studies of mesoscale systems and atmospheric chemistry will be hampered significantly unless aircraft are suitably equipped to duplicate, in part, the measurement capabilities of surface-based networks. This paper, like many others on this subject, has addressed the issue of potential, but promising candidates for airborne remote sensing have been discussed for two decades. The challenge facing the atmospheric sciences community now is to put these techniques to use effectively. There is no universal formula for success, but the following ingredients are considered by the authors to be important.

- First, there must be an established scientific need and that need should come from the community of users, rather than from the instrume[illegible] sys[illegible] developer.
- Second, users must be committed to the development process, wo[illegible] cooperatively with the instrument developer. In this way it is [illegible]ed [illegible] what is developed will be useful to the nonspecialist.
- Third, the instrument must be well engineered, that is, acceptably [illegible] use. Considerable attention must therefore be paid to reliability, calib[illegible], display, data recording, and data analysis.
- **Fourth, if airborne remote sensing is to advance to its potential, the larger aircraft platforms available in various agencies must be made available for the community at large to use with as few strings attached as possible.**
- **Fifth, there must be a commitment by the agency or group, into whose custody these instruments are placed, to provide adequate funding for maintenance of the hardware and for guaranteeing operational readiness.**

- Finally, adequate feedback between scientific users and operators must take place. This can be accomplished most effectively by establishing scientific competence within the framework of the operational team.

Within our community, we expect to see widespread use of airborne Doppler radar in three to five years. Coherent CW lidar may also be available in this time frame. Short range rapid response temperature measurement may achieve operational status in two to three years. Airborne pulsed lidar and microwave radiometric techniques are also cirtically needed and should be developed as research tools within five years.

5. ACKNOWLEDGMENTS

The authors would like to acknowledge the helpful comments that they received from Jack Warner and the information transmitted to them by Dave Atlas. Special thanks are also given to Carol Nicolaidis, Regina Gregory and Diane Wilson who helped to prepare the manuscript.

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APPENDIX A

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APPENDIX B

NASA/Goddard Space Flight Center

Remote Sensing Instrument Inventory

This Appendix list a number of the remote sensing instruments that may be available from the Goddard Space Flight Center. The information was provided to the authors through the courtesy of David Atlas, Chief of Goddard's Laboratory for Atmospheric Sciences. Details about these instruments can be obtained from Joseph McGoogan at the Wallops Island Flight Facility.

INDEX/GLOSSARY

Catalog Number	Acronym	Instrument Name
1	MCR	Multispectral Cloud Radiometer
2	CTS	Cloud Top Scanner
3	CLS	Cloud Lidar System
4	AMMS	Advanced Microwave Moisture Sounder
5	BRFI	Bidirectional Reflectance Field Instrument
6	LAPR II	Linear Array Pushbroom Radiometer
7		Biometer
8	OSC-I	Ocean Color Scanner-I
9	HCM	Heat Capacity Mapper
10	MLA(Sim)	Multispectral Linear Array Simulator
11	RMR	Rain Mapping Radiometer
12	CZCS	Coastal Zone Color Scanner
13	ALRS	Airborne Laser Ranging System
14	AMMR	Aircraft Multichannel Microwave Radiometer
15	LBMR	L-Band Microwave Radiometer
16	SWIR	Short Wave Infrared Radiometer
17	MLA	Multispectral Linear Array
18	RLS	Raman LIDAR System
19	OCE	Ocean Color Experiment
20	M^{2}S	Bendix Modular Multiband Scanner
21	NS001	Thematic Mapper Multispectral Scanner
22	U-2 TMS	U-2 Thematic Mapper Simulator
23	U-2 LAS	U-2 Linear Array Scanner
24		Hygrometer
25	AOL	Airborne Oceanographic LIDAR
26	AAFE ALT	AAFE Radar Altimeter
27	SCR	Surface Contour Radar
28	ROWS	Radar Ocean Wave Spectrometer
29	ASAS	Advanced Solid State Array Spectrometer
30	PRT	Precision Radiation Thermometer