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Introduction to Airborne Measurements of the Earth Atmosphere and Surface

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Aircraft have been applied very effectively in many aspects of environmental research. They are widely used to investigate the atmosphere and observe the ground visually and by measurements with instruments on board the aircraft. They allow for

(i) *in situ* measurement of atmospheric properties from the ground to altitudes of 20 km;
(ii) remote sensing measurements of the ground and atmosphere and even extraterrestrial properties;
(iii) targeted measurements along a selectable flight path at controllable times and places (e.g., in the atmospheric boundary layer over ocean and ice, in the free troposphere, in the tropical and polar stratosphere, or over a specific landscape);
(iv) exploration of atmospheric phenomena or events and process studies for basic understanding (e.g., thunderstorm anvils, volcanic eruption plumes, tropical cyclones, cloud microphysics, and contrails);
(v) measurements at high temporal and spatial resolutions (e.g., 1 s and 100 m are typical, and smaller scales are reached for some turbulence and cloud microphysics measurements);
(vi) acquisition of data for model development and parameterization and validation (e.g., chemical composition and kinetics, cloud microphysics, and aerosol properties);
(vii) testing and validation of remote sensing measurements (e.g., trace gas measurements from satellites); and
(viii) comprehensive airborne measurements as part of campaigns or long-term investigations within an extensive observation and modeling system approach to explore complex and fundamental Earth–atmosphere system properties (e.g., aerosol/cloud/radiation interactions with atmospheric dynamics, and climate change).

The high maneuverability of aircraft allows researchers to chase atmospheric phenomena, follow their evolution, and explore their chemistry and physics from small spatial scales up to thousands of kilometers and over time scales of fractions

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of seconds to many hours or even days. Aircraft instruments uniquely complement remote sensing instruments by measuring many parameters that are currently not available from space- or ground-based sensors (e.g., turbulence, nanometer-sized particles, and gases without or with only low radiation absorption efficiencies, such as nitrogen monoxide). Aircraft can reach remote locations and can carry *in situ* as well as active and passive remote sensing instruments. Observations may be performed along streamlines or in a fully Lagrangian manner with repeated sampling of the same air mass over extended periods. Instrumented aircraft enable remote observations of the Earth surface with very high resolution and with minimum disturbances by the atmosphere between sensor and object.

Worldwide, an impressive fleet of research aircraft is available with airborne instruments designed for many applications, although further demand still exists. Traditionally, research has been performed with manned aircraft, but increasingly, unmanned aircraft are also being used. Research aircraft include stratospheric aircraft (e.g., the Russian Geophysica and NASA ER-2 and NASA Global Hawk Unmanned Aerial System), high-level jets (e.g., Gulfstream-505 aircraft at National Center for Atmospheric Research (NCAR), the High-Altitude and Long-Range Research Aircraft in Germany, and two Falcon 20 in France and Germany), large and mid-sized aircraft operating between near ground and in the lower stratosphere (e.g., the NCAR C130 in the United States, a BAe-146 in the United Kingdom, and an ATR-42 in France), and several smaller (e.g., CASA-212 in Spain and Do-228 in the United Kingdom) and low-level aircraft (e.g., Sky-Arrow in Italy and Ultra-light at the University of Karlsruhe). In addition to specialized research aircraft, commercial airliners have been equipped with inlets and instruments and have participated in measurement programs (e.g., Swiss Nitrogen Oxides and Ozone along Air Routes Project, Measurement of Ozone and Water Vapor by Airbus In-Service Aircraft, Civil Aircraft for Regular Investigation of the Atmosphere Based on an Instrument Container, and the forthcoming In-Service Aircraft for a Global Observing System) that have produced large amounts of climatologically relevant data on atmospheric composition and properties during many long-distance flights.

Improving access to these powerful research platforms and providing professional support and user training are objectives of leading international research institutions and agencies and they have been supported by European Facility For Airborne Research (EUFAR), in particular.

The design, integration, and operation of *in situ* and remote instrumentation on aircraft platforms require a number of special considerations to achieve desired performance. The first is the rapid motion of an aircraft through the atmosphere, which in contrast to other airborne platforms, such as balloons, is required for continuous aerodynamic lift. The motion changes the pressure, temperature, and flow fields near the aircraft surfaces that generally contain air sampling inlets and other openings. *In situ* instruments, in particular, require inlets and suitable sampling strategies. An important example is the measurement of ambient air temperature using a probe that involves contact of a temperature sensor with ambient air. In this case, the deceleration (relative to the aircraft reference frame) of gas molecules from the speed of the aircraft to stagnation conditions in the probe induces a compression heating of the order of 4 K (at 100 m/s) to 25 K (at 230 m/s). Accurate temperature measurements require careful probe calibrations and the availability of accurate airspeed and ambient pressure measurements. In clouds, phase changes reduce the temperature changes and cause strong humidity changes. Short-range, remote (e.g., infrared temperature) measurements offer an option that avoids airspeed effects.

Many aerosol instruments have been successfully designed to mount inside or outside the aircraft fuselages or on the underside of the wings. In aerosol sampling, particles below a certain size follow the flow lines around the curved fuselage and wing surfaces and make sampling inlets straightforward. Larger particles cross the flow lines due to their greater inertia, thereby complicating or simplifying sampling strategies depending on the objective. Particles approach sampling inlets with the airspeed of the aircraft. In clouds, droplets and ice particles affect inlet probe surfaces, and larger particles may shatter into many smaller ones. This effect may invalidate the intended measurements if the additional particles cannot be properly accounted for. New inlet designs have minimized these shattering effects.

Many gas and aerosol instruments are too large to be installed outside the aircraft. Therefore, an atmospheric sample must be continuously transported into the pressurized cabin or other payload area. As some gases react with or are absorbed on the walls of the sample inlet lines, special inlet materials or fast sample flow rates must be used to acquire representative samples. Similarly, aerosol particles can be lost by turbulent and inertial deposition in the inlet lines. Specialized inlet systems have been designed and implemented to provide ambient air, from outside the possibly polluted aircraft boundary layer, to a suite of sampling instruments inside the aircraft, while minimizing the loss of particles on the inlet walls.

Another consideration in the design of airborne instruments is accommodation of environmental conditions that sometimes rapidly change. For instance, some instruments are located in unpressurized payload areas and exposed to ambient pressure and temperature conditions during flight. In some cases, in descent from high altitudes and low temperatures, instruments experience rapid changes in temperature or humidity, which may lead to condensation of water vapor on optical, electronic, and other components. Pressure and temperature problems are typically avoided by the use of pressurized enclosures for critical components and heaters that control temperatures throughout a flight. In many *in situ* sampling instruments, special provisions are required to maintain ambient sample flows or other parameters constant in response to changes in ambient pressure between the ground and cruise altitudes. Inlet systems and instrument sampling volumes are typically sealed to avoid contamination from cabin air.

Another important consideration is aircraft turbulence encountered both in clear air and in convective cloud systems and lightning strikes. In turbulence, aircraft instruments (and crew members) are exposed to rapid and often large accelerations in all three dimensions. Vibration from turbulence or engine operation is also a concern. With the application of good materials and structural engineering principles in the design and construction phases, instruments are generally able to maintain high measurement quality under these conditions. Lightning strikes are a physical threat when sampling near convective cloud systems. These systems are of significant scientific interest because of their chemical and dynamical properties. Although lightning strikes often cause minor structural damage and can be unnerving to the crew and passengers, the aircraft systems and instrument payload are generally unaffected. After a strike, flight directors often end the scientific portion of a flight in the interests of safety and direct the aircraft to return to base for inspection.

For many measurements, precise geographical positions and three-axis orientations are needed along the flight track. Examples are measurements of the wind vector, of upward and downward irradiances, and all types of active or passive remote sensing. Accurate information on aircraft position, velocity, and translational and rotational accelerations can be provided accurately by advanced inertial systems at high frequencies (up to 100 Hz) and by global positioning systems at frequencies up to 1 Hz.

Airborne measurements require careful consideration of aviation safety. In recent years, the effort required for aircraft and instrument safety certification has increased. Aviation safety and airworthiness certification regulations have a significant impact on the development of airborne instrumentation and the planning and execution of field experiments. Like other structural components of the aircraft, airborne instruments must withstand extreme accelerations as in the case of severe turbulence or unexpected airframe loads. This requires special attention to allow installation of a comprehensive measurement system, especially in small aircraft. Research instruments may contain radioactive, explosive, flammable, toxic, or chemically active constituents that carry additional safety and regulatory requirements. Moreover, instruments mounted outside the aircraft must be able to withstand bird strikes, icing, and lightning. Less constraining, but still crucial for aircraft integration, are instrument weight, volume, and electrical power consumption. Limits for total payload weight and payload center of gravity are necessary considerations, which are often a challenge when the payload contains a number of large and heavy instruments.

An important part of carrying out airborne measurements is campaign planning. Planning includes identification of scientific objectives and key scientific questions, site selection, aircraft preparation, and preparation of instrumentation, flight templates, time lines, and the on-site decision process. Planning activities and strategies, which are usually not well represented in the scientific literature, are generally undertaken by the scientific leaders of a campaign. It is important to recognize that planning may extend many months before a campaign and that a high-quality planning effort greatly increases the likelihood of a successful campaign.

During or shortly after campaign science flights, preliminary ‘‘quick look’’ results and analyses often become available on board or on the ground. These analyses can be used for ‘‘in flight’’ modification of flight objectives or planning for subsequent flights. Quality data processing often requires postflight instrument calibration or corrections that depend on aircraft state parameters or other variables and may take months of work effort. Intercomparison flights of two or more instrumented aircraft operating in the same or equivalent air masses, sometimes wing by wing, have been found to be important for data quality checks and instrument improvements in many campaigns. Finally, instrument data sets generally must be made available to other investigators and the public following a campaign and archived in data banks. These data sets, alone or in combination with model and other observational results, provide the basis for subsequently addressing the scientific objectives and key scientific questions of a campaign in the scientific literature.

The preface introduces the objectives and chapters of this book, which address issues specific to airborne measurements. The book serves, in part, as a handbook to guide engineers and researchers involved in airborne research in the integration of airborne instrumentation, its operation in flight, and processing of acquired data. It also provides recommendations for the development of novel instrumentation and examples of successful projects to help researchers in the design of future flight campaigns. The substantial success of instrumentation on board aircraft platforms in the past decades suggests that instrumented aircraft will continue to play an important role in meeting the ongoing challenge of understanding the processes in our complex Earth system.