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The North Dakota Citation Research Aircraft Measurement Platform

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Abstract

The North Dakota Citation Research Aircraft is a Cessna Citation II twin-engine fan-jet aircraft modified to be an atmospheric research platform that has been used on many field projects since the 1970s. The typical sampling speed of the modified Citation II is 160 knots indicated air speed (IAS), with sampling at altitudes up to 12.1 km (40,000 ft). The Citation Research Aircraft was operated by the University of North Dakota (UND) for many years but is now operated by Weather Modification International (WMI) of Fargo, North Dakota. WMI and UND together provide a unique test facility that is capable of deploying a wide range of instrumentation. WMI has the experience to install the custom instrumentation required for a specific field project and the expertise to conduct the most demanding aircraft sampling, including thunderstorm in-situ measurements. UND provides scientific know-how on obtaining measurements at the required accuracy and experience to ensure instruments are performing well. Robust, open-source software tested for over 15 years provides the ability to quickly process data to enable analysis to begin shortly after completion of an aircraft flight. Visualization software allows observations to be efficiently quality-assured, which enables timely creation of a final data set that can be analyzed to meet each project's scientific objectives. Past and ongoing projects include working with large and small companies to test airborne instruments and conduct natural icing studies. Specialized data processing methods have been implemented to obtain the liquid and total water content measurements at high accuracy. With continuing reduction in the size and power requirements of instrumentation, the future will allow the North Dakota Citation Research Aircraft to make an increasing number of observations which utilize more sophisticated processing software.

Introduction

The University of North Dakota (UND) has conducted many field projects since the 1970s using a Cessna Citation II twin-engine fan-jet aircraft. Over this time, the North Dakota Citation Research Aircraft has been involved in studies that address our understanding of aviation weather hazards, which includes the detection of hazardous conditions and the certification of aircraft for safe flight in adverse weather. The first series of airborne campaigns involved supporting the development of the Next-Generation Radar (NEXRAD) and Terminal Doppler Weather Radar (TDWR) radar algorithms. In particular, the North Dakota Citation Research Aircraft obtained measurements in environments where icing, turbulence, and low-level wind shear were present. The purpose was to provide in-situ "truth" on conditions being sampled remotely by radars. Airborne observations were more than just standard pilot reports (PIREPs) of in-flight conditions. The North Dakota Citation Research Aircraft characterized icing environments using instruments that measured the liquid water content, water drop size distribution, and ice content of the clouds and precipitation. For turbulence and wind shear studies, measurements were made from a flow angle probe and inertial navigation system. When flights were made in convective environments, operations were closely coordinated with ground-based radar observations to ensure crew safety. Campaigns were flown in a number of different locations to determine geographic variations in conditions. The early field projects with the North Dakota Citation Research Aircraft were done in partnership with the Massachusetts Institute of Technology (MIT) Lincoln Laboratories and funded by the Federal Aviation Administration (FAA).

A second period of activity occurred from 1992 to 2005 when the North Dakota Citation Research Aircraft was used to provide measurements of icing conditions for the purpose of aircraft certification. The Code of Federal Regulations (CFR), 14 CFR 23.1419 and 14 CFR 25.1419, require that the effectiveness of ice protection systems and their components be tested "in measured natural atmospheric icing conditions". These measurements include the cloud parameters of liquid water content, drop size distribution, and temperature. Several aviation companies provided funding for projects, including a series of field projects to certify the Sikorsky S-92 helicopter for flights in known icing conditions.

Most recently, the North Dakota Citation Research Aircraft has been used to collect data from 2003 to present in support of sensor development for the detection of in-flight hazardous weather conditions. Sensors include the Tropospheric Airborne Meteorological Data Reporting (TAMDAR) system, which is designed to automatically measure and report weather conditions [1]. In particular, turbulence measurements made by TAMDAR were compared with those made by the North Dakota Citation Research Aircraft in order to refine the TAMDAR's turbulence algorithm. The TAMDAR has been deployed on a fleet of commercial aircraft to provide data that improves weather forecasts [2]. Another sensor, the Optical Icing Detector (OID), is still being developed to provide information about the icing environment in the immediate vicinity of the aircraft, including high concentrations of ice crystals [3]. Funding for flight testing was provided by National Aeronautics and Space Administration (NASA) and companies developing sensors for deployment on commercial aircraft.

Today, UND continues research on aviation weather hazards; however, the North Dakota Citation Research Aircraft (Figure 1) is now operated by Weather Modification International (WMI). WMI is based at the Fargo Jet Center in Fargo, North Dakota, and has a long history of weather modification operations and research that began in North Dakota [4]. Today, WMI has expanded to conduct aircraft modification to enable deployment of research instruments [5]. WMI and UND work together to cost-effectively conduct a wide range of field projects with the North Dakota Citation Research Aircraft. The University-Private Sector collaboration enables a unique educational experience for students, and the ability to provide training in airborne observations. Current proposed projects include funding for flight testing of instruments and aircraft icing research.

Figure 1: Image of the North Dakota Citation Research Aircraft flying over the runway at the Fargo, North Dakota (KFAR) airport. In the background is the Weather Modification International (WMI) hangar where instrument uploads and ground testing is conducted.

To support atmospheric sampling that is required for understanding aviation weather hazards, the North Dakota Citation Research Aircraft has the following modifications:

- Two Wing-Tip Pylons with four Particle Measuring Systems (PMS) Cans
- Five Reinforced Fuselage Instrument Mounting Locations
- Six Fuselage Ports for Instruments, such as Electric Field Mills
- Four Side-looking Window Inserts that House Specialized Glass for Lidar Instruments
- Anti-ice Sampling Inlets for Cabin-based Gas and Aerosol Sampling

The North Dakota Citation Research Aircraft has a number of design and performance characteristics (Table 2) that make it an ideal platform for a wide range of atmospheric studies, including cloud sampling at altitudes of up to 12.1 km (40,000 ft). The Citation's straight-wing design allows for take off from relatively short airstrips and flying at slower speeds, which is necessary for many types of sampling. WMI has experience modifying aircraft for research applications [5] and installing equipment required to conduct the most demanding aircraft-based observations, including thunderstorm in-situ measurements. UND has the scientific knowledge to obtain measurements at the required accuracy and the ability to quickly process data to ensure flights obtain the necessary observations. The WMI/UND team provides the complete solution for conducting very challenging airborne field projects to obtain the data set required to meet all scientific objectives.

Table 1: List showing the important performance specifications of the North Dakota Citation Research Aircraft (N555DS). Note that aircraft endurance depends on the sampling altitude and speed. Only storms with less than 45 dBZ radar reflectivity factor are penetrated to avoid hail shafts. The typical sampling speed is 160 knots IAS.

Payload	693 – 1147 kg (1,528 – 2,528 lbs)
Range	2,222 km (1,200 nmi)
Ceiling without/with Pylons	13. 1 km (43,000 ft) / 12. 1 km (40,000 ft)
Climb Time	13 min (to 25,000 ft), 24 min (to 35,000 ft)
Endurance	3 to 5 hours
Weather	Known Icing and Storm Penetration
Airspeed Range	150 – 225 knots IAS

This paper is focused on three themes that should be part of any aircraft project. One theme is using aircraft for observing properties of flight environments, a second theme is the need for open source software for data processing, and a third theme is the creation of aircraft data sets. These three themes are illustrated using the North Dakota Citation Research aircraft; however, they apply to any observational platform. The next section contains information about the aircraft's standard instrumentation, considerations for deploying guest systems, and limitations of the overall instrumentation suite. The Scientific Software section provides details on the processing of aircraft measurements, usage of open source software, and availability of software packages. A description of the availability of testing data and data sets is described in the Data Set section. The paper finishes with the Aircraft Icing Data Processing section where details about algorithms and software for processing hot wire probe measurements are given to provide an example application that is important for aircraft icing studies. The Conclusion section summarizes the paper and comments on the future direction of aircraft measurements. The paper includes an in-depth description of processing software and quality assured data sets since the goal of utilizing any airborne measurement platform is to provide information that addresses specific objectives, not just operating instruments to obtain data.

Airborne Measurements

The basic instrument package measures the aircraft's speed and position, along with atmospheric state parameters of temperature, relative humidity, and 3-dimensional winds. Additionally, most research projects typically deploy instruments to conduct specific scientific measurements, such as hydrometeor concentration, size, and mass. Many projects deploy prototypes to flight test new instrument designs. For example, prototypes of the TAMDAR [1] and the OID [3,6] have been deployed. Most field projects involve cloud physics measurements; however, the platform has completed projects to study electric fields [7], atmospheric chemistry [8], and weather modification [4]. Each field project's instrument suite (e.g., Figure 2) is different since each project has unique observational objectives. Many projects have obtained detailed in-situ measurements to understand remote sensing observations made by surface radars [9] and satellite platforms [10,11]. Atmospheric observations made by the aircraft also provide new insights into many important processes, such as precipitation formation and the effects of emissions.

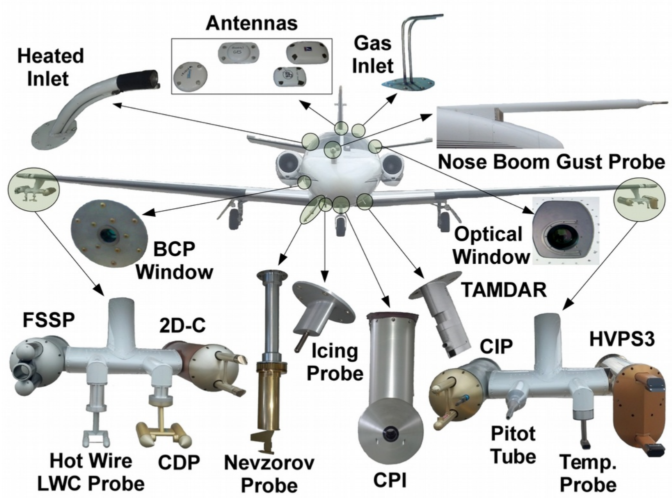

Figure 2: Image showing systems mounted on the North Dakota Citation Research Aircraft in the Fall of 2012. The Heated Inlet is a forward facing tube that is connected to a manifold with ports for connecting instruments such as a Condensation Particle Counter (CPC) that measures total number concentration of all aerosols larger than 10 nm. The top of the aircraft contains several global positioning system (GPS) and satellite transceiver antennas (Antennas). The Gas Inlet is a rear-facing inlet for gas phase measurements, such as water vapor mixing ratio made with a Tunable Diode Laser

Hygrometer (TDL) instrument. There is a 5 port gust probe (Nose Boom Gust Probe) for true air speed, attack angle, and slide slip angle measurements that is coupled to an Applanix Position and Orientation System (POS), which measures aircraft position, attitude, heading, pitch, roll, and yaw, to make atmospheric wind measurements. A Droplet Measurement Technologies (DMT) Backscattering Cloud Probe (BCP) uses a fuselage port for measuring cloud particle size distributions. Three of the side windows have special glass inserts with anti-reflective coatings (Optical Windows) for use by the Optical Icing Detector (OID). A Tropospheric Airborne Meteorological Data Reporting (TAMDAR) system, Rosemount Icing Probe (Icing Probe), and Nevzorov Total Water Content Probe (Nevzorov Probe) are mounted to the fuselage nose. The DMT Cloud Particle Imager (CPI) is mounted on the belly of the aircraft. The right pylon contains a DMT Fast Forward Scattering Probe (FSSP), a King Hot Wire Liquid Water Content (LWC) Probe, DMT Cloud Droplet Probe (CDP), and 2-dimensional Array Cloud Probe (2D-C). The left pylon contains a DMT Cloud Imaging Probe (CIP), Pitot Tube for aircraft speed measurements, a Rosemount Total Temperature Probe (Temp. Probe) for air temperature measurement, and a High Volume Particle Spectrometer (HVPS-3) for measuring precipitation-sized particles.

The aircraft's cabin is approximately 1.5 m (five feet) in diameter and more than 4.9 m (16 feet) in length, which can accommodate several instruments provided by outside investigators. Several 19-inch racks are available that provide 330 cm (130 inches) of vertical space for housing standard sized equipment. A keyboard, video and mouse (KVM) switch is available to easily interface with multiple data systems from one seat location. The aircraft has a 100 MB network with a network time protocol (NTP) server which provides time synchronization of systems. Instrument space and weight are limited; however, typically the suite of instruments deployed is constrained by available research power (Table 2).

Table 2: List showing the available power specifications of the North Dakota Citation Research Aircraft. Note that aircraft instrumentation uses more anti-icing at higher altitudes when the temperature is lower; however, power budgets are calculated based on the maximum draw of an instrument.

Total Available Research Power	7,300 W (Below 35,000 ft) 5,400 W (35,000 ft and Above)
Alternating Current Instruments	4,000 W of 110 Volts at 60 Hz
Direct Current Anti-icing Instruments	80 Amps of 28 Volts
Direct Current Power Instruments	40 Amps of 28 Volts

Typically, specific missions require the installation of guest instrumentation, either inside the cabin in available rack space or externally mounted. WMI has been modifying aircraft for cloud seeding and research for over 25 years. In that time, WMI has gained valuable experience and acquired the necessary resources to host and conduct airborne research operations. Facilities play a critical role in operating a research aircraft, and WMI provides the necessary facilities to support field projects and research using the North Dakota Citation Research Aircraft. WMI has heated, modern hangar facilities with all necessary ground support equipment and extensive maintenance capabilities with an FAA 145 repair station including a full avionics shop on site. There are office spaces and conference rooms available at WMI, which provides room for flight planning and data processing on site for the duration of a project. An electronics lab is available for instrument support with extensive testing equipment and resources. In addition to support, WMI owns many cloud physics and aerosol research instruments that can be deployed on the North Dakota Citation Research Aircraft. This gives WMI the ability to provide data from multiple sources to improve the quality of testing for an instrument in development. For example, the facilities at WMI allow for ground testing and maintenance to be done in one location as the Citation is prepared for flights.

WMI also possesses a full-service staff including pilots, mechanics, instrument technicians, and electronics specialists. WMI pilots have experience flying research missions and adapting to rapidly changing plans to achieve research objectives. Mechanics on site have worked on specialized equipment on the North Dakota Citation Research Aircraft and numerous other special mission aircraft giving them the experience to complete repairs and installations in a safe and timely manner. Instrument technicians and electronics specialists have experience troubleshooting and integrating instruments into the aircraft and data systems. Altogether, the staff at WMI has the ability and experience to adapt to the needs of individual projects and work together to achieve research objectives. This versatility and experience has been developed through an extensive history of over 100 aircraft modifications including multiple modifications for research instruments. In the event that the North Dakota Citation Research Aircraft is not operating in Fargo, North Dakota for a project, WMI also has experience operating and testing instruments in multiple locations worldwide. WMI can act as a host or deploy anywhere in the world with the same professional quality of work demanded by airborne research.

When deploying the North Dakota Citation Research Aircraft for a field project, the minimum aircraft crew is a pilot, co-pilot, and flight engineer. Two additional seats are typically available for a flight scientist and an additional flight engineer. The flight crew briefs before each flight on the planned profile; however, the plan is often modified during the flight based on observed conditions and air traffic constraints. Standard sampling profiles are developed before the start of the field project (e.g., Figure 3). The pilots are responsible for the safe operation of the aircraft. The flight scientist is responsible for ensuring the scientific objectives of the flight are obtained. Flight engineers operate the research equipment and monitor instruments using the real-time data displays. Detailed checklists are followed to ensure all instruments are powered on at the correct times and that critical parameters are reviewed. Both the flight scientist and flight engineers make written notes of interesting observations viewed out the aircraft's windows or noticed in the real-time data being displayed.

The North Dakota Citation Research Aircraft uses the Science Engineering Associates (SEA) Model M300 Data Acquisition System (DAS) for recording synchronous and asynchronous data at various rates (1 to 200 Hz) from a large variety of instruments. The M300 is configurable to do real-time data acquisition from instruments developed by many manufactures and display information in various text and graphical formats. QNX is the operating system used by the M300, which is a Unix based, real-time operating system that provides consistency related to the amount of time tasks take to execute. Execution consistency is important when acquiring, processing, and displaying data from several instruments. Alternative solutions that typically use Labview programs, which run on the Windows family of operating systems to acquire and display data, require a different computer system for each instrument to ensure applications do not interfere with the tasks of other applications. With upwards of 30 instruments routinely deployed on even a mid-sized research aircraft [5], it becomes a very time-consuming task to time sync, download, and combine data if each instrument has its own data acquisition system. With the M300, only a single time sync is required and all data is recorded into a single file, which can be easily downloaded after a flight.

The M300 is able to handle the complex algorithms and processing required for even very basic parameters such as air temperature and atmospheric winds. The wind algorithm [12] uses ground relevant measurements of the aircraft's acceleration, pitch, roll, and yaw, along with atmosphere relevant measurements of attack angle, side-slip angle, and indicated air speed to determine three-dimensional wind vectors. An Applanix Position and Orientation System that contains a strap-down gyro system and integrated global positioning system (GPS) provides the ground-relative parameters, while a 5-port gust probe provides the atmosphere- (air-) relative parameters. Processing software calculates the turbulence intensity [14] from differential pressure transducer measurements.

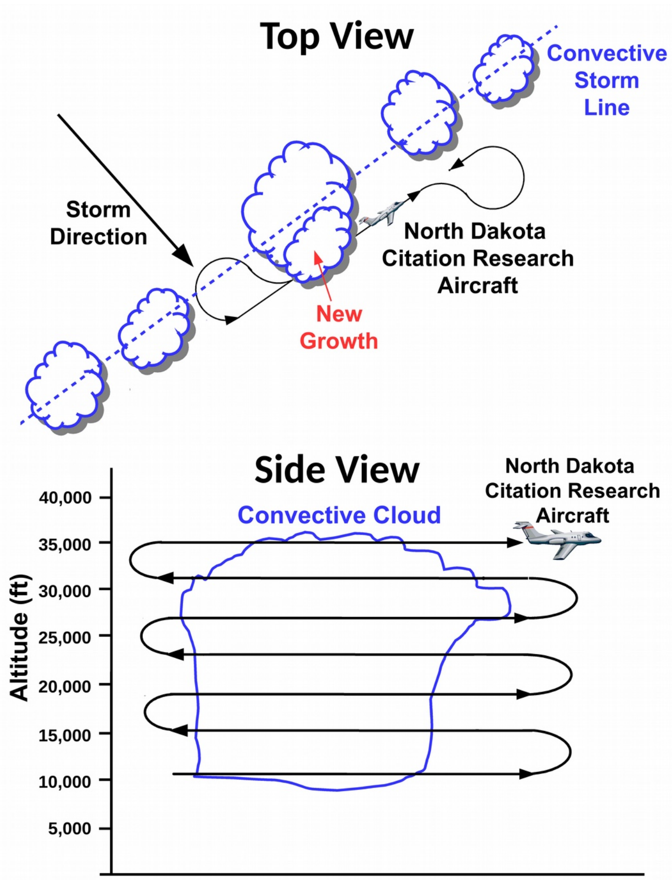

Figure 3: Image showing a flight profile plan for sampling growing cumulus clouds using the North Dakota Citation Research Aircraft.

Scientific Software

Many recent publications discuss the need to improve scientific software across all disciplines and note that researchers in most science fields have little formal software development education, do not test or document programs rigorously, and rarely release their code [12]. The solution to this problem is for developers to have a proper education in software methods and to release source code; however, developing, testing, and publishing high quality scientific software involves a significant amount of time and effort which many project managers do not currently reward. Some scientists argue that researchers should release their code regardless of the quality, and the attitudes of many scientists should change with regard to software [13]. Application of a core concept of the scientific method, reproducibility, is starting to change the scientific culture regarding codes used in generating scientific results. Some assert that anything less than the release of source programs is intolerable for results that depend on computation [14]. Accepting this assertion implies that only work based on openly available software is acceptable. Clearly, with approximately 85 % of researchers spending about 80 % of their time looking for, collecting, and getting the necessary data together in a format they can use [15], the use of well-written and documented open source software has a significant effect on the over all productivity of the field.

The open source Airborne Data Processing and Analysis (ADPAA) software package [16] has been developed and used for over 15 years to post-process and analyze data collected by research aircraft [17]. Flight data is processed, quality assured, and made available to the project's science team in a timely manner (within hours of flight completion). All ADPAA-produced data files include metadata that fully describes all parameters. Customized cross-platform software (cplot/cplot2) is freely available to quickly display and analyze the data files. All source code is available, allowing other programmers to understand how parameters are determined. By using the open source software development model [18], ADPAA administrators hope to form a sustainable development team that spans many institutions and provides a robust package that can be utilized widely. Both UND and WMI use the ADPAA software package to process data from other platforms besides the North Dakota Citation Research Aircraft.

Adoption of the ADPAA software package has been slow, despite the source code being available in an open repository [19] and having a peer-reviewed publication [17]. Within the geosciences, a well-known software package where community adoption has occurred is with the Weather Research and Forecasting (WRF) Model. WRF is a mesoscale numerical weather prediction system designed to serve both atmospheric researchers and operational forecasters that has yearly releases, an annual workshop, and over 30,000 users [20]. Similar to numerical modeling, airborne instruments (Figure 2) require complex processing codes, analysis tools, and visualization software which takes significant time to develop; however, research teams within the airborne community typically develop their own software, sometimes for single projects. While the airborne community is an order of magnitude smaller than the WRF community, community software is possible for commercial instrumentation as evident by the packages (e.g., Squirrel, Pika, etc.) available for the Aerodyne Time-of-Flight Aerosol Mass Spectrometer [21]. Furthermore, organizations such as the Earth Observing Laboratory of the National Center for Atmospheric Research have started gathering together software and releasing code as community software packages.

Adoption of community software methods is slow in the scientific community since there is limited information available on best practices, which makes it difficult for scientists to know the quality of externally developed code. Furthermore, graduate students are generally not trained to develop software for use by the community, and scientists rarely use modern development tools such as software version control. While some teams [17,22] use an open source development model, modern development tools, and software repositories, there is no recognized structure or authority for scientific software quality and no support structure to sustain long-term continued development. Furthermore, there are no common best practice standards for documentation, no requirements related to uncertainties in derived parameters, and no community that is a single source of metadata about airborne data processing software. As a result, software developed to apply required corrections (e.g., [23,24]) and address instrumentation limitations (e.g., artifacts produced during sampling in various conditions) is generally not available or difficult to implement by early-career scientists, a problem compounded by the need for very skilled user interpretation. This lack of a robust software infrastructure is a major limitation in using airborne measurements and affects the larger community. For example, scientists grapple with the problem of how to properly interpret cloud measurements for improving the algorithms used in climate and weather forecasting models [25].

To discuss and address existing issues with cloud physics, in-situ aircraft data, the European Facility for Airborne Research (EUFAR) sponsored a workshop on data processing, analysis, and presentation software during the summer of 2016. Darrel Baumgardner, Greg McFarquhar, and Andrew Heymsfield organized the workshop that was held on 23-24 July 2016 in Manchester, United Kingdom, before the start of the International Conference on Clouds and Precipitation (ICCP). During the workshop, eight software packages (Table 3) were presented [26] from different research teams for handling cloud physics, in-situ aircraft data. The recent workshop discussions of community development is very timely since these software packages have matured to the point of being useful beyond the development teams. Furthermore, software development has started that depends on multiple packages, and without a community development plan, packages risk being forked with multiple development branches. Thus, it is important to define exactly how to effectively transition packages to community-wide adoption and promote future development by the community of users of aircraft probe measurements.

Table 3: The availability of software packages presented at the European Facility for Airborne Research (EUFAR) International Conference on Clouds and Precipitation (ICCP) Workshop on Data Processing, Analysis, and Presentation Software. See the Definitions/Abbreviations section for full name of software package acronyms.

Package Acronym	Availability
ADPAA	svn://svn.code.sf.net/p/adpaa
D2G	Local Team Software, Alexei Korolev
EGADS	https://github.com/eufarn7sp/egads-eufar
OASIS	Droplet Measurement Technologies
SAMAC	https://github.com/StephGagne/SAMAC
SODA	https://github.com/abansemer/soda2
SPEC	http://www.specinc.com/downloads
UIOPS	https://github.com/weiwu5/UIOPS

Features of the software packages discussed at the EUFAR ICCP workshop can be characterized into two broad categories, packages that process optical array probe (OAP) data and packages that focus on data from other in-situ probes (Table 4). Figure 2 shows numerous in-situ probes that have been deployed on research aircraft. Many in-situ cloud probes are needed because of the large size range (nm to cm scales) over which particles are of interest [27]. OAPs cover an important size range accessible by physical optics-based measurements where hydrometeors are sized by shadows projected on an array of diodes [28]. The processing of shadow images is not straightforward [25,27]; therefore, there is still no consensus in the community related to the best processing algorithm(s). Hence, it is healthy to have several OAP software packages that implement different methodologies. The remaining four software packages (see Table 4) process data from different cloud physics instruments (for example, scattering probe to measure cloud droplets), assist with quality assurance, and/or conduct data visualization. Therefore, usage of all the available packages is advantageous instead of focusing on a single package for community-wide adoption. Furthermore, cloud physics, in-situ data processing does not need coupling of software components that is required for weather models; therefore, development can be conducted using a much more distributed system.

Table 4: List of software packages available for processing data obtained by aircraft research instruments that were presented at the European Facility for Airborne Research (EUFAR) International Conference on Clouds and Precipitation (ICCP) Workshop on Data Processing, Analysis, and Presentation Software on 24 July 2016 in Manchester, United Kingdom. The ADPAA package also includes Csh, C, Fortran, Matlab, Scilab, Igor, and Tcl/Tk programming language codes; however, most features do not utilize these languages. The Usage column provides a few papers where the software package was utilized; however, the list is not fully inclusive. Packages that process optical array probe (OAP) images to produce size spectrum data have acronyms highlighted in bold fonts. See the Definitions/Abbreviations section for full name of software package acronyms.

Package	Languages	Summary of Features	Usage
ADPAA	IDL, Python, Bash, Perl	Tools for processing many instrument's data, file conversion, quality assurance, and visualization.	[4,29,30]
D2G	Matlab	Process, quality assurance, and visualization of aircraft and radar data.	[31–33]
EGADS	Python	Toolbox for handling meta-data and units for processing data.	
OASIS	Igor	Package for OAPs (CIP, PIP/CIP-100, SPEC 2DS and HVPS).	[34–36]
SAMAC	Python	Tools for calculating, displaying and storing segments summaries.	[37,38]
SODA	IDL	Package for OAPs that provides options to derive particle spectra.	[10,39,40]
SPEC	Matlab, IDL	Tools for SPEC probe data (2D-S, HVPS3, CPI, etc.).	[41–43]
UIOPS	Matlab, C++	University of Illinois analysis package for OAPs.	[11,25,44]

An example towards community software development is provided by the GitHub-hosted Community Packages for Airborne Science (CoPAS) project which is designed to facilitate the installation, setup, and integration of open source software packages. CoPAS focuses on airborne measurements with the goal of being a sustainable distribution that promotes community code standards and methodologies at universities, national laboratories, and private companies. The aim of CoPAS is to move software from individual groups to adoption by the community and improve scientific software by educating developers in the latest computer science methodologies such as software quality control testing. Furthermore, more interdisciplinary usage of the data sets developed from using the community software will result from the focus on defining the uncertainty of parameters and the limitation of processing algorithms. Specific uncertainties are rarely provided since they are not well understood for many cloud probes and even when uncertainties are known, they are neglected since the data set generated from individual research groups are assumed to be used by experts. Likewise, limitations of processing and analysis algorithms are typically not included; however, such information is very important to include in a community software distribution where the end user and application are not known. Therefore, similar to observational data sets [45], provenance is very important for a community software distribution.

Data Sets

The North Dakota Citation Research Aircraft has been utilized to create data sets in many locations (Table 5). Several field projects have been done for companies to test airborne instruments (Ophir, UT Corp, Goodrich, and TAMDAR projects) and conduct natural icing studies (Sikorsky and L3Com), while the main government sponsor is NASA. The creation of these quality assured data sets is the first step in the scientific analysis, presentation, and publication process. The data sets are readily available for further scientific analysis since the raw data was recorded on an 8 mm tape (before 2005) or directly to a hard drive (2005 onward). Data from 8 mm tapes for field projects listed in Table 5 has been copied to a computer server so all data is easily accessible. Additionally, several data sets (e.g., NASA GPM data sets) are available in open repositories, with ongoing work devoted to archiving more data sets in repositories, including some early North Dakota field projects [46,47].

Table 5: List of data sets created using the North Dakota Citation Research Aircraft over the past 20 years. The columns provide the field project name, date from the first to last flight, the main location of the project, and the total number of flights conducted. Weather Modification International (WMI) is the owner of the North Dakota Citation Research Aircraft for the recent Ultra project, while the University of North Dakota owned the aircraft for all prior projects. Companies funded the Ultra, Ophir, UT Corp, Goodrich, Sikorsky, TAMDAR, L3Com, and Raytheon Systems projects.

Project Name	Dates	Location	#
Aerospace Ultra	2017/07/24-2017/08/03	Northern Florida	08
Ophir Winter 2016	2016/03/15-2016/04/14	North Dakota	05
GPM OLYMPEX[48]	2015/10/23-2016/01/22	Washington	23
Navy Cape 2015	2015/07/28-2015/08/11	Northern Florida	12
UT Corp Fall 2015	2015/08/12-2015/08/06	North Dakota	04
UT Corp Fall 2014	2014/09/20-2014/10/13	North Dakota	04
GPM IPHEX[49]	2014/05/01-2014/05/15	North Carolina	33
Ophir 2013	2013/08/31-2015/10/22	North Dakota	05
UT Corp Fall 2012	2012/08/16-2012/11/30	North Dakota	04
GPM GCPEX[50]	2012/01/11-2012/02/25	Ontario, Canada	18
Goodrich 2011	2011/07/09-2011/11/22	North Dakota	09
GPM MC3E[51]	2011/03/20-2011/05/02	Oklahoma	15
Goodrich 2010	2010/11/18-2010/12/30	North Dakota	07
POLCAST 2010	2010/06/21-2010/07/23	North Dakota	05
Sikorsky Fall 2005	2005/09/13-2005/09/30	Fairbanks, Alaska	08
TAMDAR 2005	2005/08/23-2005/09/09	North Dakota	06
Sikorsky Winter 2005	2005/01/09-2005/03/19	Elmira, New York	29
L3Com 2004	2004/11/03-2004/12/13	Oscoda, Michigan	16
DOE M-PACE	2004/09/02-2004/10/28	Northern Alaska	22
Sikorsky Spring 2004	2004/02/08-2004/04/26	Presque Isle, Maine	25
FAA WISP 2004	2004/02/26-2004/03/28	Colorado	08
NASA THORPEX	2003/11/12-2003/12/14	Maine	21
COBRA-NACP 2003	2003/05/23-2003/06/27	United States	21
NASA Crystal-FACE	2002/07/03-2002/07/31	Florida Keys	14
Raytheon Systems	2001/03/05-2001/03/25	Traverse City, MI	07
ABFM Field Mills 2001	2001/01/27-2001/02/17	Northern Florida	06
COBRA-2000	2000/07/28-2000/08/24	United States	12
ABFM Field Mills 2000	2000/04/29-2000/06/28	Northern Florida	19
NASA Kwajex-TRMM	1999/07/31-1999/09/15	Marshall Islands	35
COBRA-2000	1999/06/03-1999/06/16	United States	07
Rapid City	1999/04/09-1999/04/23	South Dakota	12
NASA TRMM LBA	1999/01/23-1999/03/12	Amazonia	25

Data files from past field projects are incorporated into the Airborne Data Testing and Evaluation (ADTAE) git repository hosted at Sourceforge. ADTAE is a project for testing software updates and evaluating processing methods related to scientific instruments deployed on airborne platforms. It is advantageous to separate the testing and evaluation of packages from the software code since the required data files are large compared to software code and most users do not want to test/evaluate the software but utilize packages to create data sets for their scientific analysis. Hence, testing scripts are designed for developers to ensure code changes do not break operational software.

Currently, ADTAE only contains resources related to the ADPAA package and ADPAA's linkage to the System for Optical array probe Data Analysis (SODA). Recent ADPAA development has focused on "wrapper" scripts that automate data processing using SODA. The ADTAE "test_process_soda2.cip.bash" script is used to test the ADPAA/SODA software (linkage_soda module) that creates particle size distributions from CIP images using data files contained within ADTAE. Now that ADPAA is used operationally by several groups, it is imperative any major module changes start with the development of a testing script. Future development will incorporate all the development scripts into a testing suite (toolbox) that ensures software components function as expected. For efficiency, accuracy, and transparency in science, it is necessary to develop and adopt standard sets of well-tested tools for our analyses [52].

Evaluations that demonstrate measurement limitations are a natural fit to combine with testing code since the same data files can typically be used for both. Tutorials (e.g., 2DC-2DS_Tutorial_150828Flight) and Python notebooks (e.g., adpaa_readplot_ccncdata) are currently included in ADTAE to provide a starting point for new developers and students. Another important component to the scientific software are work-flows that document the exact processing used to create analysis plots contained in scientific papers and reports. Currently, work-flows are included in both ADPAA and ADTAE. However, works-flows do not fit naturally in either package and are planned to be moved into their own repository in the near future.

With so many components (aircraft/instruments for airborne measurements, software, data sets) comprising current work-flows involving airborne measurements, it is necessary to document each component in an easily accessible and open manner. Wiki sites provide quickly constructed and editable web sites for documentation. Students in the Department of Atmospheric Sciences at UND are familiar with the expectation that writing or revising the department's Wiki site is the payment expected for receiving help, and users of the Airborne Data Processing And Analysis (ADPAA) software have contributed significantly to the package's Wiki site. While ADPAA developers include documentation and execution examples within their code, users have written the majority of the software package documentation available on the Wiki site. The Wiki site does not duplicate code documentation but provides the high level overview information of what software modules are available to conduct different tasks. Students are first taught how to access software package documentation, and then how to create such documentation themselves. Advanced users learn how to develop and submit software to distributions. Having students and users provide documentation feedback is one of the benefits that developers receive from having openly available software. Additionally, having more people use and review the code helps to catch mistakes.

Aircraft Icing Data Processing

The North Dakota Citation Research Aircraft has been involved in a number of aircraft icing studies (Table 5), including a series of projects for certification of the Sikorsky S-92 helicopter. The icing certification process involves evaluating the aircraft within the icing envelope formed by a range of atmospheric temperatures, cloud droplet sizes, and liquid water content (LWC). Typically, temperature is measured by a total temperature probe, droplet size by a cloud scattering probe (e.g., CDP), and LWC by a hot wire probe such as a King or Nevzorov Probe (Figure 2). The most difficult of these probes for obtaining reliable measurements can be the hot wire probe. Therefore, special data processing methodology has been implemented in ADPAA for hot wire probes.

The King Probe [53] was manufactured by Particle Measuring Systems, Inc. in Boulder, Colorado but is no longer sold. The King Probe can accurately measure droplets in the range between 10 and 40 µm in diameter [54]. There is an average error of about five percent for droplets smaller than 10 µm in diameter because the smallest droplets tend to follow the streamlines of air around the coil. For droplets greater than 40 µm in diameter, the error gradually increases to about 50 % for droplets of about 150 µm in diameter.

The King Probe consists of a long, thin (0.197 cm in diameter) metal coil (wire) that is 4.0 cm in length and has a 2.0 cm master coil. The coil is connected to a circuit that maintains a constant coil temperature of approximately 185 °C. Water droplets that contact the coil are evaporated due to the coil's high temperature. The latent heat energy required to evaporate the water is measured. The amount of electric power used to evaporate droplets is proportional to liquid water content (mass) of the cloud. However, not only is the power supplied to the coil used for water evaporation, but the power is also transferred to air molecules surrounding the coil. Hence, the total power (P) supplied to the coil has two terms, a dry power term (P_{dry}) and a wet power term (P_{wet}). Substituting in variables for the power terms and rearranging to calculate LWC gives the equation (see CSIRO-King Liquid Water Content Probe Manual for details):

$$LWC=\frac{P-[C(T_s-T_a)(\rho v)^x]}{ldv[L_v+c_w(T_{sw}-T_a)]}, \tag{1}$$

where C and x are calibration constants, T_s is sensor temperature, T_a is ambient air temperature, ρ is atmospheric density, v is true air speed, l is coil length, d is coil diameter, L_v is latent heat of vaporization, c_w is liquid water specific heat, and T_{sw} is temperature at which water vaporizes off the coil, which is assumed to be 90 °C.

The King Probe LWC processing uses calibration coefficients (c and x, Equation 1) that account for changes in the heat removal rate as the aircraft's air speed changes. The calibration coefficients are obtained by using an out-of-cloud flight segment where the speed is varied. For the North Dakota Citation Research Aircraft, the preferred air speed range is between 60 and 140 m/s. ADPAA has the "king_calib" script for calculating the calibration coefficients using a flight segment. After applying the air speed calibration, there is typically still an offset in the LWC measurement remaining due to changes in air density and humidity that affects the dry power term. While a more robust calibration is possible, it is found that there is always an offset remaining for out-of-cloud LWC measurements of up to 0.05 g/m³. Therefore, it is necessary to apply an offset correction to obtain the most accurate LWC measurements.

ADPAA contains software processing (king2lwc) to automatically apply an offset to the King Probe LWC measurements using the aircraft's out-of-cloud LWC measurement as zero baseline (Figure 4). Measurements from a cloud scattering probe (e.g., CDP) are used to determine an out-of-cloud segment. An out-of-cloud segment is defined as the total cloud droplet concentration being below 1.0 #/cm³ for more than 30 s. Some flights do not have many 30 s out-of-cloud segments, so a 10 s duration is used instead. A running average offset, termed "Offset Forward", is calculated for all out-of-cloud segments starting from the beginning of the flight until an in-cloud segment is located. Similarly, a running average offset, termed "Offset Backward", is calculated for all out-of-cloud segments starting at the end of the flight but moving backwards in time until an in-cloud segment is located. Offsets are again found once there is an out-of-cloud segment for the required duration. For each in-cloud segment, a linear interpolation is done along the in-cloud segment between the closest Offset Forward and Offset Backward to obtain the offset to apply to the LWC measurement. LWC with this offset applied is termed the Adjusted LWC. The out-of-cloud Adjusted LWC is typically close to zero, except when the aircraft is in cloud for a long time. The software handles measurements at different frequencies and data files containing missing value codes.

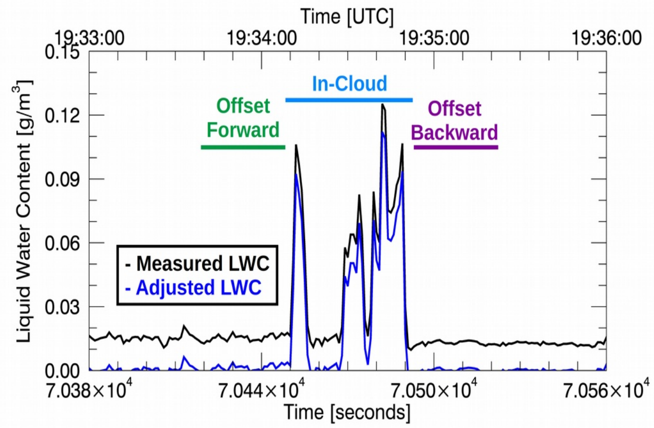

Figure 4: Plot showing a cloud penetration by the North Dakota Citation Research Aircraft on 9 March 2004. An offset of approximately 0.015 g/m³ is applied to the measured liquid water content (LWC) to obtain the Adjusted LWC. The Adjusted LWC is obtained by a linear interpolation of the average measured LWC during the "Offset Forward" segment and the "Offset Backward" segment.

The same offset methodology used to adjust the King Probe LWC measurements has been applied to the Nevzorov Probe [55] liquid and total water content measurements (Figure 5). Similar to the King Probe, the Nevzorov Probe measurement has calibrations applied to account for changes in the dry power terms that occur. However, there is an additional per flight calibration (Flight Cal. TWC) that is applied to the Nevorozov data that accounts for the specific flight conditions. An adjustment using a forward and backward offset is applied similarly to the King Probe methodology. However, the Nevorov processing uses a cloud imaging probe's (e.g., 2D-S) total concentration below 3,000 #/m³ (3 #/L) to determine out-of-cloud segments with a default duration of 5 s. The Nevzorov Probe's calibrated TWC is very close to zero; however, there is a slight improvement with the Adjusted TWC.

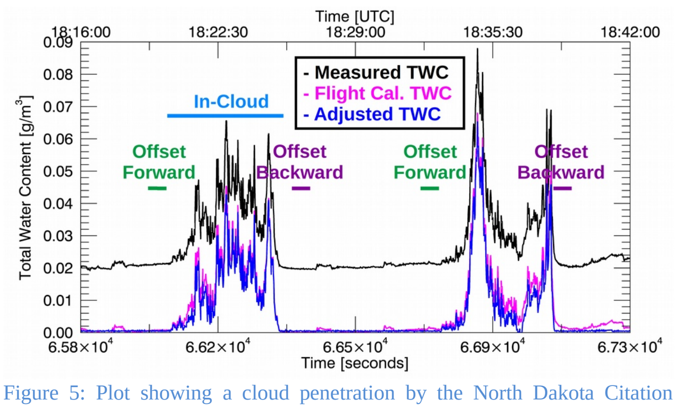

Figure 5: Plot showing a cloud penetration by the North Dakota Citation Research Aircraft on 30 July 2015. The Adjusted LWC is obtained by a linear interpolation of the average measured LWC during the "Offset Forward" segment and the "Offset Backward" segment consisting of a minimum of 5 s of 2D-S particle concentration greater than 3,000 #/m³ (3 #/L).

The implementation of the automatic LWC adjustment is done in the ADPAA nevzorov2twc_python module, which includes references to documentation included within ADPAA that fully describes the equations used to obtain the liquid and total water content. The nevzorov2twc_python module is coded in Python instead of the Interactive Data Language (IDL), which is used for the king2lwc module. ADPAA is moving away from IDL to Python by developing new modules in Python and rewriting old modules in Python when major coding changes are done; however, since software development is done as part of funded projects there is no support to just move working modules to Python. Therefore, ADPAA will likely depend on IDL for a long time. However, all ADPAA IDL modules include compiled binaries (sav files) that do not require an IDL license to execute. ADPAA development started with Python 2; however, coding is moving to Python 3. Another new practice for ADPAA developers is the creation of testing scripts for each module. For example, there is a Bash script included in ADTAE that automatically tests Nevzorov Probe processing using data from the 30 July 2015 flight of the North Dakota Citation Research Aircraft.

In addition to the King and Nevzorov Probes, ADPAA supports the Droplet Measurement Technologies (DMT) LWC hot wire probe and the SEA Multi-Element Water Content System. The automatic adjustment methodology has been implemented for the DMT LWC probe; however, an ADTAE testing script has not yet been developed. ADPAA processes data from the SEA Multi-Element Water Content System; however, the automatic offset adjustment has not been implemented. As part of upcoming projects, it is planned to add the automatic offset to the SEA probe and write testing scripts for both the SEA and DMT hot wire probes.

Conclusions

Aircraft-based cloud physics measurements are advancing with more advanced instrumentation that is smaller, which allows more measurements on research aircraft such as the North Dakota Citation Research Aircraft. Operation of research aircraft have moved away from universities to government agencies and private companies (e.g., WMI). The South Dakota School of Mines and Technology used to operate the T-28 Research Aircraft for hailstorm observations [56] and the University of Washington used to operate the Convair Research Aircraft [57]. Now, only the University of Wyoming is directly involved in research aircraft operations [58]. Universities still can play an important role in aircraft field projects by ensuring instruments are performing correctly, processing data to create quality-assured data sets, and refining processing methodologies. These tasks rely on robust, flexible and open solutions. Scientific software requires development using best practices for code writing, releasing code in open repositories, and building a community around software packages. There are existing tools for building teams to conduct aircraft field projects. Software developers can release packages in repositories provided freely by software hubs (e.g., GitHub and SourceForge) that are optimized to host open source projects. Wiki sites also enable fast, openly available documentation. Web sites provide a place to lay out the road map of projects and show current project status.

Community software packages, data sets, and tutorials can be easily integrated (e.g., CoPAS) to allow users to learn about the underlying assumptions in data processing methods and the inherent uncertainty. Researchers and students can focus on scientific understanding since they do not have to spend time developing software or gathering data sets. The benefits users receive from provided software packages will hopefully inspire them to contribute documentation and distribution tutorials. Advanced users may also contribute to software, get involved with ongoing networking activities, and develop package demonstrations. Professors, instructors, and developers should include such expectations into their classes, workshops, and courses. Of course, it is important to remember that the software developed is not the end, but the start to the scientific analysis process. The tools that ADPAA, ADTAE, SODA, and CoPAS provide are being actively used at the University of North Dakota to conduct data analysis and produce published papers [4,59–61].

The future is bright for utilization of aircraft platforms. The first joint UND/WMI field project (CapeEx19) utilizing the North Dakota Citation Research Aircraft is scheduled for July and August 2019. Advances in the instrumentation have provided us with 10 µm cloud imaging resolution [62] instead of 30 µm, reduced the size of the forward scattering cloud probe from requiring a full PMS can to being only one sensor on a cloud combination probe, and anti-shattering probe tips to reduce measurement artifacts [63]. These instrumentation advances coupled with more robust software allows us to effectively address topics of interest that have existed for a long time, such as aircraft icing caused by large supercooled drops [64,65]. While future instrument development will continue to reduce the size of instrumentation, the most sufficient advances will likely come by automatic processing and utilization of large amounts of data, typically termed Big Data. Additionally, the application of machine learning will also improve aircraft measurements. These advances will be made by teams (e.g., Universities/Private partnerships) working together to make continuous improvements while conducting aircraft measurement projects.

There are three themes that fit together for any aircraft project, which have been discussed using the North Dakota Citation Research Aircraft. One theme is the use of aircraft for observing properties of flight environments (icing, turbulence, etc.), and the instrumentation used to measure that environment, which needs to consider calibration and performance issues of the selected instruments. Another theme is the need for open source software for data processing, and the need to build a community that tests the quality of its software. A third theme is a history of past research projects and the creation/availability of aircraft data sets, and what the near future will bring. None of these three themes has tried to be emphasized over the other; instead, these themes are all important for obtaining understanding from any aircraft project. The correct aircraft platform, with the correct instrumentation, is necessary for obtaining required observations. Robust software is necessary to effectively process the observations to obtain a data set of high quality so the conducted analysis can provide the required information. Finally, experienced personnel are required to implement projects. Here we have tried to illustrate how a university research group can contribute to studies of the flight environment; however, it is acknowledged that there are several such groups that exist at universities, government labs, and private companies. All these groups face similar issues of developing and maintaining a financially-viable business model, maintaining state-of-the-art observing instruments, and supporting software to process and analyze the data. Hopefully, community workshops will continue to provide an opportunity for aircraft groups to discuss these common issues.

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Definitions/Abbreviations

2DC	Two-Dimensional Cloud Imaging Probe
ABFM	Airborne Field Mill
ASCII	American Standard Code for Information Interchange
ADPAA	Airborne Data Processing and Analysis
BCP	Backscatter Cloud Probe
CDP	Cloud Droplet Probe
CFR	Code of Federal Regulations
CIP	Cloud Imaging Probe
COBRA	CO2 Budget and Regional Airborne Study
CoPAS	Community Packages for Airborne Science
CPI	Cloud Particle Imager
Crystal-FACE	Cirrus Regional Study of Tropical Anvils and Cirrus Layers - Florida Area Cirrus Experiment
D2G	D2G Software Package
DAS	Data Acquisition System
DMT	Droplet Measurement Technologies
DOE	Department of Energy
EGADS	EUFAR General Airborne Data-processing Software
EUFAR	European Facility for Airborne Research
FAA	Federal Aviation Administration
FSSP	Fast Forward Scattering Probe
GCPEX	GPM Cold Season Precipitation Experiment
GPM	Global Precipitation Measurement
GPS	Global Positioning System
HVPS3	High Volume Precipitation Spectrometer Version 3
IAS	Indicated Air Speed
ICCP	International Conference on Clouds and Precipitation
IDL	Interactive Data Language
IPHEX	Integrated Precipitation and Hydrology Experiment
LWC	Liquid Water Content
LBA	Large-Scale Biosphere–Atmosphere
MC3E	Mid-latitude Continental Convective Clouds Experiment
MIT	Massachusetts Institute of Technology
M-PACE	Mixed-Phase Arctic Cloud Experiment
NetCDF	Network Common Data Form
NACP	North American Carbon Program
NASA	National Aeronautics and Space Administration
NEXRAD	Next-Generation Radar
ICCP	International Conference on Clouds and Precipitation
OAP	Optical Array Probe
OASIS	Optical Array Shadow Imaging Software
OLYMPEX	Olympic Mountain Experiment
PIREPs	Pilot Reports
PMS	Particle Measuring Systems
POLCAST	Polarimetric Cloud Analysis and Seeding Test
SAMAC	Software for Airborne Measurements of Aerosol & Clouds
SEA	Science Engineering Associates
SODA	System for OAP Data Analysis
SPEC	Stratton Park Engineering Company
TAMDAR	Tropospheric Airborne Meteorological Data Reporting
TDWR	Terminal Doppler Weather Radar
THORPEX	The Observing-System Research and Predictability Experiment
TRMM	Tropical Rainfall Measuring Mission
UIOPS	University of Illinois OAP Processing Software
UTC	Coordinated Universal Time
UT Corp	United Technologies Corporation
UND	University of North Dakota
WISP	Winter Icing and Storms Project
WMI	Weather Modification International
WRF	Weather Research and Forecasting