Report SDSMT/IAS/R07-01 January 2007

Report of the October 2006 Storm Penetrating Aircraft Workshop

Edited by Paul L. Smith

Prepared for:

National Science Foundation
4201 Wilson Boulevard
Arlington VA

Institute of Atmospheric Sciences
South Dakota School of Mines and Technology
501 East Saint Joseph Street
Rapid City, SD 57701-3995

ABSTRACT

This report summarizes the presentations and discussions at the Next Generation Storm Penetrating Aircraft (SPA) Workshop held in October 2006. The purpose of the workshop was to identify future scientific needs that justify the investment in a Next Generation SPA, and discuss ways to meet those needs. Many, but not all, of the needs require a capability to obtain measurements from the interiors of mature convective storms. Significant science needs for such a capability, which had been provided (with limitations) until 2004 by the armored T-28 aircraft, were identified in the areas of cloud and precipitation physics, storm structure and kinematics, atmospheric chemistry, atmospheric electricity, and the verification of radar algorithms and numerical cloud models. The workshop also identified a number of needs in areas outside the field of convective storms, such as boundary-layer meteorology, ecology, and air-sea interaction, which could be met by the Next Generation SPA. Such an aircraft must have performance characteristics in altitude, endurance and payload substantially better than those of the T-28. Prior studies had identified the A-10 as the most promising candidate for the next-generation SPA, and obtaining access to an A-10 through a collaborative effort with CIRPAS at the Naval Postgraduate School now appears possible. The discussions therefore focused on the role an A-10 SPA could play in supporting the broad range of research needs, and the broader impacts of an SPA program.

TABLE OF CONTENTS

ABSTRACT..2
TABLE OF CONTENTS...3
1. Introduction...5
2. Science Topics 7
  2.1 Convective Storms 7
  2.2 Tropical Convection...10
  2.3 Storm Chemistry and Electrification 14
  2.4 Planetary Boundary Layer 22
  2.5 Remote Sensing 23
    2.5.1 *Remote Sensing Retrievals*:..23
    2.5.2 *Local Remote Sensing of Cloud Volume around the Aircraft*:.............25
    2.5.3 *Opportunities to study and develop future satellite sensors.* 25
  2.6 Atmospheric Chemistry and Ecology 25
3. Additional Benefits 28
4. Instrumentation 29
5. Potential Projects for SPA 33
6. Education & Outreach...34
7. Broader Impacts 35
Acknowledgments...37
References...37
Appendix A: The Workshop Agenda 39
Appendix B: Workshop Attendees 40
Appendix C: The Towed Platform..42

List of Figures and Tables

Figure 1. Schematic illustration comparing tropical convection over the continents
vs. over the oceans 11
Figure 2. Radar vertical cross-section through intense oceanic convection
in tropical storm Chantal (18 Aug 2001). 12
Figure 3. Seasonal distribution of intense convection, as indicated by 40 dBz

echoes exceeding 14 km height and LIS flash rates exceeding 127/min..........................13
Figure 4. Example of a simulated distribution of NO_x in a STERAO storm................................18
Figure 5. Example of a model simulation of the distribution of CO_2 in a EULINOX storm (simulation based on aircraft data and CO_2 measurements taken in the anvil)..................20
Figure 6. Simulation of the distribution of HNO_3 in SPCZ convection (Pickering *et al.* 2001) ...22
Figure 7. Global distribution of flux measurement sites..26
Figure 8. Schematic illustration of the use of a laser scanner from an aircraft..............................27
Figure 9. Possible locations for electric field sensors on A-10..32
Figure 10. The Towed Platform..42

Table 1. Proxies for Convective Intensity..10
Table 2. Instrument List - Microphysical Studies..30
Table 3. Instrument List - Electrification Studies..30
Table 4. Instrument List - Chemistry Studies (1) 31
Table 5. Instrument List - Chemistry Studies (2) 31
Table 6. Possible education and outreach activities in conjunction with A-10 facility.................34

1. Introduction

This report summarizes the presentations and discussions at the Next Generation Storm Penetrating Aircraft Workshop held in Rapid City, South Dakota, 23-25 October 2006. The main purpose of the workshop was to provide input to the National Science Foundation (NSF) Division of Atmospheric Sciences regarding the future scientific needs for a capability to obtain measurements in mature convective storms. The armored T-28 aircraft, previously operated by the South Dakota School of Mines & Technology (SDSM&T) under a cooperative agreement with the National Science Foundation (NSF) as a lower atmospheric research facility to penetrate such storms and obtain measurements, was retired from active service in 2005. The T-28 played a key role for more than 30 years in many scientific field projects focusing on thunderstorm processes. Its retirement leaves a significant gap in observational capabilities available for supporting research in the atmospheric sciences; no aircraft currently available to the research community can safely penetrate the interiors of such storms.

The eventual need for an aircraft with greater capabilities to replace the T-28 was recognized as early as 1985 at a Special Advisory Panel session in Rapid City (see box below). The issue of a newer storm penetrating aircraft was revisited during Research Aircraft Fleet Workshops held at NCAR in 1987 (Johnson and Cooper 1989) and 1992 (Radke and Spyers-Duran 1992). A Storm Penetrating Aircraft (SPA) Workshop held in 1999 identified a number of science objectives that would benefit from the availability of an SPA with greater altitude, endurance and payload capabilities than those of the T-28 (Smith and Detwiler 1999). Discussions at that workshop, and later engineering investigations, identified the Fairchild A-10 “Thunderbolt” (commonly referred to as the “Warthog”) as the prime candidate for the Next Generation SPA. The A-10 would provide much higher altitude capability (near 40,000 ft, which would cover the full range of temperatures for supercooled liquid water in clouds), longer on-station time (3-4 hours), and greater payload capacity (up to 6000 lbs internal and more than 10,000 lbs external) than the T-28. Its design mission as a rugged ground-attack aircraft means that the A-10 is capable of relatively slow flight speeds compared to other jet aircraft, and is also suitable for low-level work.

> “…more capable storm penetrating aircraft for replacement of the T-28 within five years.”

From the report of an NSF-convened 1985 Special Advisory Panel

Little action ensued following those workshops, but a 2002 engineering study supported under the T-28 program did provide some specific information about the A-10 and the modifications that would be needed to convert it into an SPA. With the decision made in 2004 to retire the T-28, the need for a replacement became more urgent. Initial efforts to gain access to an A-10 were not met with enthusiasm by officials of the U.S. Air Force. Fortunately, it now appears that access to an A-10 through a joint working arrangement with CIRPAS at the Naval Postgraduate School will become possible in the next two years. To provide a current assessment of the scientific needs for the capabilities that would be provided by the A-10 and to assist in planning the aircraft modifications and instrument payload needed to convert the A-10 into an SPA, the NSF and SDSM&T convened this workshop in Rapid City. The workshop agenda appears in Appendix A. A group of scientists with interests in many areas of the atmospheric and related sciences (Appendix B) either participated in person or submitted written input for consideration by the workshop participants. The workshop discussions considered potential research uses of such an SPA, including ones beyond the mature-convective-storm mission, and also the broader impacts of an active SPA program.

The workshop began with a series of presentations on the history of the T-28 program, the opportunity to obtain an A-10 in the near future by working with CIRPAS, and some of the science needs that could be served by the new SPA. Those presentations are accessible at the following Web site: http://www.ias.sdsmt.edu/spa-workshop2006/agenda.htm

Most of the time was devoted to discussions and work in breakout sessions to prepare summaries of the presentations and discussions for this report. Special thanks are due to the leaders of the breakout sessions: Andy Heymsfield and Ed Zipser (storm structure, microphysics and dynamics), Mary Barth and Ken Pickering (electrification and chemistry), and Carl Friehe (remote sensing, boundary layer, *et al.*). This report focuses primarily on the results of the discussions and breakout summaries.

2. Science Topics

This section summarizes the workshop discussions of scientific questions and science objectives for which the capabilities of the next-generation SPA would contribute essential observations not obtainable by other means. It also notes some additional capabilities, not necessarily unique to an A-10, but which could be readily incorporated into the A-10 to provide a more versatile, more useful and cost-effective platform. The material is organized by broad science areas, beginning with the more traditional SPA role as previously supported by the T-28 and moving on to areas where the added capabilities of the A-10 are crucial to future progress or would be an important long-term asset.

2.1 Convective Storms

The study of convective storms, and hailstorms in particular, provided the impetus for the development of the T-28 Storm-Penetrating Aircraft. The T-28 program and other research activities over the last forty years have yielded significant advances in our understanding of convective-storm processes, but many questions about those processes remain. Listed here are some of the remaining science questions for which the next-generation SPA could provide essential observations within the storms and in their near environment.

- What are the properties of the mixed-phase region in deep, moist convection at temperatures between -5 and -40 deg C?
  - What are the thermodynamic properties of this and neighboring regions (to develop and verify retrieval algorithms and model simulations)?
  - What is the distribution of supercooled water?
  - What are the processes and rates of heterogeneous and homogeneous ice nucleation and secondary ice production, and how do they differ in continental versus maritime regimes?
  - What is the role of electrification in ice particle growth?

  - What microphysical processes occur in the supercooled regions of hurricane eyewalls? Where is the supercooled liquid water, and what is the rate of liquid to ice conversion?

- How do aerosols affect liquid and ice microphysics and cloud radiative properties in convection?
  - What is the role of aerosols in the condensation process, and what is the rate of aerosol scavenging?
  - What are the roles of dust and the indirect effects of aerosols on ice production?
  - How do effluents from biomass burning affect convective cloud microphysics and precipitation formation?
  - How do aerosols influence precipitation efficiency?
  - How are cloud radiative properties influenced by aerosol composition and updraft strength?
  - What dynamical and microphysical processes occur in pyro-cumulonimbus?

- What are the kinematic, microphysical and related characteristics of severe thunderstorms?
  - How do drop-size distributions in downdrafts (e.g., the rear and forward flank regions) affect the cold pool?
  - What is the effect of cold pool strength on tornado genesis?
  - How do low-level jets influence the storm inflow/boundary layer?
  - How do pressure perturbations and 3D winds vary across convection?
  - How does air enter a storm via entrainment or the rear flank downdraft, and where does that air originate (Q, thetaq)?
  - What temperature profiles are found through the rear flank downdraft?
  - What processes affect the buoyancy of the updraft, and how do they operate?
  - How is turbulence distributed in convection (partly to verify radar inferred values), and what is the importance of the turbulence processes?
  - What dynamic and microphysical processes occur in mammatus?
  - How do microphysical properties evolve downwind from convection?

- What are the microphysical characteristics of hailstorms, and how do they relate to kinematics in the storms?
    - Where and how do hail embryos originate?
    - What particle trajectories are needed for large hail production?
    - How are graupel and hail size distributions influenced by updraft dynamics and thermodynamics, and aerosol composition?
    - What are the densities and fall velocity characteristics of ice particles in graupel and hail regions, and how do they vary with storm thermodynamics?

- How can we improve microphysical parameterizations for convection in a wide variety of conditions?
    - What particle habits and particle size distributions are found under various conditions in the storms?
    - How do particle habits, from pristine crystals through heavily rimed crystals or raindrops to graupel and hail, and particle size distributions affect the radar echoes at various wavelengths and polarizations?
    - How do liquid and ice microphysics vary in continental versus maritime convection?
    - How do these change with the thermodynamic environment?

- How do cloud droplets and raindrops grow in convection?
    - What is the role of turbulence in coalescence growth?
    - What is the role of drop charge and electric field on drop coalescence and breakup?

- What are the differential microphysical and electrical characteristics across the melting layer in convection?

2.2 Tropical Convection

In the tropics as well as during summer at mid latitudes, rainfall is mostly convective; in the tropics it is almost 100% convective in origin. Direct measurements of the characteristics of tropical convection, and even observations by nearby ground-based radars, are limited to a few locations. To obtain the global coverage needed for investigations of global weather and climate requires use of proxy indicators, based on satellite observations, of the characteristics of tropical convection. Early satellites used the lowest IR temperature as an indicator of convective intensity; later satellites added microwave radiometric and (in the TRMM era) radar observations. Table 1 lists the primary indicators now available for convective intensity; knowledge of just how good they really are, or which of them might be best, is sorely needed. Moreover, convective intensity is not the same as total mass flux or total rainfall. Sorting all this out requires comparisons with *in situ* data that can only be obtained by means of a storm-penetrating aircraft with sufficient range to reach the tropical convective events of concern.

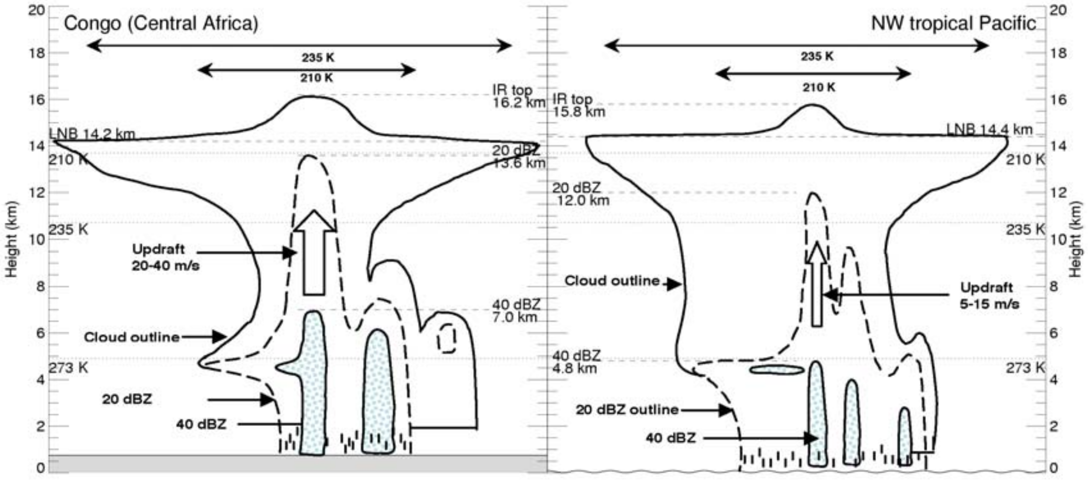
Table 1: Proxies for Convective Intensity

- Lowest IR temperature: gives indication of cloud top height, but poorly related to convective vertical velocity (might even be only thin cirrus)
- Highest altitude with radar echo >20 dBz – good
- Highest altitude with radar echo >40 dBz – good
- Total lightning flash rate – good
- Lowest brightness temperature at 85 GHz or 37 GHz – good

How good? Which are best?

The study of tropical convection is not a new or non-traditional area of research, but it is one for which a storm-penetrating platform is essential for future progress. The storms are not heavy-duty hailstorms, but the inability of traditional aircraft to conduct the research safely and/or reliably compromises the objectives of many programs. In the CRYSTAL-FACE project in Florida, many researchers were involved in objectives related to what the clouds were transporting from the lower troposphere to the upper troposphere and exporting into the anvil region. However, the available aircraft could not safely penetrate the core of the convection to acquire the needed *in situ* data. Another similar example occurred in the N-AMMA program, involving effects of African dust or biomass burning. Just as one is about to get to the interesting part of the storm, the active updraft, prudence dictates that the usual aircraft should avoid it.

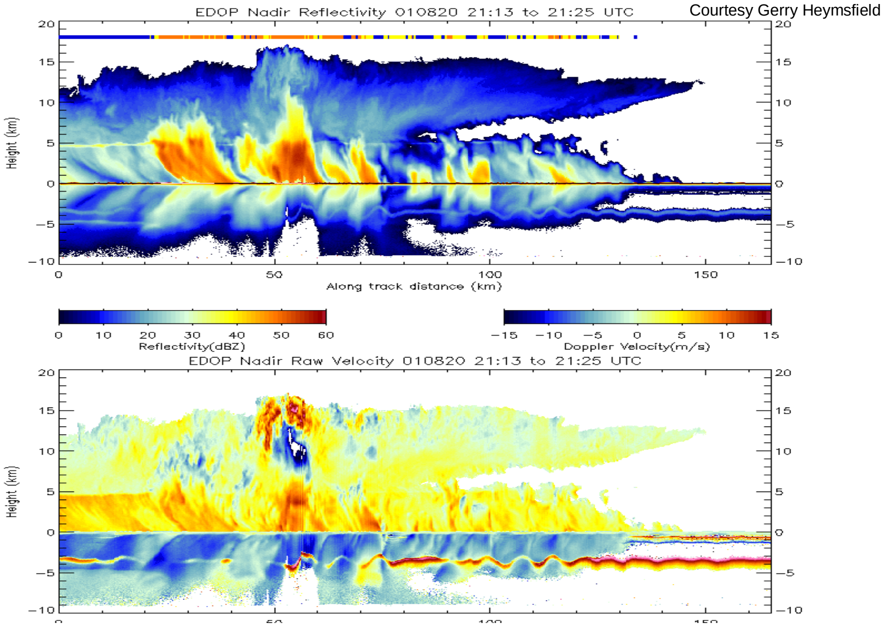
Tropical convection over the oceans differs in significant ways from that over the continents, as indicated in Figure 1 below, and tends to be weaker than continental convection. However, not all oceanic convection in the tropics is weak, as the example in Figure 2 demonstrates. Tropical cyclones and cyclogenesis are important topics for which data in the mixed-phase region (especially between the -5 and -20 deg C levels) are needed. Thus an aircraft with robust storm-penetration capability is needed to investigate these storms.



Convection over tropical continents	Convection over tropical oceans
Updrafts 20-40 m/s	Updrafts 5-15 m/s
Radar echoes much higher	Radar echoes limited in height
Anvils thinner but large optical depth	Anvils thicker with smaller optical depth
Larger fraction of convective rain; smaller stratiform area	Smaller fraction of convective rain; larger stratiform precip area

(after Liu, Zipser, Nesbitt, J. Climate, in press)

Figure 1. Schematic illustration comparing tropical convection over the continents (left panel) vs. over the oceans (right).



EDOP Nadir Reflectivity 010820 21:13 to 21:25 UTC

Courtesy Gerry Heymsfield

EDOP Nadir Raw Velocity 010820 21:13 to 21:25 UTC

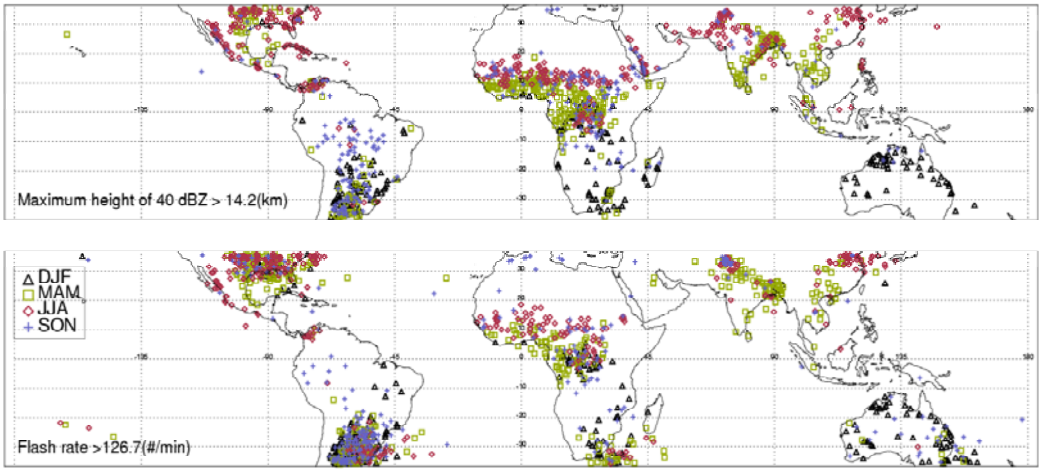
Reminder from tropical storm Chantal that not all oceanic convection is weak. DC8 flew through this at 11 km and "iced up".

Figure 2: Radar vertical cross-section through intense oceanic convection in tropical storm Chantal (18 Aug 2001). (Top) reflectivity; (bottom) Doppler vertical velocity; data below 0 km altitude are due to surface reflections.

Figure 3 shows the global distribution of intense tropical and sub-tropical convection, as indicated by the TRMM precipitation radar (top panel) and a satellite-borne lightning sensor (LIS; bottom panel). The general lack of intense convection over the tropical oceans is evident, but the figure raises several interesting scientific questions. For example:

- Why is central Africa so dominant compared to the Amazon and Indonesia?
- The southern Amazon does have some powerful storms in their spring, which also happens to be the burning season; is the smoke affecting the storms?
- What's happening in the ocean off South Africa (and to a lesser extent off North and South America as well as Australia)?

Investigations of oceanic convection, including tropical depressions and hurricanes, will require operation over water, which was feasible only to a very limited extent with the T-28. The main considerations are flight safety and crew rescue capabilities. The A-10 has twin engines, which would be an asset, and an in-flight restart capability. Its ejection seat includes a life raft and survival kit. The crew rescue situation would vary with the situation: How far out the operations would be feasible would depend on the available rescue capabilities. Fortunately, many maritime environments of interest are not too far offshore. For example, hurricane genesis experiments have been conducted at Darwin, Costa Rica, and the Cape Verde Islands. A ferry flight of 1-1.5 hours gets a jet aircraft like the A-10 a long way offshore. Moreover, the A-10 has an in-flight refueling capability; that feature, and the facilities needed for coordination between the plane and tankers, should be retained.



Seasonal distribution of intense convection, measured by 40 dBZ echoes exceeding 14 km and LIS flash rates > 127/minute (after Zipser et al. BAMS Aug 06)

- Dominance of TX-OKLA, Argentina no surprise. Land dominance no surprise. Sahel storms in JJA no surprise.
- Why does central Africa stand out compared with the Amazon and Indonesia?
- What's happening in the oceans east of South Africa?
- Storms in southern Amazonia strongest in SON (burning season). Is this a coincidence? Significance for vertical transport?
- Storms in Pakistan and Kashmir strongest in monsoon, near the Bay of Bengal and SE Asia in pre-monsoon.

Current global models don't know the difference between intense and ordinary convection. Better knowledge of dynamics, cloud and precipitation microphysics, lightning, radiative properties, and chemical transports of ALL classes of convective clouds is needed for credible models of our current atmosphere, let alone for the earth system in future climates. In situ data in convective clouds is a necessity to complement remote sensing data and model simulations.

Figure 3: Seasonal distribution of intense convection, as indicated by 40 dBz echoes exceeding 14 km height (top) and LIS flash rates exceeding 127/min (bottom); (Zipser *et al.* 2006)

Current global models don't know the difference between ordinary and extreme convection. If the global models don't know, we need better knowledge of dynamics, cloud and precipitation microphysics, lightning, radiative properties, and chemical transports.

2.3 Storm Chemistry and Electrification

Ozone (O_3), a greenhouse gas (GHG) in the upper troposphere, is produced from NO_x and HO_x radicals. Thus, quantifying the sources of NO_x and HO_x (which are sources of O_3) in the upper troposphere is key to understanding the climate implications of upper tropospheric O_3. The primary production of NO_x in the mid to upper troposphere occurs in lightning discharges. Consequently these storm chemistry and storm electrification processes are intimately linked.

In addition, lightning is a major cause of wildfires in the Western US and a significant threat to aviation and public safety. Lightning, particularly total lightning, is also a strong indicator of the intensity of deep convection and a useful nowcasting tool. Thus, the important scientific questions begin with the electrification and lightning processes; in general,

- How do clouds become electrified?
- How is lightning initiated?
- What determines the path and termination of the flash leader?

Detailed questions in these categories are listed below, with the types of measurements required and suggested experimental strategies for addressing them included in many cases.

- What conditions lead to initial electrification in clouds? Can these conditions be inferred from routine ground-based weather sensors (i.e., dual-polarized radars and surface electric field mills)? Do these conditions suggest the possibility of new ground-based remote sensors to profile electric fields in clear air to thunderstorm cores?

- Are the charges observed on particles consistent with hypothesized storm charging mechanisms (e.g., the non-inductive ice-ice charging hypothesis)?

  Measurements are needed of particle charges as well as types, numbers, and size distributions. Such measurements are needed across the storm cores in the temperature range -15 to -20 deg C, to study the horizontal variability and the time variation of these quantities. An SPA capable of making the measurements in these locations is the only realistic way to obtain these observations.

- Where is the electrical charge located in thunderstorms, and how is it related to where lightning propagates?

  A Lightning Mapping Array (LMA) can be used to tell where lightning discharges go. The A-l0 penetrations can be directed on the basis of the LMA observations to fly to the vicinity of recent lightning, and measure field changes to examine the redistribution of charge.

- How is the electric field in anvil clouds related to particle types and NO?

  Knowledge is needed of the location of the NO source(s) in relation to that of the electric field/lightning discharge. We also need to know the distribution (both vertical and horizontal) of the electric field in relation to particle types and concentrations. Currently we have to infer answers to such questions on the basis of data taken from existing aircraft in portions of anvils well away from convective cores. Measurements near the source are necessary, which dictates the need for an SPA. A related question concerns any charge separation in the anvil, perhaps in mesoscale convective systems (MCS).

- How are the electric field and the NO in anvil clouds related to storm characteristics, such as the charge regions, where lightning is propagating, or the vertical extent of LWC and IWC? Can forecasting of lightning, both intra-cloud and cloud-to-ground, in anvil clouds, and of cloud-to-ground lightning from thunderstorm debris clouds, be improved?

  The charge structure of the storm is needed along with LMA data, with inverted charge structures of particular interest. Also needed is information about the mass distributions and mass fluxes of cloud particles, and the updraft profile.

- How is lightning initiated? Are runaway electrons involved?

  We need airborne measurements of X-rays in cloud, as observed within roughly 500 m from the source, along with ground (LMA) observations. An SPA is necessary to do this, especially for all kinds of storms in different locations. Small instruments, similar to those developed over the past decade for balloonborne flight, are available for this purpose, so routine measurements are practical. Balloons cannot be steered to the desired positions close to the lightning discharges and provide primarily vertical profiles, with any indication of horizontal variability dependent on the trajectory and convolved with the vertical variability. Including this instrumentation in the core suite for the SPA will allow every SPA mission to add to the knowledge base regarding this question.

Terrestrial gamma-ray flashes (TGFs, millisecond bursts of high-energy radiation seen over thunderstorms from orbit; Fishman *et al.* 1994, Smith *et al.* 2005) are almost certainly caused by relativistic runaway breakdown (RRB; Gurevich *et al.* 1992), which produces MeV-range gamma-rays by the bremsstrahlung of accelerated electrons. Recent evidence suggests that only the very highest-altitude TGFs are seen from space, and that their origin is at the tops of thunderstorms, in association with +IC lightning (Dwyer and Smith 2005; Cummer *et al.* 2005; Stanley *et al.* 2005; Williams *et al*. 2006). A very similar flash of MeV gamma-rays, at an estimated altitude of origin of 6 km, has been observed from the ground in Florida (Dwyer *et al.* 2004), suggesting that the process may be universal to all classes of lightning. The RRB process is also one of the leading candidates for the basic lightning-initiation process (Smith *et al.* 2005); one of the key questions is whether TGFs are related to the cause of lightning or are a side-effect – or whether they might even occur independently (Cummer *et al*. 2005).

Electric and magnetic field measurements from DC to HF frequencies can indicate where and when atmospheric breakdown occurs, but only the addition of gamma-ray observations can determine whether RRB or another process is responsible. Observations of the TGFs from space, at a distance of 600 km, involve the capture of only a few dozen photons, even in relatively large instruments. If the distance were reduced to 6 km, 10,000 times as many photons would be available from a TGF. The Airborne Detector for Energetic Lightning Emissions (ADELE), currently being built, will have a large collecting area, a fast response, and a sensitive energy range matched to the observed TGF spectra (20 keV to 20 MeV). The A-10 is the ideal platform for ADELE, since frequent and close visits to the vicinity of thunderstorms are paramount. The limited data available (Dwyer and Smith 2005; Cummer *et al*. 2005; Stanley *et al.* 2005; Williams *et al.* 2006) suggest that 10-15 km may be the most common altitudes of origination for TGFs. However, events starting above the airplane and beamed upwards will be easily detected via Compton scattering of the gamma rays by the atmosphere above.

- What conditions lead to the End of Storm Oscillation in the electric fields? What conditions preclude the last lightning flash? Can these conditions be inferred by routine ground-based weather sensors (i.e., dual-polarized radars and surface electric field mills)?

- How do aerosol types and concentrations affect thunderstorm characteristics, including storm electrification?

  The relative lack of lightning discharges in marine vs. continental thunderstorms was noted in Sec. 2.2.; the different aerosol environments presumably play a key role in this difference. Better understanding of the linkage aerosols (nuclei) → particle size distributions → particle charging is needed. Some storm situations occur with special aerosol environments: storms over biomass burning regions or over industrial regions. Electrification and lightning also occur in "pyro-cumulonimbus" (both the smoke and thermal effects can affect electrification and storm polarity) and in volcanic plumes.

- What microphysical and dynamical processes are related to the relative lack of lightning in tropical maritime convection, especially hurricanes?

The scientific questions then extend to the chemical processes associated with the discharges; in general,

- How and where are the important chemical species produced?
- In what quantities?
- Where do they go?

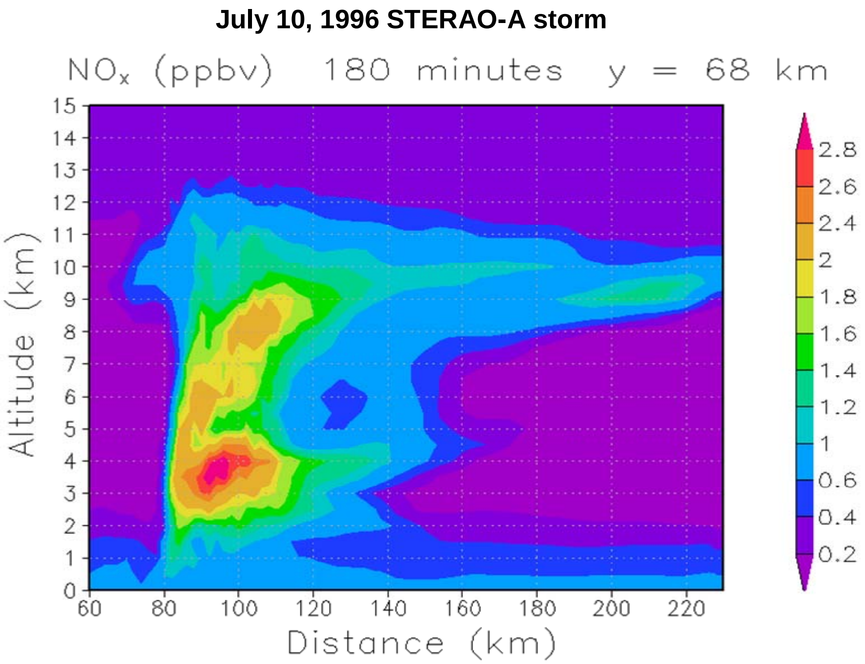
Important chemical families include:

$NO_x = NO + NO_2$

After NO is produced it rapidly comes into equilibrium with NO_2. The NO_2 can be further oxidized to many other reactive nitrogen products. NO_y (total reactive nitrogen) is defined as

$NO_y = NO_x + HNO_3 + PAN + NO_3 + N_2O_5 + RONO_2$

The model simulation of a 1996 STERAO storm illustrated in Figure 4 below illustrates the complexity of the distribution of NO_x in a storm, and its concentration in the most active regions.


July 10, 1996 STERAO-A storm

Ott et al. (2006b, JGR, in prep.)

Figure 4: Example of a simulated distribution of NO_x in a STERAO storm.

Again, detailed questions in these categories are listed below, with the types of measurements required and suggested experimental strategies for addressing them included in many cases.

- What parts of the lightning discharge produce NO? What physical parameters of electrical discharges are relevant to the production of NO and other species? How large is the perturbation to NO_x mixing ratios in the convective region of storms? Where does the NO go once it is produced?

Is the primary NO production (i.e. lightning) occurring within updrafts, downdrafts or transition zones? Does the production differ between lightning trunks versus lightning branches? Measurements are needed of the NO_x and NO_y families, along with O_3, across the storm core along with the LMA observations of the discharge locations. By flying within the field of view of LMA systems such as those at NASA Kennedy Space Center, in central Oklahoma, in New Mexico and elsewhere, the production of various species can be tied closely to the locations and characteristics of the lightning discharge channels.

- How much NO is produced from cloud-to-ground lightning versus intracloud lightning?

  Traditionally it has been assumed that the production of NO from an intracloud (IC) discharge is on average 10% of that from a cloud-to ground (CG) discharge. Recent modeling and theoretical work suggests that the values are actually similar. SPA measurements of NO production after recent CG and IC strikes at different altitudes are needed to validate this suggestion.

- How much variability of NO production by lightning is there from flash to flash?

- What is the vertical profile of NO produced from lightning?

  Balloon measurements provide some comparison of NO between low, middle and high altitudes. Cloud/chemistry models have provided some indication of the integrated effect of numerous lightning discharges on the profile of NO_x within a storm (e.g., Figure 4). SPA observations that can be directed to the proximity of the discharges are needed to improve the quality and quantity of these data sets.

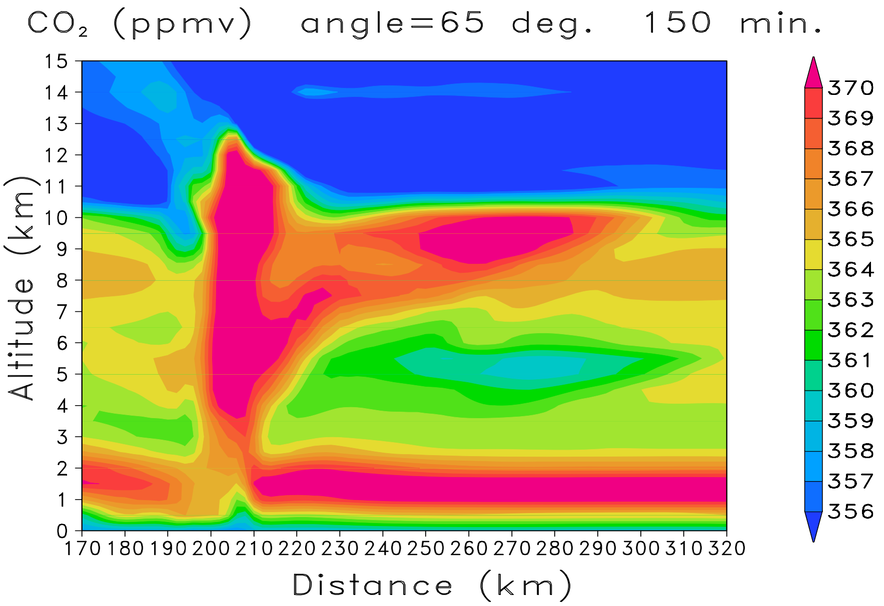
- What other species (e.g. O_3, OH, HO_2, CH_2O, CO) may be produced from lightning?

  Measurements are needed of O_3 and the other species across the storm core, along with the LMA observations of lightning locations.

- What are the mass fluxes of chemical constituents? What are the transport characteristics of the updrafts and downdrafts, and how do they vary within different types of convection?

Tracer measurements of constituents that do not change through chemical or physical processes, such as CO, O_3, CO_2, hydrocarbons, or CH_3I, are needed across storm cores, along with velocity data for flux calculations. Figure 5 indicates the complexity of the CO_2 distribution in a 1998 EULINOX storm, with high concentrations at mid levels in the active region of the storm that would be accessible with the SPA.

July 21, 1998 EULINOX storm



Ott et al. (2006a, JGR, in press)

Figure 5: Example of a model simulation of the distribution of CO_2 in a EULINOX storm (simulation based on aircraft data and CO_2 measurements taken in the anvil).

- How are the ozone (O_3) concentration and distribution affected by convection? In particular, what is the perturbation to O_3 mixing ratios by NO production from lightning? Can O_3 perturbations be seen within the storm (core + anvil) and can they be attributed to lightning (vs. entrainment)? Is there indirect production or destruction of O_3 from lightning discharges? Measurements of NMHC are also needed; an autonomous Whole Air Sampler is available but it has poor time resolution.

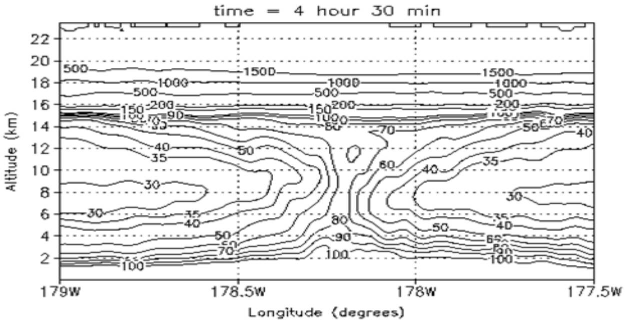
- How is the actinic flux distributed and/or perturbed within a thunderstorm?

  A spectral actinometer can make the needed measurements, but the current version of the instrument is fragile and may not be suitable for use in hailstorms. Means for shielding the instrument from hailstone impacts can be developed.

- By how much are photolysis rates perturbed within a storm?

- How are soluble species distributed within thunderstorms? What processes (transport, scavenging, ice microphysics, adsorption of gases onto ice) are important to these species? What fractions of soluble species are degassed during freezing of hydrometeors?

  Measurements are needed of species such as CH_2O, H_2O_2, HNO_3, CO, SF_6, O_3, CH_3OOH, and HCOOH, especially in riming regions of the storms. Measurements are also needed of gases dissolved in the cloud water or adsorbed/entrapped in the ice. Supporting data on LWC and IWC are required. Figure 6 below illustrates the importance of scavenging processes in the storms. Another question is whether OH and HO_2 concentrations are controlled by perturbations in the radiation field, in aqueous chemistry, or in gas chemistry?



HNO3 simulation for SPCZ convection
without wet scavenging

Observations show 5-10 pptv HNO3 at 11 km
compared with ~70 pptv in model

Therefore, 85 - 93% removal had occurred
within the cloud

Figure 6: Simulation of the distribution of HNO_3 in SPCZ convection (Pickering *et al.* 2001).

These questions lead into longer term questions such as:

- Can we connect thunderstorm properties, constituent (e.g., O_3) mixing ratios, and climate to be used in earth system modeling?
- Can we connect biogenic emissions of trace gases, their conversion to aerosols and their precursors, the activation of cloud condensation nuclei, cloud properties (e.g., radiation and precipitation), and their feedbacks on biogenic emissions?

2.4 Planetary Boundary Layer

The T-28 was not used to address science questions related to the planetary boundary layer (PBL), and other aircraft are capable of PBL observations in many situations. However, the near-storm environment feeds back into the evolution of the storm life cycle and the PBL is an important area that requires *in situ* measurements in such regions as gust fronts or cold pools. Storm updraft-inflow and precipitation-filled boundary layer (BL) morphology, turbulence and fluxes should be examined in greater detail. For example, current "wind law" profile theory neglects diabatic and precipitation loading effects. Whether focused on the ambient PBL or extending into the storm, the low-level operating capability of the A-10 would provide an excellent platform for such measurements if equipped with an appropriate sensor suite. The rugged nature of the aircraft would enable measurements to be made in high-wind boundary layer environments with associated turbulence. Another example is the high-wind BL over the ocean, where further understanding is greatly needed to feed into the understanding and prediction of hurricanes. Recent research has indicated a critical regime change of wind/energy exchange over the ocean with surface winds above 20-25 m/s. Aerosol measurements with the A-10 would also be valuable in determining the importance of sea spray in ocean-atmosphere energy exchange.

The heavy payload capacity of the A-10 would enable dispensing of expendables such as dropsondes, radar chaff, or ocean drifter probes. A newly developed towed platform capability would allow measurements very near the surface (30m) while the aircraft is flying above at a safe altitude. Appendix C provides more information about this potentially significant value-added benefit of the A-10 SPA.

2.5 Remote Sensing

Remote sensing is an important means of obtaining information about the atmosphere and about clouds and storms. Such information supports research on a wide variety of scientific questions, and a good understanding of the capabilities as well as the limitations of the remote sensing techniques is essential to the effective use of the observations. Remote sensing questions relevant to the use of an SPA fall into two broad categories:

- Are the quantities inferred from remote sensing retrievals accurate?
- How could remote sensing expand the purview of the SPA observations, and vice versa?

2.5.1 *Remote Sensing Retrievals*: Recent advances in remote sensing technology (both passive and active) have pushed the technology to a mature level. The planned polarimetric upgrade to the NEXRAD radars makes use of research achievements over the last two decades, including microphysical retrieval algorithms for which data collected by the T-28 have provided part of the basis. Satellites now operating (such as TRMM, Cloudsat/CALIPSO and AQUA) and new generations of satellites (such as NPOESS and PMM) lead to monitoring at global scales, with inferences about cloud and storm microphysics as well as more traditional quantities. The retrieval algorithms based on passive or active remote sensing must be verified by *in situ* observations, and an SPA is the only platform suitable for accomplishing this in mature-storm environments. Such observations also provide the basis for development of new and improved algorithms.

A closely-related problem arises with numerical models, and especially storm-scale models, that include microphysics as well as kinematics and dynamics. Such models employ microphysical parameterizations that are not yet in agreement with remote sensing observations, and the available *in situ* observations are not adequate to establish the validity of either. A related problem is that cloud models have grown in detail to the extent that they routinely predict quantities such as hydrometeor concentration and mixing ratio within mixed-phase precipitation environments; present-day radars are unable to discriminate or quantify these things. Moreover, the vertical winds and the turbulence in model storms, or inferred from Doppler radar observations, need to be verified against *in situ* observations. Severe-weather storm scale modeling, in particular, is still limited by the lack of *in-situ* verification data at the time and spatial scales of severe weather. A next-generation SPA would provide valuable support to improvement of the models as well as the remote-sensing retrieval algorithms, in addition to providing “anchor points” for improved understanding of the storm processes.

In situ measurements to obtain hydrometeor type, size, shape, density and fallspeed are needed to bridge the current gap between remote sensing retrievals and models. These microphysical measurements will provide the data needed to improve and calibrate/validate remote sensing tools. The intensity of the radar return generally depends on the 6th power of particle size, so it is very important to measure the tail of the hydrometeor size distribution. This requires sampling with instruments having large sample volumes, for which the large payload capacity of the A-10 would be an asset.

In situ measurements in the most active regions of the storms are fundamental to the basic understanding of the physical environment and mechanisms of storms. A capability to follow the evolution of a storm cycle, for example from initiation through to the supercell stage, with a platform whose performance (endurance, altitude) matches the cycle time of the storm is needed. The typical lifetime of a supercell is 1-2 hours (Bunkers *et al.* 2006) and the A-10 with an on-station endurance of 3 hours would provide a good match to the time and space scales of such a storm.

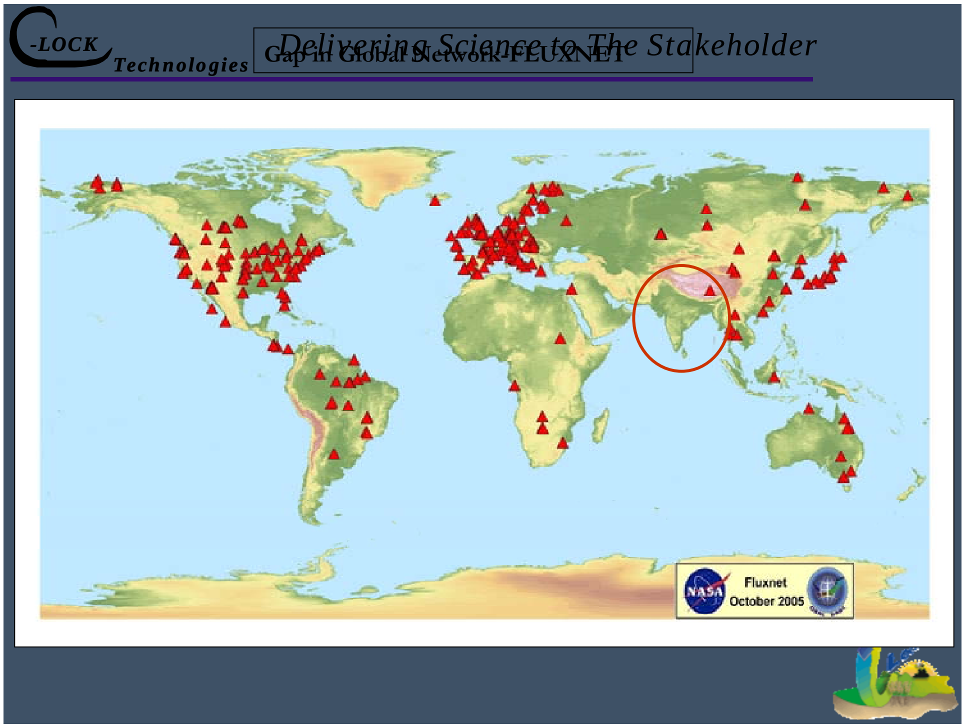
Large field campaigns typically use a variety of aircraft along with satellites and ground sensors in an effort to observe storms from all aspects - but as noted earlier, this usually excludes the violent interior of storm. This gap in the information needed for comprehensive process understanding can only be filled by a storm penetrating aircraft like the A-10.

2.5.2 *Local Remote Sensing of Cloud Volume around the Aircraft*: The payload capacity of the A-10 would permit carrying local remote sensors such as lidar or radar to measure and characterize the region around the plane as it traverses the storm. With a lidar or radar, the observations of the storm interior would be extended from a point or line to give a volumetric picture of the storm structure, over a distance of perhaps a few kilometers. It would add a new dimension by combining *in-situ* and remote sensing to help bridge the spatial scales of the observations. For example, vertical beams could give distributions of particle fall speeds and up/downdrafts in the storms. A cross-polarized channel would characterize regions of melting and wet ice, including wet-growth regions in hailstorms. Polarized horizontal beams could give distributions of rain water content. Such observations taken together with the *in situ* measurements will give an unprecedented insight into the physical processes inside storms.

2.5.3 *Opportunities to study and develop future satellite sensors.* New measurements obtained with the next-generation SPA may prompt development of new remote sensing techniques and sensors for future satellite systems or ground arrays.

2.6 Atmospheric Chemistry and Ecology

The measurement of fluxes in the PBL is essential to an understanding of ecological processes and land-atmosphere interactions. Figure 7 shows that the global distribution of routine flux measurements is limited and concentrated in a few areas, mainly in the northern hemisphere. The A-10 capability for low-and-slow flight, and its payload capacity, would make it an excellent platform for carrying flux-measuring instruments to cover the gaps between surface stations and help extend the coverage of these observations. Those capabilities lend the aircraft to direct observation or remote sensing of the above, supporting carbon cycle research or studies of land use or radiation balance.


Delivering Science to The Stakeholder

Gap in Global Network-FLUXNET

Figure 7. Global distribution of flux measurement sites

Investigations of the biogeochemical role of cumulonimbus clouds require similar flux measurements of the substances in the boundary layer being ingested into intense convection. The A-10 SPA would be capable of both the flux measurements and the in-cloud measurements required for these studies.

The gun bay of the A-10 would also provide sufficient space and payload capacity to carry a downward-looking lidar, as illustrated in Figure 8. This would provide detailed information about the plant canopy and the terrain profile.

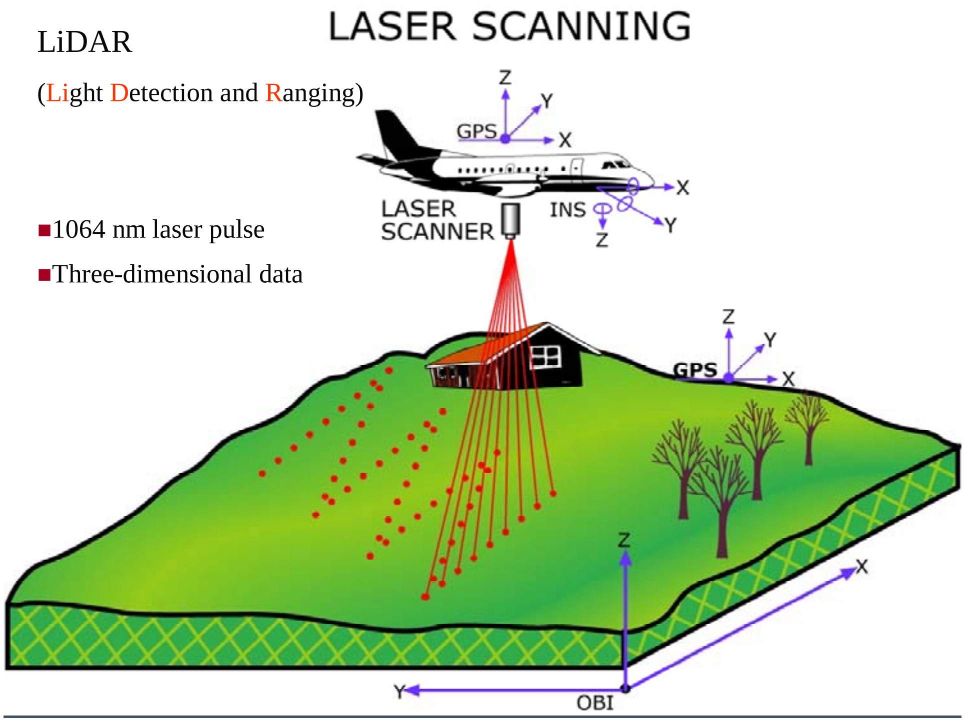


Figure 8. Schematic illustration of the use of a laser scanner from an aircraft.

3. Additional Benefits

The large payload capacity of the A-10 would permit carrying a wide variety of instrumentation for auxiliary measurements, not necessarily related to the storm-penetration mission. Such capability is not unique to the A-10, but the aircraft does have performance capabilities that could be useful in many situations. Some examples of such measurement possibilities, several of which have been mentioned in earlier sections, are:

- Fluxes (momentum, heat, chemical species)
- Radiation
- Land remote sensing
- Ocean wave sensing
- Launching expendables (sondes, ocean probes, radar chaff)
- Towed platform for low-level measurements
- Ecological (canopy-sensing lidar) system sensing

The A-10 will also be useful in experiments testing the multifunction (e.g., track-while-scan) capabilities of the phased-array radar system at the National Weather Radar Testbed in Oklahoma. Such experiments will provide the basis for decisions concerning the possibility of combining weather surveillance, air traffic control, and homeland security missions in a single radar network.

The T-28 was basically a warm-season aircraft, with few winter deployments. The better performance characteristics of the A-10 could permit some winter-time activities. For example, in lake-effect situations the lake is typically partially covered with (mostly) thin ice. It is difficult to fly low enough to obtain valid flux measurements, and small-scale variations are hard to measure. The combination of being able to take downward-looking measurements to correctly measure the ice cover as well as to get the low-level flux measurements with the A-10 would be of value in lake-effect studies. Also, most severe heavy snows tend to be electrified and data from those situations would be of great value.

4. Instrumentation

Instrumentation was not a primary topic of discussion at the workshop, but numerous suggestions for instrumentation emerged during the deliberations. This section provides a brief summary as background for future detailed consideration of the SPA instrumentation complement.

For the storm penetration mission, instruments suited to withstand hail impacts and severe icing conditions will generally be required. The experience gained from the T-28 operations in mature-storm environments will provide valuable background to the development of any new instruments.

Proceeding from the instrument suite previously flown on the T-28, a list of additional desired instrumentation might include the following:

- Accurate in-cloud air temperature and water vapor mixing ratio measurements (new development)
- Better particle shape discrimination (e.g., CPI, 2D-S)
- Increased particle probe sampling volume with better sizing accuracy and shape information (new development)
- Measurement of condensed (liquid + ice) and liquid water contents (e. g., CVI)
- Small-ice detector probe that differentiates liquid from ice (e.g., SID-2)
- CCN and ice nuclei counters (new development for autonomous operation)
- Collectors for residuals to be studied with electron microscopy (e.g., Twohy CVI)
- Dropsonde microphysical probes (new development)
- Upward or downward looking radar; sideward looking polarimetric radar (e. g., like CASA radar)
- On-board weather radar
- High quality 3D winds (pressure ports)
- Differential GPS
- Electric field meters and field-change antennas
- Extinction/transmissometer (e. g., CIN, new development)
- Dispensers for radar chaff and other expendables
- Towed platform for low-level measurements

Tables 2-5 below provide an assessment of the relative priority and state of readiness of the instruments needed for studies of microphysics, storm electrification and related chemistry issues. Figure 9 indicates a possible arrangement for electric field mills on the A-10.

Table 2: Instrument List – Microphysical Studies

Variable/Instrument	**Priority**	**Readiness**
Particle phases, habits, size distributions	High	Development Needed
Condensed water content	High	Ready
Extinction/Transmission	Medium	Development Needed
Water isotopes	Medium	Development Needed
Particle collectors	Low/Medium	Development Needed
Water vapor concentration	High	Ready

Table 3. Instrument List - Electrification Studies

Variable/Instrument	**Priority**	**Readiness**
Field mills, field change	High	Ready
Particle charge, phase, habit (shape), size	High	Development needed
X-ray	High	Ready
Optical – broadband visible	Medium low	An idea

Table 4. Instrument List - Chemistry Studies (1)		
Constituent/Instrument	**Priority**	**Readiness**
CO analyzer	High	Ready
O_3 analyzer	High	Ready
NO (1 Hz or better rate)	High	Ready
NO_2	Medium low	An idea
HNO_3 (CIMS)	High	Ready
H_2O_2, CH_3OOH	High	Automated instrument ready in 2-4 years
HCHO	High	Need to automate

Table 5. Instrument List - Chemistry Studies (2)		
Variable/Instrument	**Priority**	**Readiness**
SO_2 (CIMS)	High	Ready
CH_3I	Medium – must for ocean	Have tech.; automation?
NMHCs (WAS)	Medium	Ready
Spectral actinometer	High	Ready; needs hail protection
Aerosol number concentration	High	Instrument vulnerability issues
Aerosol composition (AMS, PILS, PALMS)	High	Automation? Inlet, size issues
Condensate composition	Medium	Challenge
OH, HO_2	Medium	Ready
RO_2	Medium	Needs automation

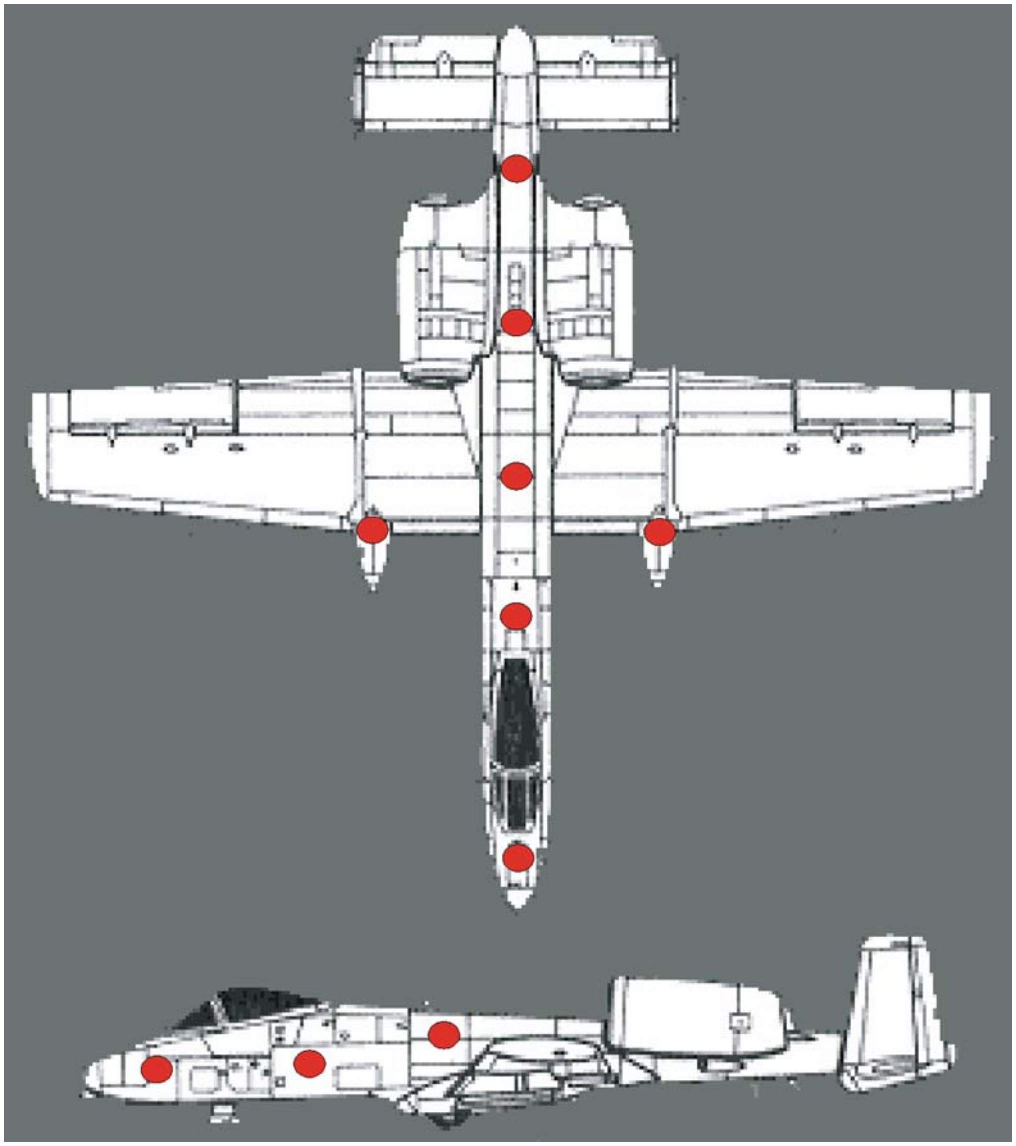


Figure courtesy of Doug Mach)

Figure 9: Possible Locations for electric-field sensors on A-10

In addition to the instrumentation *per se*, the SPA facility should include provision for the necessary supporting ground-based infrastructure. This might include an operations center for directing the A-10 flights, with communications capabilities linking the center with the aircraft and any supporting radar systems, LMA, or the like. The aircraft should have SatCom capability and means for telemetering key data to the operations center. The SPA will often be involved in multi-aircraft projects, and provision for coordinating those aircraft will also be needed.

5. Potential Projects for SPA

Projects planned over the next few years that would benefit from the availability of an SPA include:

- DC3
- Staccato
- Vortex 2
- NASA UTLS NO_x mission

6. Education and Outreach

The next-generation SPA would offer many opportunities to enhance education and outreach activities. As was often the case with the T-28, static displays would be of great interest to students as well as to the public at large. Interest in severe storms, their characteristics and manifestations is widespread. Real-time transmission and display of the *in situ* information during flight operations, perhaps using Internet capabilities, would provide many opportunities for education and stimulation of interest in the work and in science. The NSF Research Experience for Undergraduates (REU) program involved students with the T-28 program, and would also be appropriate for the new SPA. Table 6 lists other ideas for possible education and outreach activities in conjunction with the A-10 facility.

Flight simulators are an important part of training activities in the aviation industry. Hail impact data from the T-28 windscreen microphone have been used in the Army helicopter pilot training program as part of the simulator program. The SPA data could also be useful in the COMET program, and additional opportunities to use data from the A-10 in training applications can be anticipated.

Table 6. Possible education and outreach activities in conjunction with A-10 facility
Student experiments on board using existing instrumentation (high schools and undergraduates) o Take plane to airport near school o Web locator of A-10
Train new generation (high school, undergraduate, graduate) o Hands-on activities o Use of A-10 data from web
Lesson plans o Give students weather forecast and have them decide whether to fly, or not (then discuss what actually happened)
Underrepresented groups? (existing programs)
Policy Planning o Flight safety

7. Broader Impacts

A next-generation SPA would provide important kinematic and microphysical data for NEXRAD algorithm development for severe-storm situations, as well as for the design of future satellite systems. The aviation industry has used T-28 data about the interior characteristics of storms to help understand the problems of engine flameout due to water and ice ingestion, and to develop turbulence algorithms for aircraft radar and other sensing systems. The fact that the A-10 can reach the operating altitudes of commercial jet aircraft would enhance the value of the data it collects for these applications. The inclusion of a weather radar on the plane would help improve interpretation of airline weather radars and also contribute to icing research with the FAA.

The pilots of an SPA have unique experience with extended intervals of flight inside mature thunderstorms. They are thus specially qualified to educate other pilots (and the rest of the aviation community) about the hazards involved and about the best ways to stay out, or get out, of trouble when encountering such storms. The T-28 pilots have been quite active in presenting their experiences to the aviation community and writing articles in aviation journals. Pilots of the A-10 would certainly continue this tradition, as a contribution to the broader aviation community.

The nation’s space program is quite sensitive to weather factors, especially to lightning hazards at launch sites. The new SPA could help improve lightning forecasting through in-cloud measurements of initial electrification in developing cumulonimbus that could be correlated to operational sensors, particularly dual-polarized radar. Another benefit from this type of research would be improved Lightning Launch Commit Criteria (LLCC) and Space Shuttle Flight Rules (FRs). Lightning advisories are the most frequently issued weather watch/warning/advisory at Cape Canaveral Air Force Station and NASA Kennedy Space Center (CCAFS/KSC), ensuring resource protection and personnel safety. The greatest technical challenge to meteorologists is the timely cancellation of these advisories while ensuring personnel safety. Improvements in this area have the potential to save the Government and taxpayers several millions of dollars per year in unnecessary work stoppage and space launch schedule delays.

All space launches from NASA, Air Force, and entrepreneurial ranges under FAA jurisdiction must obey the same set of Lightning Launch Commit Criteria, a complex set of 12 weather rules to avoid natural and rocket-triggered lightning. (The Flight Rules apply only to space shuttle landings.) Since the exact weather conditions for natural and triggered lightning cannot be specified, these rules are necessarily conservative to assure launch safety. A better understanding of these lightning conditions would allow less restrictive LLCC and avoid unnecessary launch delays and scrubs. The possible cost savings are significant; typical costs associated with a space shuttle mission scrub typically exceeds $1M. Most of the LLCC try to infer the possibilities of hazardous electric fields aloft from the presence of various weather phenomena. Development of an effective remote profiler of electric fields would allow eliminating about half the LLCC, with increased safe launch opportunity and cost savings.

A special interest in LLCC improvement is the present ‘Thick Cloud Rule’. This LLCC essentially says to avoid stratiform clouds 4,500 ft thick or more if any part of the cloud has a vertical extent such that a portion of the cloud has temperatures of 0^{O}C to -20^{O}C within 5 nmi of the launch path. While electric fields capable of causing rocket-triggered lightning can exist in these clouds, the current rule has a False Alarm Ratio of approximately 80%; this is a frequent source of LLCC violations at the launch ranges.

Acknowledgments

The Storm Penetrating Aircraft Workshop was sponsored by the National Science Foundation through Grant No. ATM-0633861.

References

Bunkers, M.J., M.R. Hjelmfelt, and P.L. Smith, Jr., 2006: An observational examination of long-lived supercells. Part I: Characteristics, evolution, and demise. *Wea. Forecasting*, **21**, 673-688.

Cummer, S. A. *et al.*, 2005: Measurements and implications of the relationship between lightning and terrestrial gamma-ray flashes. *Geophys. Res. Lett.*, 32, CiteID L08811.

Dwyer, J. R., and Smith, D. M., 2005: A comparison between Monte Carlo simulations of runaway breakdown and terrestrial gamma-ray flash observations. *Geophys. Res. Lett.*, 32, CiteID L22804.

Dwyer, J. R., *et al.* 2004: A ground level gamma-ray burst observed in association with rocket-triggered lightning. *Geophys. Res. Lett.*, 31 L05119.

Fishman, G. J. *et al.*, 1994: Discovery of Intense Gamma-Ray Flashes of Atmospheric Origin. *Science*, 264, 1313.

Gurevich, A. V., G. M. Milikh, and R. Roussel-Dupre, 1992: Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm. *Phys. Lett. A*, 165, 463.

Johnson, W.B. and W.A. Cooper, 1989: Meeting Review: The Second NCAR Research Aircraft Fleet Workshop. NCAR/TN-332+PROC, National Center for Atmospheric Research, Boulder, CO, 84 pp.

Liu, C., E. J. Zipser, and S.W. Nesbitt, 2007: Global distribution of tropical deep convection: Differences using infrared and radar as the primary data source. *J. Climate*, in press, 2007.

Ott, L. E., K. E. Pickering, G. L. Stenchikov, H. Huntrieser, and U. Schumann, 2007: The effects of lightning NO_x production during the July 21 EULINOX storm studied with a 3-D cloud-scale chemical transport model, *J. Geophys. Res.*, in press.

Ott, L. E., K. E. Pickering, A. DeCaria, G. Stenchikov, R.-F. Lin, D. Pickering, K. E., et al., Trace gas transport and scavenging in PEM-Tropics B South Pacific Convergence Zone convection, *J. Geophys. Res.*, **106**, 32,591-32,602, 2001.

Pickering, K. E., *et al.*, 2001: Trace gas transport and scavenging in PEM-Tropics B South Pacific Convergence Zone convection, *J. Geophys. Res.*, **106**, 32,591-32,602.

Wang, S. Lang, and W.-K. Tao, Production of lightning NOx and its vertical distribution calculated from 3-D cloud-scale chemical transport model simulations, *J. Geophys. Res.*, in preparation, 2007.

Radke, L.F. and P. Spyers-Duran, 1992: Meeting Review: Third NCAR Research Aircraft Fleet Workshop. NCAR/TN-374+PROG, National Center for Atmospheric Research, Boulder, CO, 79 pp.

Smith, P.L. and A.G. Detwiler, 1999: Summary of Storm Penetrating Aircraft Workshop, 33 pgs.

Smith, D. M. *et al.* 2005, Terrestrial Gamma-Ray Flashes Observed up to 20 MeV, *Science*, 307, 1088.

Stanley, M. *et al.*, 2005: A link between terrestrial gamma-ray flashes and intracloud lightning discharges. *Geophys. Res. Lett.*, 33, L06803.

Williams, E., *et al.* 2006: Lightning flashes conducive to the production and escape of gamma radiation to space *J. of Geophys. Res., D*, 111, D16209.

Zipser, E.J., D.J. Cecil, C. Liu, S.W. Nesbitt and D.P. Yorty, 2006: Where are the most intense thunderstorms on earth? *Bull. Amer. Meteorol. Soc.* **87**, 1057-1071.

Appendix A: Workshop Agenda

Monday, 23 October	
1:00 - 1:05	Welcome: Dr. Charles Ruch for the School of Mines
1:05 - 1:10	Welcome: Dr. Gautam Pillay for School of Mines Research
1:10 - 1:20	Workshop Objectives: Dr. John Helsdon
1:20 - 1:45	Development of the T-28: Dr. Paul MacCready
1:45 - 2:00	The T-28 and the Next Generation SPA: Dr. Paul Smith
	The Opportunity:
2:00 - 2:10	Dr. Jim Huning (NSF)
2:10 - 2:30	Dr. Robert Bluth (CIRPAS)
2:30 - 2:45	Additional Capabilities (low-level missions, remote sensing): Dr. Patrick Zimmerman
2:45 - 3:00	Discussion
3:00 - 3:30	Break
3:30 - 5:00	Scoping the Science to be Supported: Open Discussion (science questions, gaps in current capabilities, anticipated projects)
5:30	Group dinner (Speaker TBA)
Tuesday, 24 October	
8:00 - 9:45	Science objectives vis-à-vis instrumentation:
8:00 - 8:20	Review T-28 instrumentation
8:20 - 9:45	Discussion of instrumentation needs Validation of remote-sensing inferences Electrification Remote sensing Microphysics Kinematics Chemistry Surface and PBL observations
9:45 - 10:15	Break
10:15 - ~11:00	Continue discussion and identify break-out leaders
~11:00 - 12:00	Breakout sessions: discussion and begin writing
12:00 - 1:30	Lunch
1:30 - 3:00	Continue group discussion / writing sessions
3:00 - 3:30	Break
3:30 - 5:00	Plenary discussion to compare notes
Wednesday, 25 October	
8:00 - 10:00	Finalize draft contributions (overnight, as necessary)
10:00 - 10:30	Break
10:30 - 12:00	Plenary summary session
12:00	Adjourn

Appendix B: Workshop Attendees

Researchers

Name	***Organization***
Barth, Mary	NCAR
Beasley, William	University of Oklahoma / National Weather Center
Bluth, Robert	Naval Postgraduate School
Bringi, VN	Colorado State University
Capehart, William	IAS / S.D. School of Mines
Chandrasekar, V.	Colorado State University
Farley, Richard	IAS / S.D. School of Mines
Friehe, Carl	University of California, Irvine
Helsdon, John	IAS / S.D. School of Mines
Heymsfield, Andrew	NCAR
Hjelmfelt, Mark	S.D. School of Mines
Johnson, Gary	IAS / S.D. School of Mines
Jonsson, Haf	Naval Postgraduate School
Kliche, Donna	IAS/S.D. School of Mines
Knight, Charles	NCAR
Knight, Nancy	NCAR
Lasher-Trapp , Sonia	Purdue University
Mach, Douglas	University of Alabama in Huntsville
Oolman, Larry	University of Wyoming
Pickering, Kenneth	NASA, Goddard Space Flight Center
Seielstad, George	University of North Dakota
Smith, Paul	IAS / S.D. School of Mines

Straka, Jerry	University of Oklahoma
Warner, Tom	Institute of Atmospheric Sciences
Winn, William	New Mexico Tech
Yuhas, Cheryl	NASA Science Mission Directorate
Ziegler, Conrad	NOAA / National Severe Storms Laboratory
Zimmerman, Patrick	S.D. School of Mines
Zipser, Edward	University of Utah
Zondlo, Mark	Southwest Sciences

Provided written contributions

Bluestein, Howard	University of Oklahoma
Fromm, Mike	Naval Research Laboratory
Roeder, William	US Air Force (45th Weather Squadron)
Smith, David	University of California Santa Cruz
Straka, Jerry *et al.*	University of Oklahoma, NSSL

National Science Foundation Representatives

Detwiler, Andy	NSF/ATM
Huning, James	NSF/ATM
Milne, Peter	NSF/ATM

Graduate Students in Attendance

Franks, Chris	S.D. School of Mines
Jacobs, Shawn	S.D. School of Mines
Malone, Kelly	S.D. School of Mines
Wetenkamp, John	S.D. School of Mines

Appendix C: The Towed Platform

The towed platform is a 6 ft. long, 10 in diameter missile target drone suspended from a winch on the plane. The payload is about 90 lbs., with about 30 lbs. available for instruments. Instruments installed measure temperature, dewpoint, winds, turbulence, and sea surface temperature; other arrangements are possible. In its present configuration, an operator releases the vehicle on a 2000 ft. cable (1 mm steel wire), though it would be possible to use a thicker flexing cable with fiberoptic cable. It was tested this spring for aeronautical qualifications, and was deployed from the CIRPAS Twin Otter about 1500 ft. down to fly 30 ft.over an ocean storm. The vehicle has its own GPS unit and a radar for altitude control, with room for instrumentation and 400 W power available. There are three radio links between the vehicle and the mother ship: radar altitude control, TV camera, and data link. With the array of hard points on the A-10, it may be possible to carry more than one drone to sample different altitudes below the plane.

Figure 10. Photo (courtesy Zivko Aeronautics) of the towed vehicle (STV) being lowered from the CIRPAS Twin Otter. In operation it would be up to ~1000 feet below the towing aircraft.