THE NSF/NCAR GULFSTREAM GV:
A NEW PLATFORM FOR STUDIES OF CLOUDS

William A. Cooper, Jeffrey L. Stith, David C. Rogers, and Jorgen B. Jensen
National Center for Atmospheric Research, Boulder CO USA

1. AIRCRAFT CHARACTERISTICS

A new research aircraft, operated by the National Center for Atmospheric Research for the National Science Foundation, is now in operation (Fig. 1):

Figure 1: The NSF/NCAR GV Research Aircraft (HIAPER) at takeoff.

The aircraft, also called “HIAPER” (High Altitude Instrumented Airborne Platform for Environmental Research), is capable of flight to 15.5 km MSL (51,000 ft), and its range (typically around 8000 km or 5000 n mi) makes studies possible that have global scale. The aircraft was selected for its ability to support research in climate science, atmospheric chemistry, weather and mesoscale studies, global atmospheric cycles, aerosols, clouds, and many other areas of geoscience. It provides special opportunities for research in the upper troposphere and lower stratosphere and for studies that exploit its range to achieve coverage up to global scales.

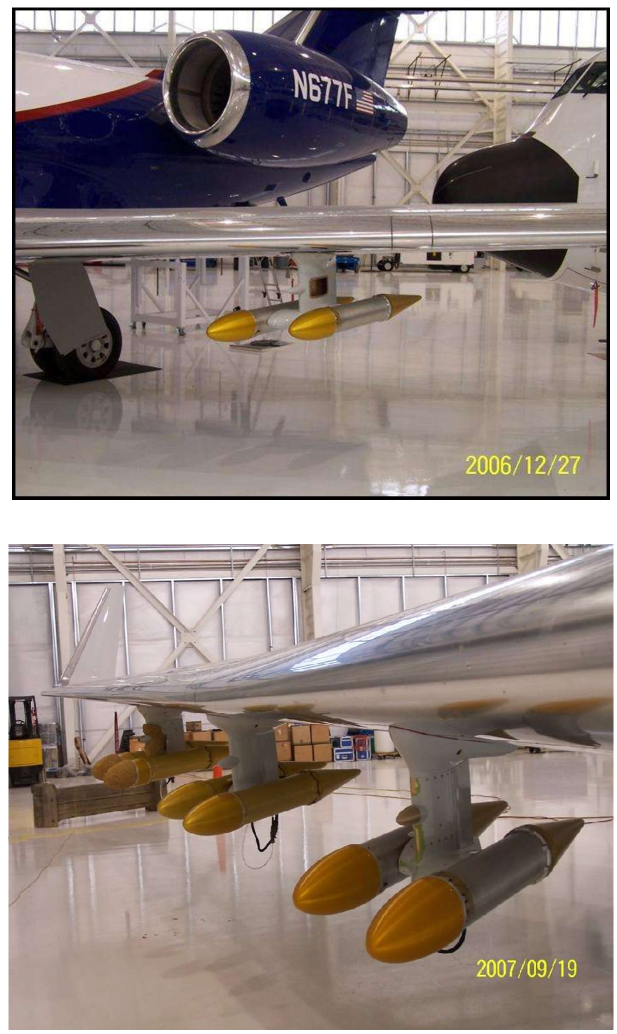

Figure 2: Modifications to be able to carry instrument canisters under the wings.

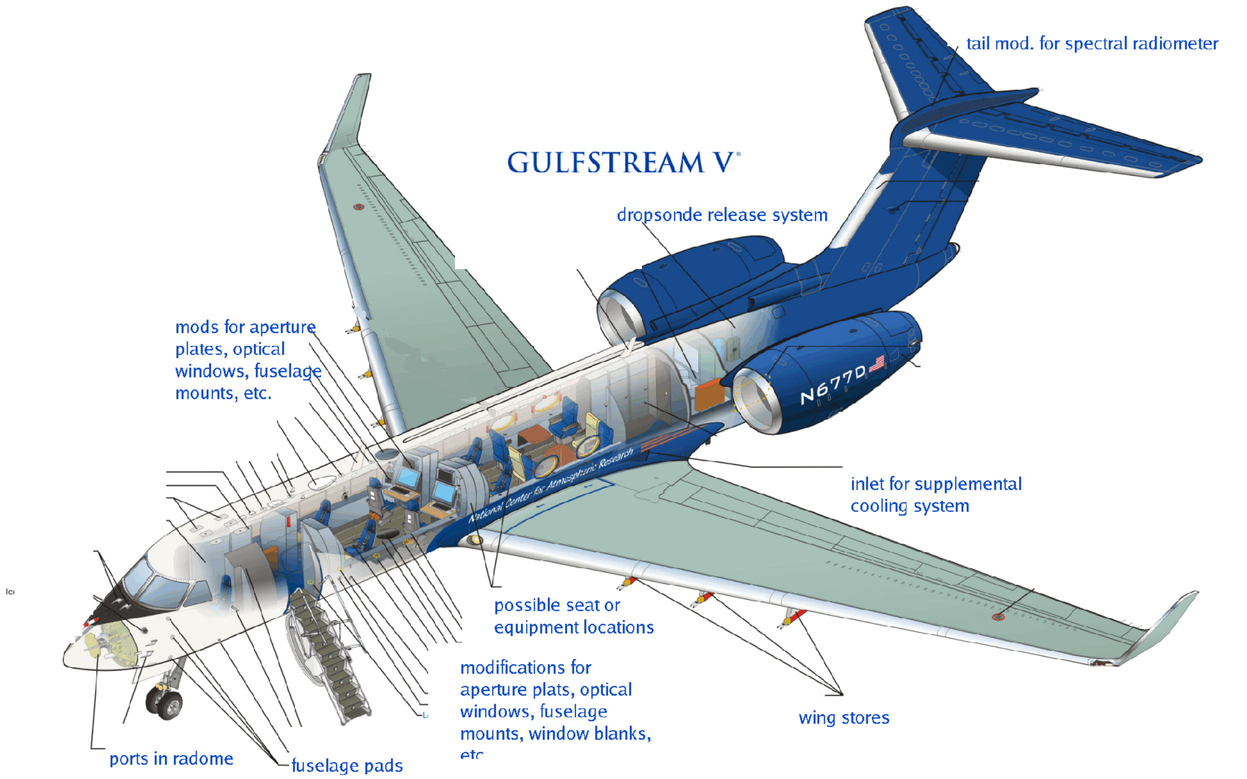

Figure 3: Illustration of some of the mechanical modifications made to the aircraft to accommodate research equipment. In addition, extensive installation of cables and other wire provides for research power distribution to instrument locations, signal routing, and data acquisition and monitoring.

The aircraft has been modified extensively to accommodate research equipment, as illustrated by Figs. 2 and 3. These modifications included the installation of aperture pads (e.g., for inlets), instrument aperture plates, optical view ports, fuselage mounts, and four forward fuselage pads. Cabin pressurization (to a pressure altitude of 6000 ft when flying up to its ceiling) provides a comfortable working environment for instrument operators and other crew members. The payload with maximum fuel is 3400 lb; maximum payload is 8300 lb, but typical payloads are about 4000 lb and are often limited by the available floor space. Substantial power is available for research instrumentation, up to 20 KVA of 115VAC at either 60 or 400 Hz (or split between these). The platform is certified for flight as a standard-category aircraft, and instrumentation provided also meets these certification standards (as must all equipment provided by users).

The aircraft was delivered in 2005 and began flights in support of research in 2006, although infrastructure upgrades have continued and are still continuing (e.g., the addition of wing stores). The acquisition and performance of the aircraft are described by Laursen et al. (2006), and the Investigator's Handbook provides additional detail; the latter and additional documents are available from the NCAR Research Aviation Facility web site: www.eol.ucar.edu/instrumentation/aircraft/G-V.

2. INSTRUMENTATION

Standard instrumentation: For normal missions, there are likely to be three categories of instrumentation in use, standard, special-request, and user-provided. The first is standard for the aircraft and normally operated on all flights; this set includes measurements of position (duplicate Honeywell LASEREF IV inertial systems, Honeywell 12-channel global positioning systems (GPS), and when useful a GPS system with differential capability), state parameters (pressure, temperature, and dewpoint), and wind (using a gust system sensing pressure differences among ports placed in the forward radome). There are also a set of standard inlets to provide air samples to cabin-mounted instruments, and a camera for video recording is mounted under a wing to provide a good view. Most experiments will also use some of the available aerosol instruments and/or hydrometeor spectrometers, including a cabin-mounted CN counter and mobility analyzer and wing-mounted size spectrometers for aerosols, cloud droplets, and ice crystals. The spectrometers have fast electronics to permit measurements at flight speeds up to about 235 m/s, a speed common during high-altitude flight of this aircraft. A tunable-diode laser hygrometer is available for measuring humidity at upper troposphere / lower stratosphere values. These capabilities are all available on request and the instruments are operated and maintained by NCAR.

Table 1, appended to the end of this paper, summarizes the available standard instruments. Some additional instruments for atmospheric chemistry are supported by the Atmospheric Chemistry Division of NCAR and are also requestable.

Special-request instruments. An extensive set of special instruments have been or are being developed for use on the GV. (See Table 2 at the end of this paper.) These instruments are designed specifically to operate on the GV, and so will meet certification requirements for expected deployments. For some, operation of the instrument is best conducted by arrangement and involvement of the developers, although some will be operated by NCAR for the community.

Of special interest to the cloud-physics community will be the instruments for characterizing hydrometeors. A wing-mounted Small Ice Detector (SID-2) has been developed for use on the aircraft, and a new probe called a 3V-CPI is under development by SPEC Corp.; the latter combines two orthogonal 2D-array spectrometers (as in the SPEC 2D-Stereo instrument) with a SPEC Cloud Particle Imager (CPI), using the spectrometers to trigger the CPI. Also of special utility to studies of clouds will be the cloud radar (initially W-band, but envisioned to become dual W/K band), a high spectral resolution lidar (HSRL), and a radiation-sensing package consisting of spectral radiometers as well as measurements of spectrally resolved actinic flux. An aerosol mass spectrometer will provide information on the composition of aerosol particles, and a counterflow virtual impactor is available for measuring total water content in clouds and for providing residue particles from evaporated cloud droplets or ice particles to instruments for analysis.

User-supplied instruments. Most payloads will also include user-supplied instruments for special needs. There is ample power for most such instrumentation, and there are capabilities for incorporating the measurements into the recorded data files or for providing information from the standard data system to these instruments. Some special requirements are associated with certification of such instruments, so early discussion is needed before such planned uses.

3. SATELLITE COMMUNICATIONS

Early operations of the aircraft have shown that the satellite communications system enables a new style of operation, in which a distributed team of investigators can participate in the missions remotely while the aircraft covers continent-spanning distances, perhaps without returning to the originating point for a week or more. The system provides for telemetry of measurements to the ground where they are made available via internet to an extended observing team, some of whom can remain at their home institutions and still participate in missions. It also provides for transmission of images from the ground to the aircraft so that investigators on the ground can construct images representing developing weather situations or other events pertaining to flight objectives and then transmit those to the crew on the aircraft. Communications are via text messages (internet relay chat) that are logged so that they can be dealt with when it is convenient for the air crew. Those on the ground can see the measurements as they are made, see the images from the video camera on the aircraft, and communicate with the scientists on the aircraft. Those in the air can see updated satellite or radar images sent from the ground, receive updated weather information and "nowcasts" and other model output during the flight, and discuss flight procedures with the extended team on the ground. It may laterprove possible and advantageous to transmit measurements from the aircraft for incorporation or assimilation into models. The platform is also attractive to consider for exploiting targeting of observations, because targets could be determined during flight and transmitted for incorporation into the flight plan.

These capabilities were exploited during the PACDEX (Pacific Dust Experiment) campaign by PIs J. Stith and V. Ramanathan. Some results from that experiment are included elsewhere in this conference; cf., e.g., Stith et al., 2008. The flight crew consisted of ten people who flew from Colorado to either Alaska or Hawaii and then on to Japan (cf. Fig. 4) in order to cover large parts of the Pacific Ocean. To conduct repeated flights, a ground-based team monitored the weather and developed tentative flight plans that were communicated to the flight crew during and between flights. The operations center re-

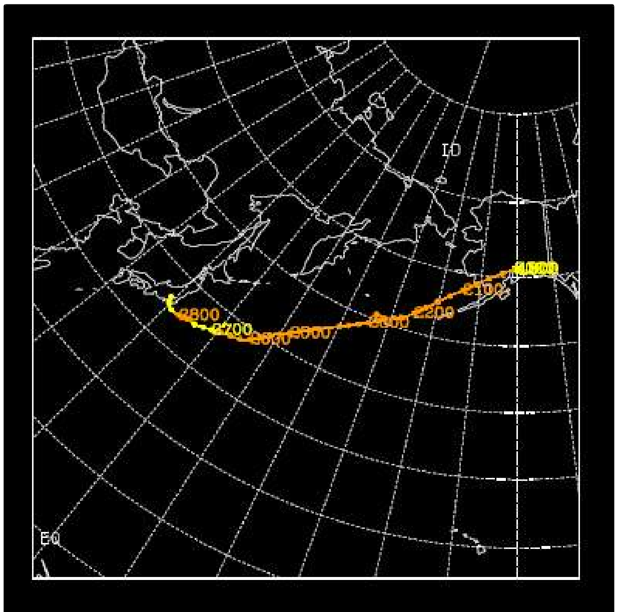

Figure 4: Sample flight track (15 May 2007), showing a flight segment from Anchorage Alaska to Japan during PACDEX, with a low level flight segment (in yellow) enroute to study dust emerging from Asia.

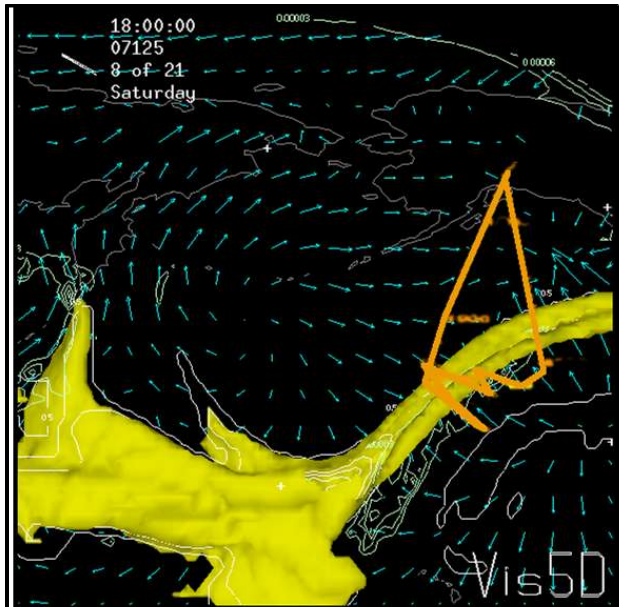

Figure 5: The flight track of the PACDEX flight of 5 May 2007 to study a cold front over the Pacific Ocean. The flight began and ended in Anchorage Alaska; to set the scale, Hawaii is visible at the bottom of the plot and Japan on the left side. The yellow contour is the dust plume predicted by the STEM model of G. Carmichael (Univ. of Iowa) and collaborators for the time of the flight, with a dust plume riding along a jet associated with the cold front. This image was transmitted to the aircraft during the flight to help them design the flight track, shown as the orange line.

mained in Colorado even for the flights conducted from Japan. Investigators at locations including the University of Iowa (G. Carmichael) were able to run chemical transport models while remaining at their home institution, then communicate the results to the operations center for flight planning and for forwarding to the air crew.

Another example was the Terrain-Induced Rotors Experiment (T-REX; cf. Grubišić and Doyle, 2006), which was conducted by PI V. Grubišić and associates from a location in the lee of the Sierra Nevada Mountains of California while the GV remained based in Colorado. Ferry to or from Colorado required less than 2 h, leaving about 6 h for operations in the study area. This allowed the instrument operators to remain based in Colorado and yet be able to respond quickly when the weather was appropriate for flight operations. The speed and range of the aircraft make it possible to conduct flights from a single base and yet cover many flight objectives, perhaps even those of different experiments (as was done in the "Progressive Science" flights of 1996, when four different teams shared use of the aircraft in order to meet their different needs, requiring flight sometimes to near the

Arctic Circle, sometimes to the Pacific Ocean off the coast of Mexico, and sometimes across the latitudinal span of the U.S., all from a single base in Colorado.) The START-08 project recently conducted a flight from Colorado to over the Hudson Bay and back in a single flight, as shown in Fig. 6. This range enables a different experimental model, using the ability of the aircraft to reach distance weather events and conduct experiments with multiple objectives and weather targets.

It is likely that this continent-spanning style of operation will become common in future uses of the aircraft. The speed of the aircraft makes it possible to collect measurements over distances that span regions observed by satellites or modeled by global models, opening new opportunities for validation studies. The communications link also provides opportunities for educational uses of the operations that are only beginning to be developed.

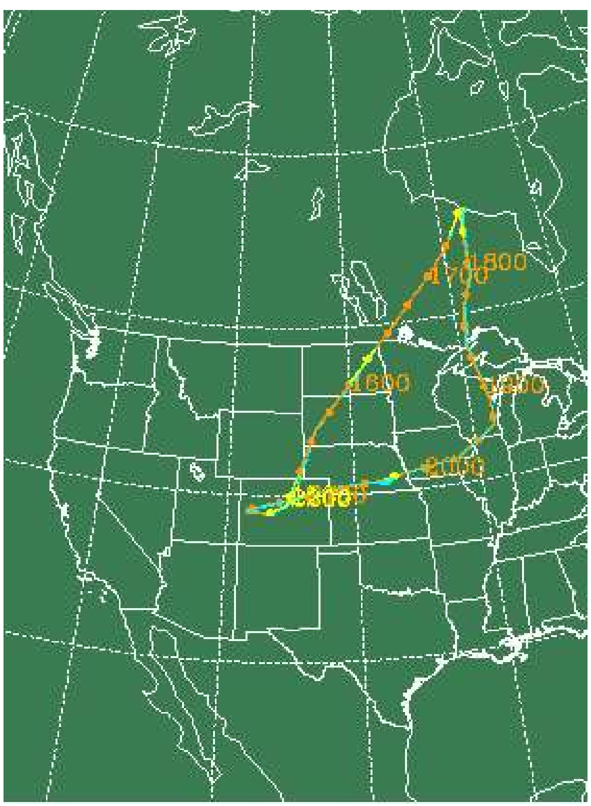

Figure 6: Sample long-range flight (START-08 flight 1, 18 April 2008, 7 h duration).

4. SPECIAL OPPORTUNITIES FOR STUDIES OF CLOUDS

The capabilities of this aircraft and instrumentation provide new opportunities for studies of clouds, many linked to the performance of the aircraft but others also associated with the newly developed or under-development instrumentation. These include:

- The ability to reach most sub-tropical Cirrus clouds and to measure the size distributions, ice-crystal residues after evaporation, and radiative properties of such clouds;
- The ability to climb rapidly, at rates matching ascent rates of most Cumulus clouds, and so to observe the vertical development of Cu via repeated penetration of rising parcels; cf. Fig. 7;
- The ability to cover distances appropriate for climate-scale studies, so that it is possible to characterize clouds over areas comparable to grid sizes in global models or to reach remote mid-ocean locations in order to characterize the clouds in ways that have climatological significance;

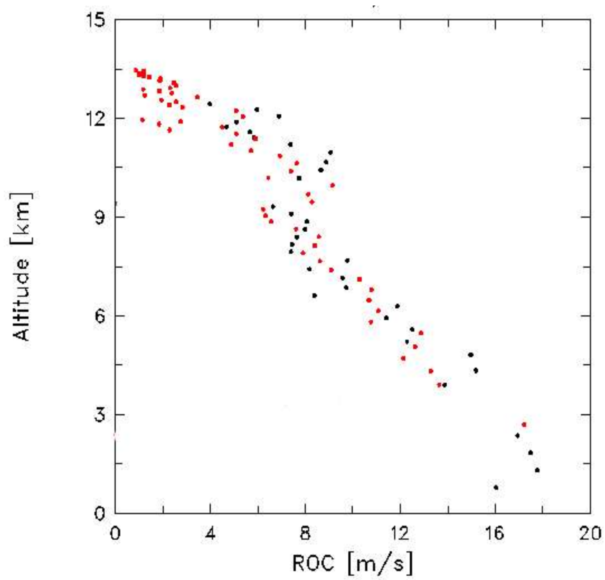

Figure 7: Measured rate of climb (ROC) vs altitude for sample climbs of the GV with normal payload. Red dots show an initial climb with full fuel; black dots show a climb midway through an 8-h flight.

- High-speed response to developing weather, so that clouds can be reached rapidly during their early stages of growth or practical research areas can be covered to target particular cloud or weather conditions;
- Mobility upward and downward, so that observers on the aircraft can benefit from an unobstructed high-altitude view of developing cloud conditions and then reach targets of interest and so that soundings can be measured routinely;
- Linking airborne observations and nowcast modeling during flight so that operations can adapt to evolving weather patterns;
- Downward and upward irradiance measurements associated with clouds, conducted above, below, or within clouds, along with the ability to characterize the hydrometeor and aerosol populations and trace gases affecting those irradiances;
- Coupling of trace-gas measurements with studies of clouds to learn about entrainment and detrainment processes or other processes in clouds and to detect and follow cloud-processed air;
- Use of a Microwave Temperature Profiler and/or dropwinsondes to measure the temperature structure of the atmosphere and so characterize the environment in which clouds develop;
- Use of pressure measurements in combination with the high-resolution differential-GPS measurements to study pressure perturbations associated with clouds and other dynamic effects arising from pressure gradients that have been difficult to study;
- Exploitation of new hydrometeor probes that offer the ability to measure small ice or drizzle-size hydrometeors with increased confidence and so to address questions related to the effective radius of Cirrus ice particles or the development of drizzle in clouds;
- The combination of a W-band radar with a high spectral resolution lidar, which can support high-resolution characterization of cloud structure and motions, cloud boundaries, and early precipitation development.

5. AN EXAMPLE: A POSSIBLE APPROACH TO DETERMINING INDIRECT CLIMATE EFFECTS OF CLOUDS

A key uncertainty in predictions and understanding of global warming remains that associated with the indirect effects of aerosols on climate, especially the effect of increasing concentrations of cloud condensation nuclei on the radiative properties of clouds. If the albedo of low clouds is increased by such increasing concentrations, this may reduce the warming expected in a future climate. The remainder of this paper discusses a possible approach to study of this effect that would exploit the capabilities of this new research aircraft and also the very capable research aircraft available elsewhere, including the BAe-146 of the UK and the German “HALO” aircraft under development at DLR. This is offered here as an example of the ways in which a continent-spanning aircraft can begin to establish links between cloud-scale processes and the global scale needed if studies are to be relevant to climate.

An approach to determining effects on a global scale might be along the following lines:

- Use chemical-transport models (CTMs) to predict where sulfate aerosols are enhanced. Concentrate on areas where models predict that clouds have significant radiative impact, like the Sc regions of the California coast or the Chile coast and elsewhere.
- Test those predictions against observations (of CCN and sulfate) in regard to position and amounts. Aircraft observations are probably needed for these tests; some information can also be gathered from satellite radiances, esp. over the ocean, and from satellite-lidar observations. Ground stations in the aerosol networks are also possible sources of information.
- (if the preceding test is encouraging) Determine if the CTM predictions can be used to predict CCN concentrations. This probably requires CCN measurements from aircraft, perhaps complemented by measurements at ground stations. This step would benefit from the existence of multiple CCN spectrometers, intercompared or identical, for use on different aircraft, because the task probably is best conducted by more than one aircraft in more than one area.
- (if the preceding test is encouraging) Determine how CCN properties relate to cloud characteristics. This is probably best done by correlating sulfate predictions with satellite-measured cloud albedo, bypassing the CCN step -- but the CCN step would be important anyway for developing confidence in the chain of cause-and-effect. Aircraft measurements of radiative properties of clouds, esp. albedo, may play a role here also, especially in studying the fine-scale variations in albedo.
- (if warranted by the preceding steps:) Use predictions of effects on cloud characteristics to generalize globally and so develop an estimate of the indirect effect of aerosols on the global radiation balance.

Components of this study might be:

- A chemical-transport model or a global model with chemistry incorporated. The model would need to represent meteorological fields, sources of various chemicals and aerosols, and scavenging and transport, in order to be able to predict trace-gas and aerosol fields over large areas.
- Aircraft studies in different regions, conducted in coordination and collaboration, to increase the extent to which the coverage can be considered representative of global conditions. The GV is a good candidate for studies in remote areas or requiring long range. The BAe-146 provides superb capabilities for characterizing the aerosol, chemical, and radiative properties. HALO would of course offer capabilities like those of the GV. It may be possible to interest other groups in a coordinated study, because of the obvious importance of this problem.
- Satellite observations of cloud albedo, which would have a key role to play in extrapolating results over broad areas and in developing possible correlations between aerosol-model predictions and satellite observations of albedo. (Indeed, one might think of undertaking the study only with this latter step, but such a correlation would be less convincing without verification of the steps in the cause-and-effect chain.)

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Table 1: Standard Requestable Instruments

Measurement	***Instrument(s)***
position, attitude, ground speed	inertial reference units and GPS receivers, Honeywell LASEREF III/IV with Garmin GPS-16
pressure	Paroscientific Model 1000 Digiquartz Transducer, separate fuselage static buttons
temperature	HARCO Model 100990-1 De-iced TAT Sensor (2 units/4 outputs); Rosemount Model 102AL TAT Sensor.
dewpoint	Buck Research Model 1011C Hygrometers (dual units)
dynamic pressure	Mensor Model 6100 Digital Pressure Transducer
wind gust sensing	Mensor Model 6100 Digital Pressure Transducers measuring differential pressures between ports on the forward nose radome
aerosol measurements	Condensation nuclei (water based) and differential mobility analyzer, scanning
stratospheric water vapor	tunable diode laser system
cloud water content	heated wire (King) probe, DMT, and Rosemount icing probe
aerosol size distribution	PMI Ultra-High Sensitivity Aerosol Spectrometer
cloud droplet sizes	DMT cloud droplet spectrometer
ice sizes and shapes	2D probe, modified for the high speed of the GV

Table 2: Special-Use Instruments

Measurement	***Instrument / Developer***
hydrometeor sizes	3V-CPI / Lawson, SPEC, Inc.
small ice crystals	small ice detector (SID-2) / Heymsfield, NCAR
aerosol backscatter	high spectral resolution lidar / Eloranta, U. Wisconsin
temperature profile	microwave temperature profiler (MTP) / Mahoney, JPL
spectral irradiance, actinic flux	HIAPER Airborne Radiance Package (HARP) / Shetter, NCAR
full-range humidity	Vertical Cavity Surface Emitting Laser Hydrometer / Zondlo, SW Sciences
nitric acid, SO_2, & others	Chemical Ionization Mass Spectrometer / Huey, Georgia Tech.
CO, CO_2, CH_4, N_2O	Quantum Cascade Laser Spectrometer (QCLS) / Wofsy, Harvard
O_3	ozone photometer / Rawlins, PSI
O_3 (fast response)	chemiluminescence detection / Campos, NCAR
organic trace gases	Trace Organics (TOGA) / Apel, NCAR
occultation sounding	GPS full-spectrum receivers / Garrison, Purdue
aerosol composition	Time-of-Flight Aerosol Mass Spectrometer / Jimenez, U. Colorado
aerosol particles from evaporated hydrometeors, or total water content	Counterflow Virtual Impactor / Twohy, U. Oregon
radar reflectivity and Doppler velocity	HIAPER Cloud Radar (HCR), a pod-mounted Doppler W-band radar / NCAR