A NEW INSTRUMENTED AIRBORNE PLATFORM FOR ATMOSPHERIC RESEARCH

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The instrumented Alpha Jet aircraft can respond quickly to unexpected atmospheric conditions, validate satellite retrievals, and carry out pollution studies and flux measurements. Present measurements include profiles of wind, CO_2, CH_4, O_3, and H_2O.

If you watched the documentary television program about climate change, *Years of Living Dangerously*, you might remember the opening scenes in which Harrison Ford walks across the apron of the National Aeronautics and Space Administration (NASA)'s Moffett Federal Airfield and climbs into a sleek olive green airplane to make measurements of atmospheric trace gases over a patch of Nevada desert. In this paper, we describe this unique aircraft, its measurement capabilities, and its future uses as well as presenting a typical flight path and some of the results obtained.

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THE AIRPLANE. The Alpha Jet (Fig. 1) is a two-person light subsonic attack jet and advanced trainer developed jointly by Dassault-Breguet and Dornier for the French and German militaries. It is powered by two turbofan jet engines, flies at speeds up to 1,000 km h^{-1}, and has a ferry range of nearly 3,000 km and a ceiling of about 14.5 km. The French Air Force (Armee de l'Air) used the Alpha Jet primarily as a trainer but found that it was "too forgiving" and led to longer learning curves for pilots assigned to combat aircraft that were more difficult to fly. The Alpha Jet is still used by the Patrouille de France, the flight demonstration team of the French Air Force. The Luftwaffe used the Alpha Jet mainly in a light strike role and retired the aircraft in 1997. Production of the airplane ceased in 1991 but it is still in use by the air forces of some 12 countries, including Belgium, Canada, and Portugal. The flight measurement program involving the Alpha Jet at NASA Ames Research Center is called AJAX, an approximate acronym for "Alpha Jet Atmospheric Experiment."

The modified (demilitarized) Alpha Jet is owned by a private company called H211, LLC, and used by them for pilot training. Since this is no longer a military aircraft, it can land at any commercial field and does not require special permissions. By a Space Act

Fig. 1. Alpha Jet in front of hangar at NASA Ames Research Center, Moffett Field, CA.

Agreement between NASA Ames Research Center and H211, the Alpha Jet is stationed at NASA's Moffett Field and can be used by NASA when not required by H211. This somewhat unique public–private collaboration has given us the use of an excellent platform for scientific studies of the atmosphere.

The Alpha Jet flies faster and higher than propeller-driven research aircraft. Its speed is an asset when carrying out various traverses of an interesting area, as one obtains a closer approximation to a "snapshot" than with measurements made with a slower platform. This property was evident during recent measurements of methane emissions from an oil field when the Alpha Jet performed three passes at different altitudes within 20 min. Low-level, fast measurements are useful in making boundary level flux measurements by reducing uncertainty due to the evolution of the atmosphere during the measurement period. Since it was designed as a ground attack airplane, the alpha jet is uniquely suited for safely conducting both high- and low-level atmospheric sampling. In unpopulated regions (desert and marine areas where prescribed lateral offsets are available) it routinely takes measurements below 25 m.

The Alpha Jet can reach the lower stratosphere and we have made ozone and meteorological measurements up to the tropopause at 14 km, but the operation of the Picarro measurement system limits carbon dioxide and methane measurements to altitudes less than about 9 km for reasons described below.

It might be mentioned that jet-powered research aircraft, such as the National Science Foundation (NSF)/National Center for Atmospheric Research (NCAR) High-Performance Instrumented Airborne Platform for Environmental Research (HIAPER) Gulfstream-V and the NASA Falcon have the same advantages of speed, rate of climb, and high ceiling, as well as significantly greater range and payload. The same is true, for example, of NASA's ER-2, which, however, is seldom flown at altitudes much less than 60,000 ft. Such aircraft are often involved in deployments that involve several scientists, many instruments, and schedules that are determined months in advance. Perhaps the best comparison to the Alpha Jet is the NASA WB-57, which is also an adapted military airplane. Both are two-seater aircraft, so there is no room on board for instrument specialists. The WB-57 is significantly larger than the Alpha Jet and has a greater payload. They fly at about the same speed and have roughly the same range, but the Alpha Jet has a higher ceiling and a faster rate of climb. The WB-57 is a more general platform that can be adapted to various research projects, whereas the Alpha Jet, at least in its present configuration, has a fixed number of instruments permanently stored in external drop tanks and can be ready to deploy at short notice.

The plane has four wing pods. The outboard pods are fuel tanks. The inboard pods are redesigned fuel tanks mounted at locations originally used for armaments. One of these inboard pods has been repurposed to contain scientific instruments, as shown in Fig. 2, and the second one will be used for future instrumentation. These pods have an available volume of about 0.15 m^3 and can carry a 245-kg payload. We are planning to eventually instrument a modified belly tank with a usable volume of 0.08 m^3 and a payload of 160 kg.

The Alpha Jet is operated as a "restricted experimental aircraft," which means that it does not require Federal Aviation Administration (FAA) certification when modifications are made to it (as when new instruments are incorporated into the pods). Nevertheless, it must go through a rigorous internal NASA airworthiness and safety review. Science flights are made above or below the commercial flight regions, and permission is required to fly through them (flight plans must be filed). The aircraft has no deicing mechanisms and cold clouds and lightning storms are avoided.

Aircraft and instrument support is fairly minimal. At present, the Alpha Jet science flights have all been staged out of NASA Ames, but if it should go on deployment to a distant location, the required support would consist of the pilots, an aircraft ground crew of one person, a three-person instrument ground crew, and a ground power cart.

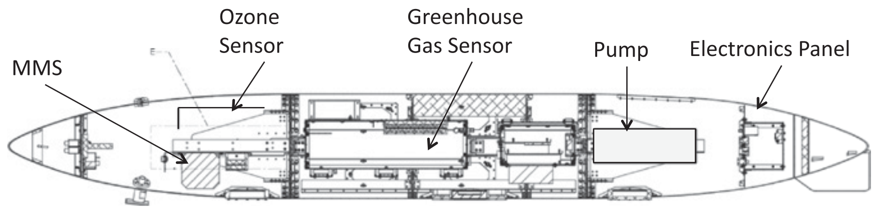

Fig. 2. The pod and its instruments.

THE INSTRUMENTS. The instruments, as shown in Fig. 2, are presently mounted in the right instrument pod and consist of an ozone monitor, a cavity ring-down spectrometer (to measure concentrations of carbon dioxide, methane, and water vapor), and a Meteorological Measurement System (MMS) to monitor ambient temperature, pressure, and 3D winds. The aircraft is also fitted with GPS and inertial navigation systems. Electrical power in flight can be drawn from a 28-V DC or a 115-V AC, 400-hz supply. Data are recorded for each instrument separately onto a PC card with compact flash.

The standard instrument stainless steel inlets extend 15 cm outside the pod and are backward facing to avoid ram effects and to prevent moisture from entering the system. There is a separate exhaust line.

We now describe the AJAX instruments in terms of their measurements.

Ozone. Ozone mixing ratios are determined with a commercial ozone monitor: 2B Technologies, Inc., Model 205. This instrument utilizes two detection cells: one containing ozone-scrubbed air and the other the sample air. The roles of the cells alternate, allowing for near-continuous measurements. The cells are illuminated with 254-nm UV light and intensity measurements are made simultaneously every 2 s. These are compared to yield ozone mixing ratios. The raw data, taken every 2 s, are averaged over 10 s to reduce the signal to noise ratio, giving an overall uncertainty of 3 ppbv at 10-s resolution.

The monitor has been modified by upgrading the pressure sensor and pump to allow for measurements at high altitudes, including a lamp heater to improve the stability of the UV source and the addition of fans and vibration isolators to control the monitor's physical environment. Calibration tests are performed before and after each flight, using an ozone calibration source referenced to the National Institute of Standards and Technology (NIST) scale. Technical details are found in Yates et al. (2013).

Carbon dioxide, methane, and water vapor. Three trace species—carbon dioxide, methane, and water vapor—are measured with a cavity ring-down spectrometer (CRDS, Picarro, Inc., Model G 2301-m). The "m" designation means that the instrument was modified for flight by the manufacturer. The AJAX team carried out further modifications; specifically, the instrument was repacked into two separate boxes so that it would fit into the pod, two additional fans and an additional insulation blanket were added, and a filter was added to protect the optics from the deposition of particles (Tadic et al. 2014).

In ring-down spectroscopy, laser light is introduced to a cavity with mirrors at either end, so that the light bounces back and forth, quickly filling the cavity (O'Keefe and Deacon 1988). One of the mirrors is not perfectly reflecting (having a reflectivity of about 99.995%), so that a small fraction of the light leaks out of the cavity. (Our instrument has a 25-cm cavity and light from a laser pulse bounces back and forth some 100,000 times yielding an effective pathlength of over 10 km.) The intensity of the transmitted light is given by a Beer's law relation, expressed in terms of time rather than distance: $I = I_0\exp(-t/\tau)$. The CRDS mounted in the Alpha Jet uses three wavelengths in the IR at which the three trace gases are highly absorbing; specifically, the lasers are tuned to scan over the individual spectral lines of CO_2 at 1603 nm and CH_4 and H_2O at 1651 nm (Chen et al. 2010). The overall uncertainty ranges from 0.31 to 0.39 ppm for carbon dioxide and from 3.5 to 5.6 ppb for methane. [A detailed description of the instrument precision, repeatability, linearity, and calibration are presented in Tadic et al. (2014).] It might be noted that the instrument requires a pressure difference of at least 135 hPa between the ambient pressure and the pressure in the cavity (about 185 hPa). This limits our greenhouse gas science flight altitudes to pressure levels greater than about 320 hPa (≤9,000 m). The instrument takes data at 3 hz, binned to 3 s.

Meteorological Measurement System. The MMS is a NASA–Ames-developed airborne instrument that provides calibrated, science quality, in situ measurements of static pressure, static temperature, and wind in three dimensions. This instrument has been integrated into a number of NASA aircraft including the ER-2, the DC-8, the Global Hawk unmanned aircraft, and now the Alpha Jet. The MMS system is mounted in the nose of the instrumented pod, as shown in Fig. 2. This is the pod with the unpainted ring near the nose, illustrated in Fig. 3.

The MMS instrument consists of three major systems: an air motion sensing system, an inertial navigation system, and a data acquisition system. The basic concepts and instrumentation of the MMS system are as described by Scott et al. (1990), but specific instruments have been updated repeatedly over the years. [For example, the older pressure and temperature transducers have been replaced by a Honeywell Precision Pressure Transducer (PPT) and a Rosemount platinum wire. Details of the MMS are given on the website http://geo.arc.nasa.gov/sgg/mms.] Earlier versions of the MMS system were compared with Vaisala radiosonde and radar tracking of balloons in 1986 and comparisons of the wind data with radar-tracked "Jimsphere" balloons were conducted in 1989 (Gaines et al. 1992). In both cases, the results support the MMS measurement accuracy.

The measured parameters are GPS positions, velocities, accelerations, pitch, roll, yaw, heading, angle of attack, angle of sideslip, dynamic total pressure, and total temperature. The primary products of MMS are pressure (precision of ±0.3 mb with accuracy of 0.5%), temperature (±0.3 K, 0.2%), horizontal wind (±1 m s^{-1}, 3.3%), and vertical wind (±0.3 m s^{-1}). The derived parameters are potential temperature, true airspeed, turbulence dissipation rate, and Reynolds number.

PLANNED INSTRUMENTATION. The instrumentation presently flown on the Alpha Jet gives a significant amount of information on the chemical and physical state of the atmosphere, but planned measurements will allow us to measure to higher altitudes and to measure other important trace species.

AirCore. The AirCore is an innovative yet extremely simple atmospheric sampling system invented by Pieter Tans at the National Oceanic and Atmospheric Administration (NOAA)/Earth System Research Laboratory (ESRL) (Tans 2009; Karion et al. 2010). It consists of a thin, very long, coiled, stainless steel tube (0.64-mm diameter connected to 0.32-mm diameter). The tube is (initially) closed at both ends. Upon reaching maximum altitude, one end of the tube is opened and the enclosed air escapes to the lower pressure environment, effectively evacuating the tube. As the airplane descends, air at lower altitudes (and higher pressures) enters the tube, compressing the higher-altitude air. Thus, the tube contains a record of air at decreasing altitudes (much as an ice core contains a record of ice history). The diffusion of molecules in the tube is extremely slow, so the air at a given location in the AirCore can be specified as air that was originally at a particular altitude. A CO_2 molecule at 208 K will diffuse about 1.6 m day^{-1}. We plan to sample the air within 3 h following a flight to minimize the effect of diffusion. However, even if the air were not sampled until 24 h after collection, CO_2 would only have diffused 1.6 m in either direction. Thus, the midpoint of each 3.2-m length of the tube can be assumed to contain air representative of a particular altitude. This means that the 150-m tube contains 47 air parcels each representing air from a different altitude (Karion et al. 2010). The AirCore has been evaluated and shown to have measurement precisions for CO_2 and CH_4 that are equal or better than

Fig. 3. Alpha Jet pods. The near pod (with unpainted ring) is the instrumented pod. Note the reflection of the pilot's helmet in the canopy. (Photograph courtesy of R. Simone.)

obtained by grab sampling with silicate glass flasks. The mass of air entering the AirCore at each pressure is the same, so a given length of air in the tube can be associated with a given range of pressure altitude.

Including the AirCore in the Alpha Jet instrument suite will allow us to make measurements of carbon dioxide and methane up to 14.5 km—the Alpha Jet ceiling.

After each flight, the AirCore will be taken to our laboratory where the air in the tube can be analyzed with an appropriate instrument. If the Alpha Jet flight terminates at a location remote from our laboratory, the onboard Picarro ring-down spectrometer will be used to measure the composition of the air in the AirCore.

Formaldehyde measurements. We recently installed an instrument to measure formaldehyde. (This instrument, developed by Dr. Thomas Hansico at NASA Goddard Space Flight Center, is denoted COFFEE, for "Compact Formaldehyde Fluorescence Experiment.") Formaldehyde measurements are of interest because they will give us a better picture of the atmospheric breakdown of carbon-containing substances and because formaldehyde is the end member of aldehyde decomposition in the atmosphere. Formaldehyde is also an important tracer in biomass burning and will be a valuable asset for flights targeting urban pollution and forest fires.

PAST AND ONGOING MEASUREMENT OPPORTUNITIES.

Alpha Jet flights are part of an ongoing validation program for the *Greenhouse Gases Observing Satellite* (*GOSAT*) of the Japan Aerospace Exploration Agency (Yokota et al. 2009). *GOSAT* was launched in January 2009 and has been collecting total column amounts of major greenhouse gases, particularly CO_2 and CH_4. *GOSAT* validations have involved the ground-based Total Carbon Observing Network (TCCON), which consists of a network of ground-based Fourier transform spectrometers recording direct solar spectra in the near-infrared spectral region (Toon et al. 2009). From these spectra, accurate and precise column-averaged abundances of CO_2, CH_4, N_2O, HF, CO, H_2O, and HDO are retrieved. TCCON provides validation for the Orbiting Carbon Observatory (OCO), Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY), and *GOSAT*. The Alpha Jet has made measurement on several occasions at the TCCON site at the NASA Armstrong (formerly Dryden) base, but it has primarily validated the *GOSAT* instrument during overpasses of Railroad Valley Playa, Nevada. The playa is a dry lakebed about 15 km by 15 km (roughly *GOSAT*'s footprint) with no vegetation and nearly Lambertian reflectance. It has been used for the calibration and intercomparison of various satelliteborne instruments (Thome 2001; Tonooka et al. 2005). During satellite overpasses, the Alpha Jet carries out simultaneous spiral vertical profiles from 8,500 m down to about 25 m above ground level. It then carries out low-altitude passes at about 2,000 MSL over Warm Springs Summit and Berlin Ichthyosaur State Park where there are ground-based ozone measurement stations. A detailed discussion of the results of some 50 such flights over a period of two years is presented in Tanaka et al. (2015, manuscript submitted to *IEEE Trans. Geosci. Remote Sens.*). Greenhouse gas profiles obtained with the Alpha Jet were extrapolated upward to the top of the atmosphere using three different extrapolation schemes and the 3D Goddard Earth Observing System Chemistry (GEOS-Chem) model (Bey et al. 2001). The comparisons are discussed in

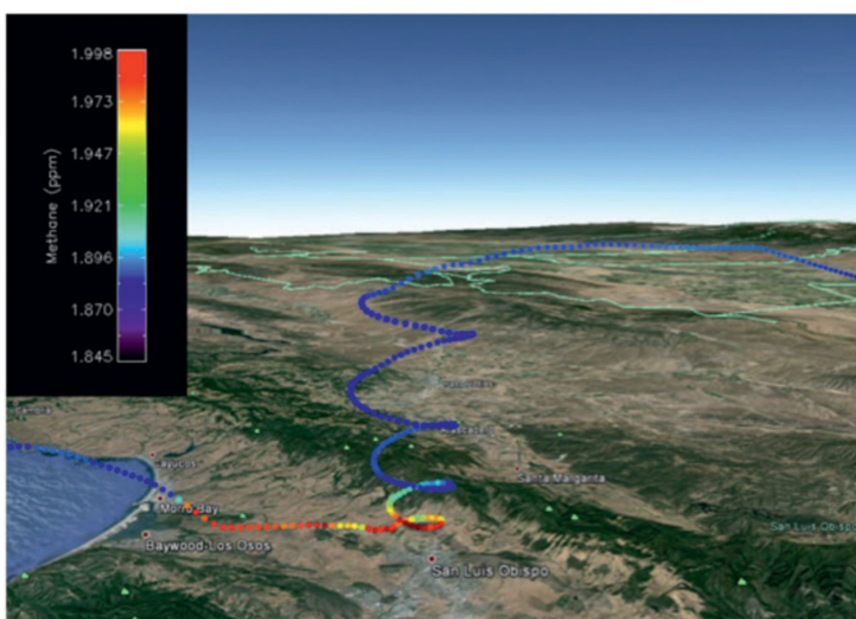

Fig. 4. Methane mixing ratios measured on AJAX flight 116 (5 Mar 2014).

detail in Tanaka et al. (2015, manuscript submitted to *IEEE Trans. Geosci. Remote Sens.*) and show excellent agreement between satellite and aircraft measurements.

Johnson et al. (2014) discuss the AJAX methane measurements made on six flights during the DISCOVER-AQ-CA field campaign. These flights were made in the San Francisco Bay Area and the northern San Joaquin Valley. The purpose of the field campaign was to measure methane emissions in urban regions and from livestock in the San Joaquin Valley, which were suspected of being underestimated in the Emission Database for Global Atmospheric Research (EDGAR) emissions inventory (http:\\edgar.jrc.ec.europa.eu). Johnson et al. concluded that the GEOS-Chem model (Bey et al. 2001) using the EDGAR emissions inventory has an overall negative bias in methane compared to AJAX measurements, particularly during periods when AJAX sampled elevated methane mixing ratios.

The Alpha Jet dedicated two flights to measuring the outflow from the exceptionally large Yosemite ("Rim") wildfire during the summer of 2013 (Yates et al. 2015, manuscript submitted to *Atmos. Environ.*) and also made measurements of fires in Northern California during the summer of 2014. These measurements are important because in the western United States, wildfires are much more frequent than prescribed burns (ignited by land management programs to reduce the risks of wildfires). However, most current emission sampling is of prescribed burns, and given the differences in fuel, size, and weather conditions, these may not be a suitable proxy for wildfire emissions. Consequently, emission data

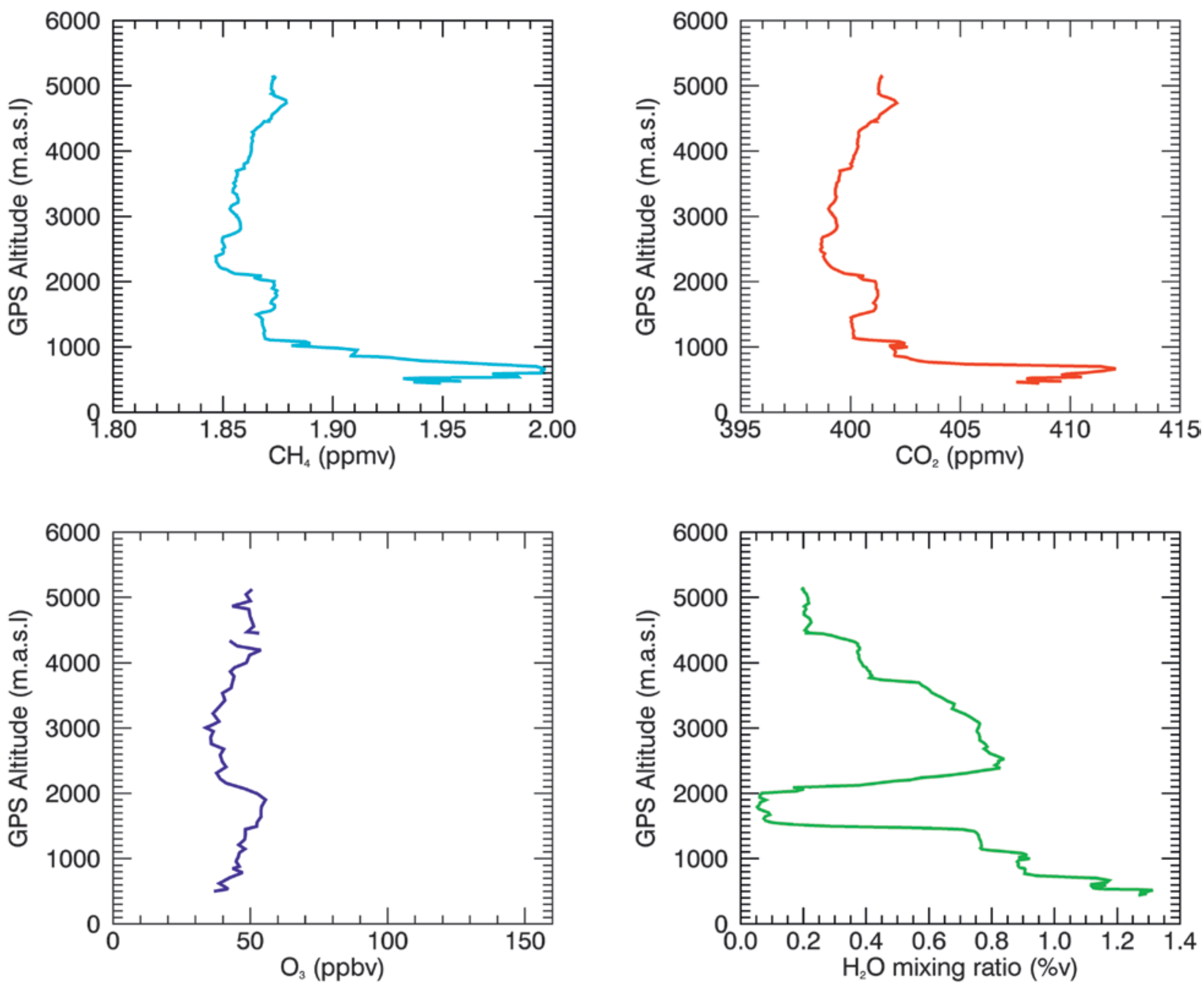

Fig. 5. Profiles of methane, carbon dioxide, ozone, and water mixing ratio during the downward spiral over San Luis Obispo as obtained from Alpha Jet flight 116 (10-s averages for ozone; 3 s for methane, carbon dioxide, and water). Note the strong increases in methane and carbon dioxide at low altitudes.

from wildfires provide valuable information for air quality and fire modeling studies.

The North Pacific midlatitude storm track is a preferred location for deep stratosphere to troposphere transport (Sprenger and Wernli 2003). On two occasions in June and July of 2012, the Alpha Jet was able to capture the distinguishing characteristics (low water vapor, high ozone, high potential vorticity) of such stratosphere to troposphere transport (Yates et al. 2013). The AJAX measurements also indicated that the stratospheric air was significantly depleted in CO_2, suggesting its use as a nonconventional tracer of stratospheric air. It is interesting to note that the tropopause fold events we observed over California led to surface ozone measurements in Wyoming exceeding the allowed National Ambient Air Quality Standards value, as described in an "Exceptional Event Demonstration Package" prepared by the State of Wyoming Department of Environmental Quality.

A TYPICAL ALPHA JET FLIGHT: TRAJECTORIES AND RESULTS. AJAX flights have been conducted since January 2011 and by June 2015 the Alpha Jet had completed over 160 science flights. To illustrate a typical flight and the data collected we consider flight 116 (5 March 2014) in which the Alpha Jet flew from Moffett Field, over the San Joaquin Valley (at about 8-km altitude) to San Luis Obispo, where it spiraled down. The winds being easterly, the Alpha Jet then flew west from San Luis Obispo toward Monterey Bay with the aim of following the emission plume to the coast. It then returned to Moffett Field. This flight was part of a project called COWGAS organized by Dr. Ira Leifer of Bubbleology Research International, Santa Barbara. It involved multiple platforms to measure methane emissions from a dairy farm operated by the California Polytechnic University.

Figure 4 illustrates a portion of the flight path showing the methane mixing ratio as the Alpha Jet approached San Luis Obispo and spiraled down over the California Polytechnic University Dairy Farm to an altitude of 500 m above sea level. During the downward spiral, the methane increased from a value of about 1.89 ppm to nearly 2.0 ppm at some 700 m above sea level. Figure 5 presents the vertical profiles of various trace gases measured on board the Alpha Jet. Figure 6 shows a plot of altitude and speed for the entire flight. On this flight, measurements were made of ozone, CO_2, CH_4, and water vapor.

CONCLUSIONS. The purpose of this paper is to introduce the scientific community to an instrument platform that is still under development but has already proved its value. When completely instrumented, it will be a rapid response airborne system that can be used to study suddenly occurring events, such as large forest fires or severe air quality events and can be also be used routinely for validation of other aircraft or satellite measurements.

The many successful AJAX flights demonstrate the capabilities of this small, principal investigator–driven, instrumented aircraft measuring program. The system is highly adaptable as illustrated by the response to forest fires described by Yates et al. (2015, manuscript submitted to *Atmos. Environ.*) or the investigation of tropopause folds (Yates et al. 2013). It can be used to carry out routine measurements such as the profiles over the Railroad Valley Playa that supported the CO_2 measurements made by *GOSAT*. The Alpha Jet can be deployed quickly to essentially any location without being hampered by complicated logistics.

Flight hours on the Alpha Jet can be requested through NASA's Science Operations Flight Request

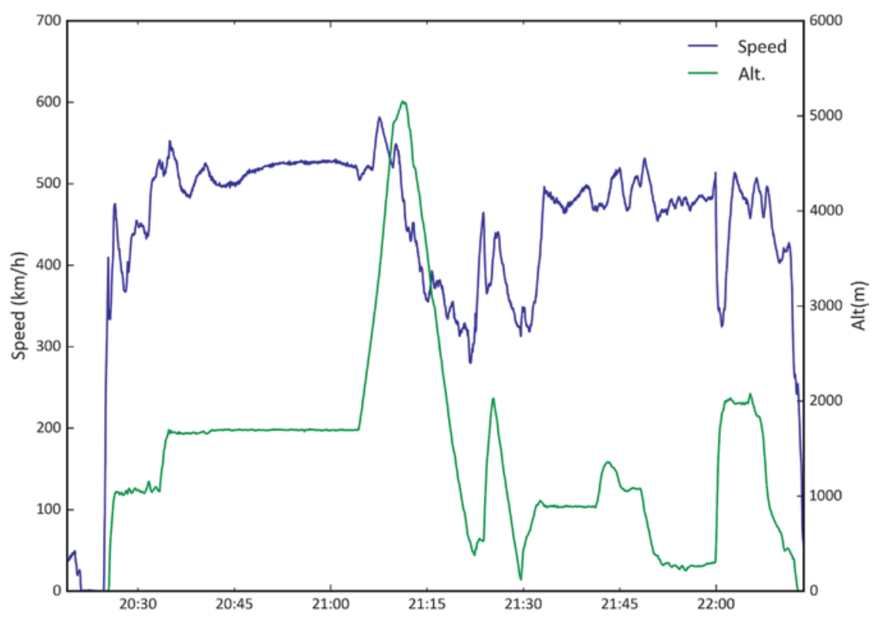

Fig. 6. Speed and altitude plots as a function of time for Alpha Jet flight 116.

System (SOFRS). Scientists who have a serious interest in placing an instrument on the NASA Alpha Jet are invited to contact Dr. Laura Iraci to request a copy of the "Experimenter's Handbook."

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