

# Turbulence and mountain wave conditions observed with an airborne 2-micron lidar

Edward H. Teets Jr.\*<sup>a</sup>, Chris Ashburn<sup>b</sup>, Jack Ehernberger (retired)<sup>a</sup>, and Rodney Bogue (retired)<sup>a</sup>

<sup>a</sup>NASA Dryden Flight Research Center

<sup>b</sup>AS&M, Inc.

## ABSTRACT

Joint efforts by the National Aeronautics and Space Administration (NASA), the Department of Defense, and industry partners are enhancing the capability of airborne wind and turbulence detection. The Airborne Coherent Lidar for Advanced In-Flight Measurements (ACLAIM) was flown on three series of flights to assess its capability over a range of altitudes, air mass conditions, and gust phenomena. This paper describes the observation of mountain waves and turbulence induced by mountain waves over the Tehachapi and Sierra Nevada mountain ranges (California, USA) by lidar onboard the NASA Airborne Science DC-8 airplane. The examples in this paper compare lidar-predicted mountain waves and wave-induced turbulence to subsequent aircraft-measured true airspeed. Airplane acceleration data is presented describing the effects of the wave-induced turbulence on the DC-8 airplane. Highlights of the lidar-predicted airspeed from the two flights show increases of 12 meters per second (m/s) at the mountain wave interface and peak-to-peak airspeed changes of 10 m/s and 15 m/s in a span of 12 seconds in moderate turbulence.

**Keywords:** clear-air turbulence, aviation safety, mountain wave, rotors, vortexes, lidar, accelerations, airplanes, terrain-induced

## 1. INTRODUCTION

Current commercial and general aviation aircraft in service lack the capability to detect and mitigate atmospheric turbulence phenomena. Significant turbulence capable of adversely affecting aircraft ride comfort and controllability can be generated by convective storms (in visible clouds and in clear air), jet streams (at the confluence of multiple streams and near boundaries) and mountain waves and rotors (upward propagating and vortexes).

To improve the detection ahead of the airplane, turbulence and mountain wave observations were made using the Airborne Coherent Light detection and ranging (Lidar) for Advanced In-Flight Measurements (ACLAIM) system<sup>1</sup>. The ACLAIM was supported by the NASA Aviation Safety Program's Weather Accident Prevention (WxAP) Project, Turbulence Prediction and Warning Systems (TPAWS) element. The purpose of the ACLAIM program is to determine the viability of forward-looking lidar as a sensor for advanced detection of clear-air turbulence (CAT) and wind shear detection<sup>2</sup>. One goal of the program was to develop technology that could "see" in front of the aircraft with sufficient time to warn of impending CAT and to mitigate the effects on aircraft passengers and crew.

The ACLAIM was flown on the NASA Airborne Science DC-8 airplane. The ACLAIM team participated in over 30 DC-8 flights as part of the Convection And Moisture EXperiment 4 (CAMEX-4), Cold Land Processes Field Experiment (CLPX), and the southern California coastal eddies missions. Figure 1 shows the lidar placement on the DC-8 for the year 2003 missions. During these missions, the ACLAIM was operated as a "piggyback" experiment. All flight profiles were driven by the primary mission objectives. On two flight days during the coastal eddies mission, the ACLAIM lidar became the primary experiment allowing the ACLAIM project personnel to determine the flight profiles. The data collected from these two flights are the focus of this paper.

\*[edward.h.teets@nasa.gov](mailto:edward.h.teets@nasa.gov); phone 00 1\* 661 276-2924



Fig. 1. The lidar window assembly on the NASA Airborne Science DC-8 airplane; the rotating periscope is pointing toward the back, in the stowed position (inset).

Two nearly identical ACLAIM systems were built by Coherent Technologies, Inc. of Lafayette, Colorado, USA: one system for the United States Air Force (USAF) optimized for downward conical scanning and one system for NASA optimized for forward-looking scanning. The USAF lidar was used in the 1990s by the Airdrop Ballistic Winds (ABW) team at the Air Force Research Laboratory (AFRL) at Wright-Patterson Air Force Base (AFB) to flight-test an innovative wind-measuring instrument that would permit real-time determination of ballistic winds and thereby improve the accuracy of high-altitude airdrops<sup>3</sup>. During the spring 2003 NASA airborne science flight campaigns, the ACLAIM transceiver built for the AFRL was installed on the DC-8 airplane together with the electronics built for the NASA ACLAIM system. Table 1 lists the lidar specifications<sup>4</sup>.

Table 1. Lidar transceiver specifications (based on autumn 2002 tuneup).

Parameter	Value
Wavelength, meters	2.0125
Laser pulse energy, mJ (out of telescope)	9.3
Laser pulse duration, nsec	650
Pulse repetition frequency, Hz	100
Beam diameter, cm	8
Telescope aperture, cm	10
Focal distance, km	2.5
System efficiency, percent	14
Power, W	470

The ACLAIM lidar experiment was an independent experiment operated in conjunction with the NASA Airborne Science DC-8 coastal eddies mission. The primary goal of the coastal eddies mission was to use surface in situ measurements and airborne side-looking synthetic aperture radar (AIRSAR) to understand the generation of spiral-shaped "slicks" on the ocean surface that may result from small eddies typically 5 to 10 km in diameter. These flight missions took place over the Southern California Bight, a region off the California coast between the Santa Barbara Channel and the Gulf of Santa Catalina. These missions required clear skies and at least fairly benign wind conditions to meet the desired objectives. Confined to this restraint, the coastal eddies mission offered little in the way of turbulence. However, it was during this campaign that the ACLAIM was permitted flight time as the primary experiment. The lidar team decided to seek and observe mountain waves and turbulence of mountain wave rotors as the source of disturbed

airflow for the lidar evaluation. Mountain waves are the result of restricted vertical motion in a stable atmosphere due to the forcing of air over mountain ranges. The vertical motion triggers an oscillating wave motion similar to waves formed by water flowing over rocks in a fast-running stream<sup>5</sup>. A mountain wave rotor is a turbulent low-level horizontal vortex that forms downstream in close association with mountain waves<sup>6</sup>. This paper details examples of mountain wave and rotor turbulence data collected during these two flights.

## 2. FIELD OPERATIONS OF APRIL 23–28, 2003

The flight of April 23, 2003, dedicated to the lidar team, planned to search for mountain waves being generated off the southern Tehachapi range, notably the Three Sisters. The Three Sisters are three co-located peaks ranging from 6300 to 6700 ft (1921 to 2043 meters) in elevation. The flight plan called for a series of flightpaths parallel to the Tehachapi mountain range (perpendicular to the wind field) beginning at 4000 ft (1220 meters) mean sea level (msl) and progressing upward at 2000-ft (610-meter) intervals to 8000 ft (2439 meters) msl. Both northwesterly and southeasterly flightpaths were flown at each altitude. A second set of flightpaths were flown perpendicular to the mountain range (parallel to the wind) beginning at 8000 ft (2349 meters) msl with subsequent 2000-ft (610-meter) descents to 4000 ft (1220 meters) msl. Like the first set of flightpaths, both east and west flightpaths were flown at each altitude. Figure 2a shows a closeup view of the flight track used for the April 23 flight.

The flight plan for the mission of April 28, 2003 allowed the ACLAIM team to “search” for turbulence. With a Pacific storm affecting the west coast of California, the turbulence search was conducted in the Owens Valley, which is located approximately 100 miles (160 km) north of Edwards Air Force Base (EAFB). The Owens Valley is well-known for producing numerous and monstrous mountain waves<sup>7</sup>. A number of mountain wave research programs have been conducted in the Owens valley area over the years, two of which were the Sierra Wave project from 1950 to 1955<sup>8</sup> and the Terrain-Induced Rotor Experiment (T-Rex) in the spring of 2006<sup>9</sup>. The current absolute altitude world record for a sailplane (49009 ft) (14942 meters) was achieved in the same vicinity as that in which the turbulence search was conducted<sup>10</sup>. While the DC-8 airplane was at 22000 ft (6707 meters) msl, a NASA Dryden Flight Research Center F-18 pilot on a proficiency flight reported turbulence at 15000 ft (4573 meters) msl. The ACLAIM team then called for the DC-8 airplane to drop to 15000 ft (4573 meters) msl to investigate. Once at that altitude, the DC-8 encountered moderate turbulence associated with a mountain wave rotor. Figure 2b shows a closeup view of the flight track of the April 28 turbulence encounter.

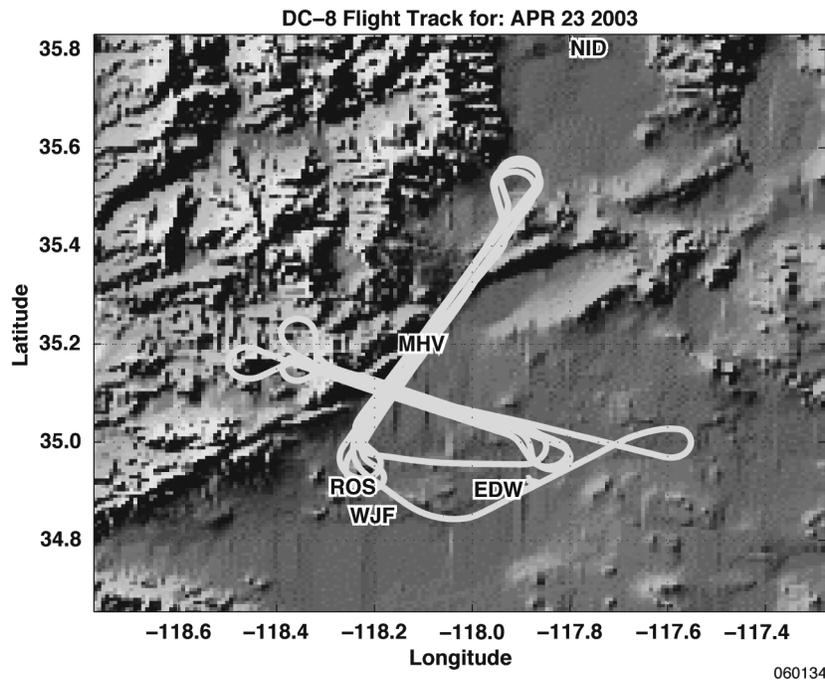


Fig. 2a. Closeup view of the NASA Airborne Science DC-8 flight track of April 23, 2003.

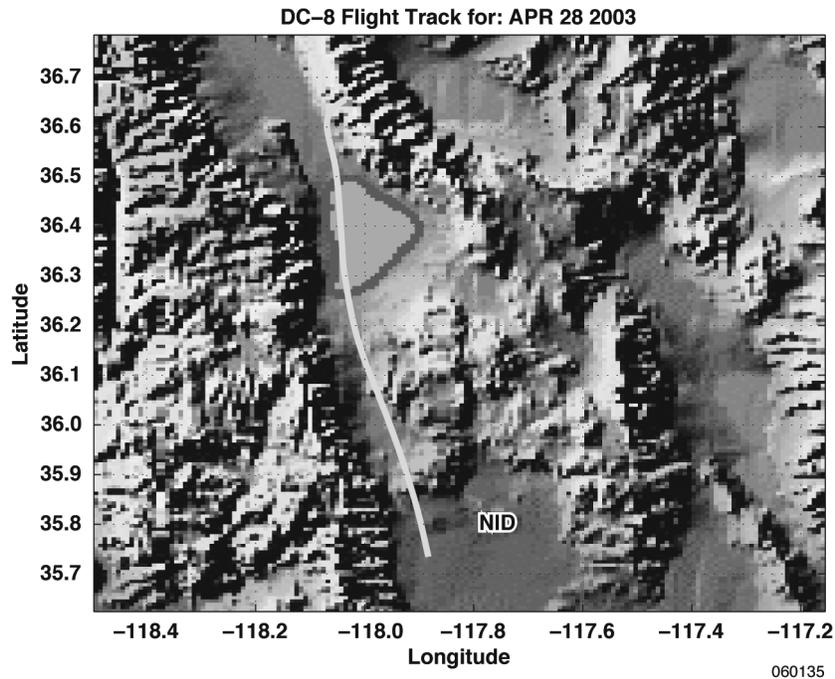


Fig. 2b. Closeup view of the NASA Airborne Science DC-8 flight track of April 28, 2003.

### 3. DATA RESULTS

The lidar data display shows radial wind velocity component changes versus distance ahead of the aircraft and is compared to the aircraft true airspeed minus true groundspeed ( $TAS - TGS$ ). In order to perform this comparison, it was necessary to first translate the aircraft data into the same coordinates as the lidar display. This was accomplished by using the DC-8 groundspeed and the data sample rate to estimate a distance through space. By translating the DC-8 data versus distance from a given point, the lidar and the aircraft  $TAS - TGS$  changes can both be plotted as a function of distance ahead of the aircraft. With the configuration of the lidar system, this method of comparison will yield significant lidar-to- $TAS$  correlation if: 1) the aircraft is not maneuvering (i.e. banking or ascending/descending away from the event), 2) the predicted turbulent event is relatively stationary, 3) the lidar signal-to-noise ratio (SNR) was sufficient to produce valid data, 4) the turbulent event is not of such small scale that the DC-8 data acquisition system cannot record it, and 5) the event was somewhat isolated, so that a boundary between perturbed and unperturbed flow can be distinguished.

During the April 23rd flight, the lidar wave signatures were pronounced. Figure 3 shows examples of lidar signals compared with aircraft  $TAS$  as a function of distance ahead of the airplane. Figure 3a shows the lidar signal at 21:32:36 UTC approaching the mountain wave at an altitude of 8000 ft (2349 meters) msl with the airplane  $TAS$  prior to encountering a mountain wave which is located about 5 km ahead of the aircraft. Gaps in the lidar data are a result of SNR being below specified limits and are considered unreliable. The ACLAIM system was built on mid-1990s technology and as a result was underpowered for the long-range detection in clear air that was desired by the project requirements. Figure 3b, taken 45 seconds later, shows a well-developed wave with a 12 meters per second (m/s) increase in  $TAS$  predicted by the lidar. Figure 3c, taken at 21:37:15 UTC with the DC-8 at 6600 ft (2012 meters) msl and descending on a southeast heading with a tailwind, presents the mountain wave encounter showing the 12 m/s increase in  $TAS$ . The lidar signal prediction of a 3-km-long mountain wave and the aircraft  $TAS$  confirmed this observation. The event was isolated, and the lidar was able to predict the wave structure out to 4 km (approximately 20 seconds) ahead of the aircraft.

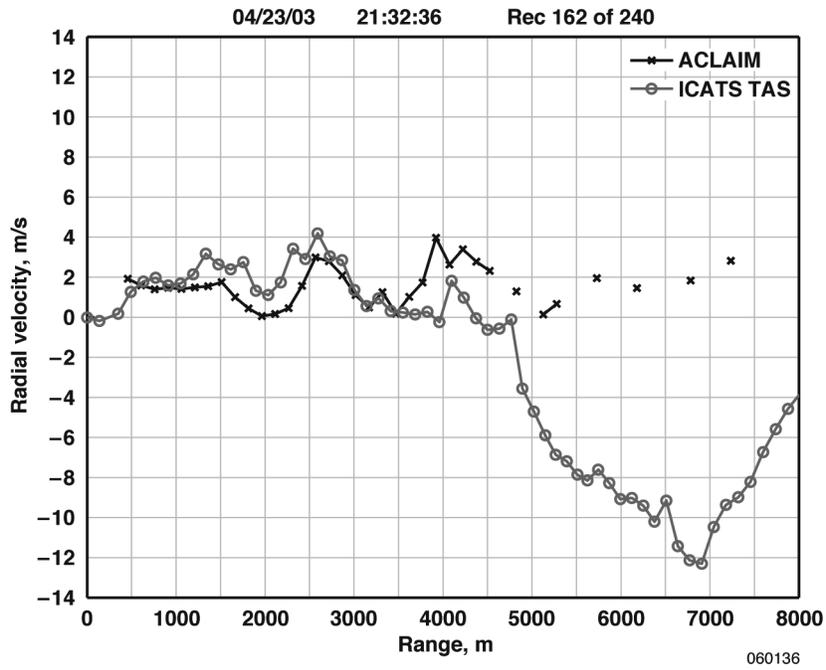


Fig. 3a. The ACLAIM signature approaching a mountain wave.

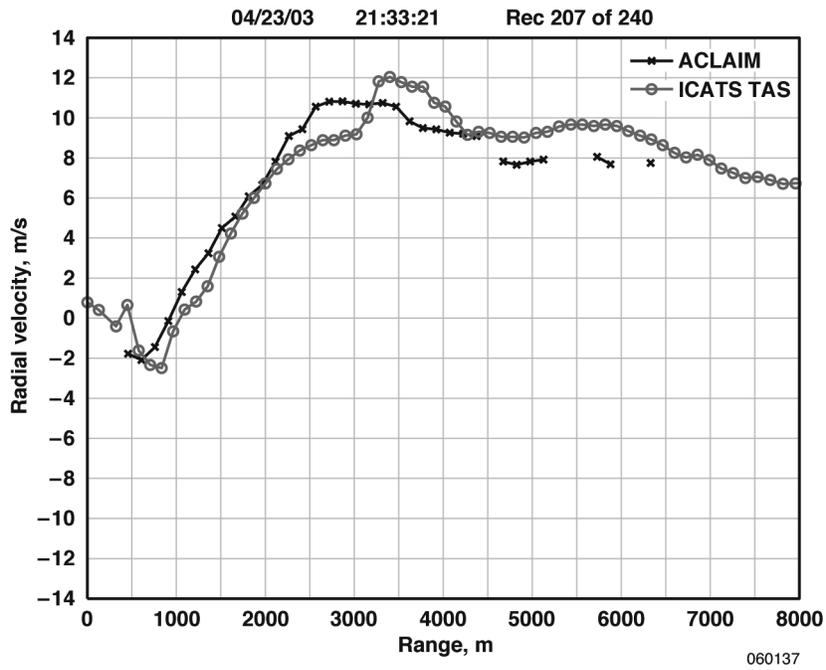


Fig. 3b. The ACLAIM signature just prior to a mountain wave encounter.

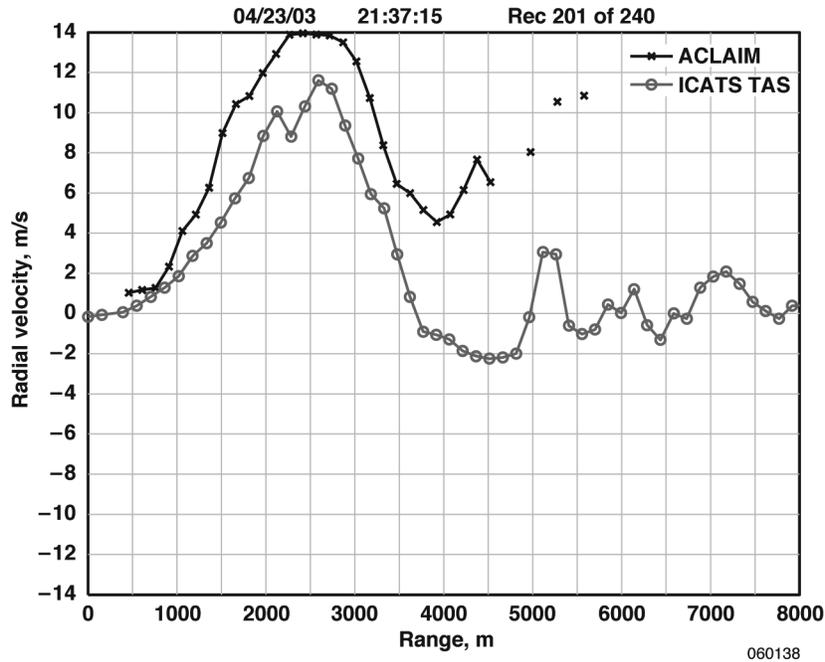


Fig. 3c. The ACLAIM signature of the entire mountain wave.

The most significant turbulence events from all of the ACLAIM-dedicated flight times occurred during the April 28 mission. At this time, near 20:29 UTC, the DC-8 airplane was on a north heading at 15000 ft (4573 meters) msl between the Sierra Nevada and Inyo mountain ranges and perpendicular to the wind field (as shown by the flight track on figure 2b). Figure 4 shows a comparison of the lidar prediction to the observed DC-8 TAS during the turbulence encounter. This figure shows the lidar at 20:29:11 UTC with signal returns to 3.5 km while in turbulence. The 15 m/s peak-to-peak (1500 m to 2400 m) corresponds to the 1.3-g excursion shown in figure 6. Some signatures of turbulence are observed, but with the prevailing wind being perpendicular to the lidar beam, it is very difficult to see the extent of the turbulence signatures parallel to the beam. Figures 5 and 6 show DC-8 acceleration data obtained while flying into and out of the turbulence region. All acceleration data was recorded at 30 samples per second. Evidence of this rotor is observed in figures 5 and 6 by the abruptness at which the aircraft entered and exited the moderate-to-strong turbulence. The first and last 25 seconds of data show very little in the way of significant accelerations. Figure 5 shows the lateral and longitudinal accelerations as recorded by the DC-8 airplane. Figure 6 shows the vertical accelerations obtained during the turbulence encounter. The g-values (normalized to  $9.8 \text{ m/s}^2$ ) listed on these figures represent the instantaneous g's as measured by the accelerometers without additional averaging. The 1.3-g vertical acceleration near 193 seconds observed in figure 6 corresponds directly to the lidar signatures in figure 4.

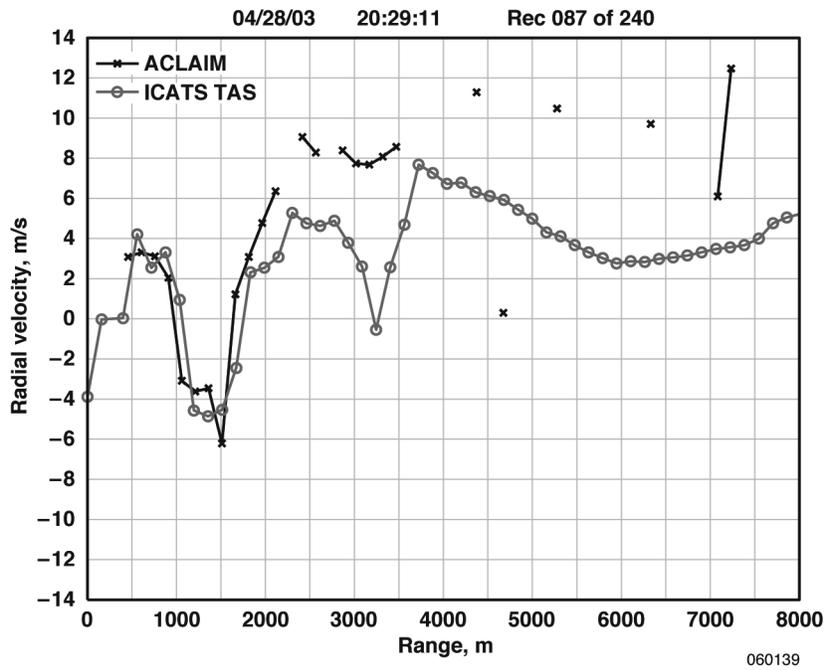


Fig. 4. Example of lidar signal (+) compared with airplane TAS (o) as a function of distance ahead of the airplane.

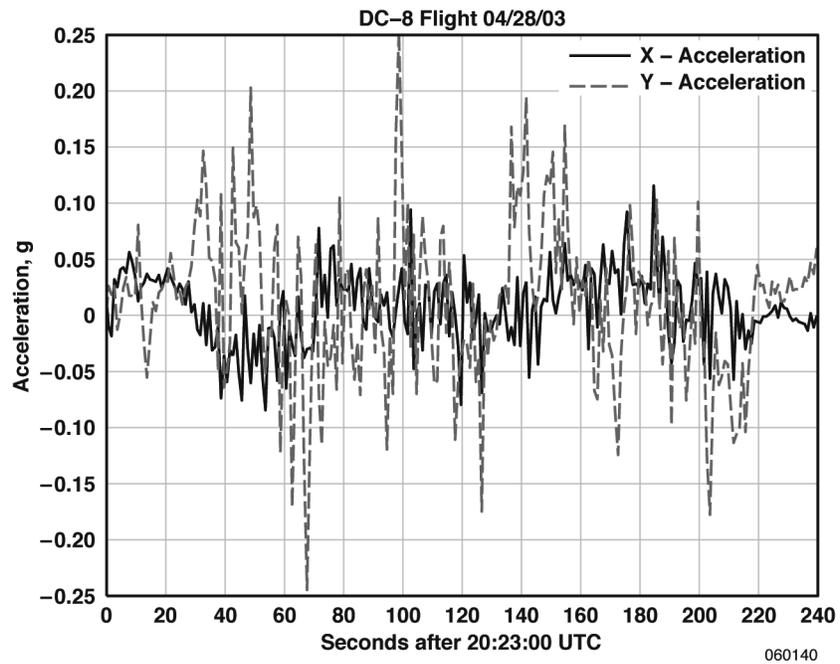


Fig. 5. Lateral and longitudinal acceleration data for the April 28, 2003 case; time start = 20:26:00, time stop = 20:30:00.

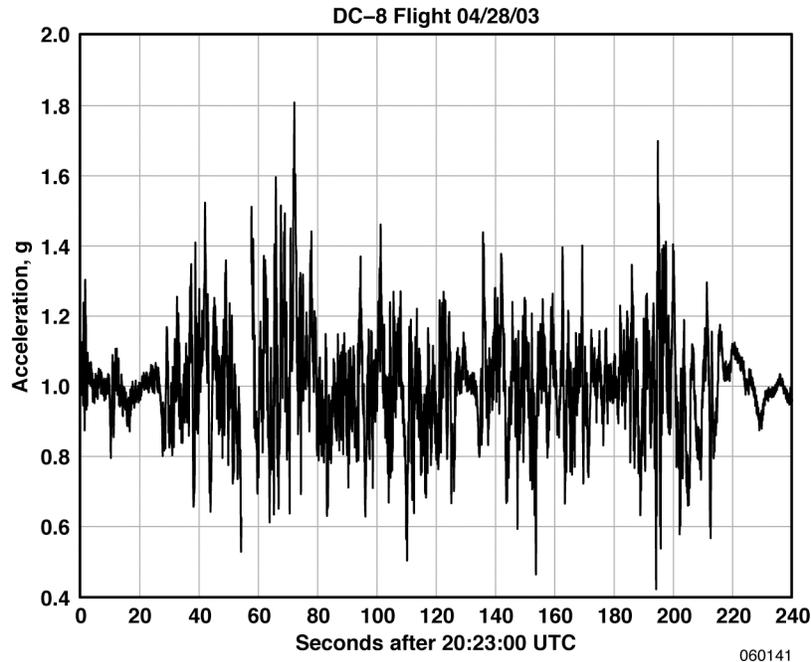


Fig. 6. Vertical acceleration data for the April 28, 2003 case; time start = 20:26:00, time stop = 20:30:00.

#### 4. CONCLUSION

The ACLAIM lidar sensor flown on the NASA Airborne Science DC-8 airplane detected turbulence and mountain waves at ranges of nearly 4.5 km at 15 000 ft (4573 meters) msl and nearly 6.0 km at 6000 ft (1829 meters) msl altitude. The longer range of turbulence detection at lower altitude is a result of the presence of more atmospheric aerosols off of which the lidar energy could reflect. The ACLAIM detected continuous mountain wave signatures as the aircraft passed through the wave. Turbulence signatures were detected by the ACLAIM system up to entering the turbulence field, at which point significant maneuvers reduced effective detection. With increasing altitude, detection range was only slightly reduced. Significant increases in lidar power will improve the quality of the returned signal, increasing the range of turbulence detection and thereby increasing the advance time of detection.

#### REFERENCES

1. D. Soreide, R.K. Bogue, L.J. Ehernberger, S.M. Hannon, and D. Bowdle, "Airborne Coherent Lidar for Advanced In-Flight Measurements (ACLAIM) Flight Testing of the Lidar Sensor," prepared for the American Meteorological Society Ninth Conference on Aviation, Range, and Aerospace Meteorology, Orlando, Florida, September 11–15, 2000.
2. D. Soreide, R.K. Bogue, L.J. Ehernberger, and H. Bagley, *Coherent Lidar Turbulence Measurement for Gust Load Alleviation*, NASA TM-104318, 1996.
3. J. Carr, J. Root, R. Fetner, M. Salisbury, and R. Richmond, "Airdrop Ballistic Winds Operationally Capable Lidar," *IEEE AES Systems Magazine*, May 1999, 31–36.
4. R.K. Bogue and H.W. Jentink, *Optical Air Flow Measurements in Flight*, NASA TP-2004-210735, 2004.
5. E.H. Teets, Jr. and E.J. Carter, "Atmospheric Conditions of Stratospheric Mountain Waves: Soaring the Perlan Aircraft to 30 km," preprint 6.10 for the American Meteorological Society 13th Conference on Applied Climatology and 10th Conference on Aviation, Range, and Aerospace Meteorology, Portland, Oregon, May 13–16, 2002.
6. American Meteorological Society, Glossary of Meteorology, [http://www.ametsoc.org/MEMB/onlinemembservices/online\\_glossary.cfm](http://www.ametsoc.org/MEMB/onlinemembservices/online_glossary.cfm), accessed July 12, 2006.
7. R.F. Whelan, *Exploring the Monster, Mountain Lee Waves: The Aerial Elevator*, Wind Canyon Books, Inc., Niceville, Florida, 2000.

8. J.R. Holmboe and H. Klieforth, "Investigation of Mountain Lee Waves and the Air Flow over the Sierra Nevada," Department of Meteorology, University of California Los Angeles, final report, contract number AF 19(604)-728, March 1957.
9. V. Grubisic and J.P. Kuettner, "Sierra Rotors and the Terrain-Induced Rotor Experiment (T-REX)," American Meteorological Society 11th Conference on Mountain Meteorology and the Annual Mesoscale Alpine Program (MAP), Atlanta, Georgia, June 21, 2004.
10. Fédération Aéronautique Internationale (FAI), The World's Air Sports Federation, Aviation and Space World Records, <http://www.fai.org/records>, accessed July 12, 2006.