Velocity Sensor for an Airborne Optical Air Data System

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Abstract

THE feasibility of an optical air data sensor (OADS) based on sheet-pair transit-time velocimetry has been demonstrated on an F-16 from sea level to 50,000 ft and up to supersonic speeds during exposure to bright sunlight, clouds, and smoke. Measurements corresponded well with conventional pneumatic airspeed and attitude measurements, with significantly better response time and data rates exceeding 100/s. The prototype system proved reliable on all flights and retained acceptable calibration.

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Compared with pneumatic systems, optical air data systems offer potential advantages of constancy of calibration, high update rate, low latency, high reliability, and little need to modify skin shape or properties. In early 1990, Spectron demonstrated flight-worthy hardware and software implementing the "two-sheet" velocimetry principle in an opto-avionic package mounted in the radome of an F-16. True airspeed (TAS), angle of attack (AOA), and angle of sideslip (AOS) were reported continuously at 50 Hz to the vehicle 1553 bus throughout the 24 test flights. As part of this optical air data system, temperature and pressure were also measured using an innovative remote optical sensor.[1]

The transit-time velocimeter technology was implemented as a carefully specified pattern of six sheets projected into a 6-cc measuring volume four feet from the vehicle. This configuration permitted measurement of the velocity vector of the vehicle with respect to the local air mass beyond the region of significant perturbation by the vehicle. The sheet pattern is swept across submicron particles stationary with respect to the atmosphere and the detected light processed to give nonorthogonal velocity components normal to each sheet pair. These are combined and, with aircraft installation geometry and body rates, permit the real-time reporting of aircraft speed and attitude. Small aerodynamic calibration may be necessary for some vehicles, depending upon sites available for installation.

Extensive computer modeling guided the design that was implemented and shown capable of making the required air data measurements. Prior to the flight demonstration, the major perceived risks were concern over ubiquitous sufficiency of suitable particles in the atmosphere, the possible need for aerodynamic and/or other compensations, the guarantee of initial and retained geometrical calibration, and concerns common to any opto-avionic system, i.e., size, weight, power demand, reliability, lifetime, maintenance, and, of course, cost. These risks are now quantified and shown to be manageable.

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Implementation

Four boxes constituted the prototype velocimeter system: optical sensor, signal processor, power supplies, and thermal controller. For a production system these would become one unit, reducing the prototype weight by a factor of 10 to about 25 lb. The power demand and cost would reduce by similar factors. Six 1-W GaAlAs laser transmitters were arranged in a rigid frame around a common receiver optical system. This focused light scattered from small atmospherically entrained particles in the sheet pattern on to a field mask and then via a narrow band filter and field splitter to six avalanche photodiode detectors. Auxiliary electronic systems controlled laser power and wavelength, detector gain, and thermal environment with extensive monitoring of system health and real-time behavior.

Each detector observes a light pulse as its sheet passes a particle. The time of this transit is found using a centroiding algorithm, and the event time and amplitude are stored for later correlation. Events that cross both sheets of a pair are accumulated and their mean transit time between sheets reported. The accumulation time is controlled by how often an output is requested. The mean transit time is inverted using the sheet separation and reported as velocity component normal to that sheet pair.

The seven discrimination processes used in sequence are optical, spatial, and spectral filtering (to reduce flare from ambient light); automatic gain control; matched filtering, digital thresholding; conditional data editing; and centroid estimation.[2] The nonlinear properties of these permit the accuracy demanded by this type of velocimeter, which is both higher than that realized in former systems and more difficult to test because all ground-based facilities contain residual turbulence.

System control is based upon Inten®80286 engines with the signal processing performed by three TMS320C25 DSPs (digital signal processors), one for each sheet-pair channel. Diagnostic capability was augmented by a software architecture implemented as a one-to-one mapping between all hardware and software modules and interfaces.

Velocimetry Observations

A major motivation for this flight-test program was to evaluate and minimize risks. These included sufficiency of atmospheric particles, operational integrity, accuracy and dynamic ranges of velocity and attitude, and consequences of background light.

Two-sheet technology exhibits potentially high accuracy where two criteria apply: a particle must be unambiguously detected and then the time at which it crosses its sheet must be measured. For the prototype, even if only one photon gives rise to the detected event, the root-mean-square (rms) position error at the sheet will average one-quarter of the sheet $1/e^2$ width, a worst-case velocity error of less than 0.2%. If as many as 100 photons are detectable above the noise during the sheet transit—typical of a 0.6-μm-diam particle—the accuracy improves to 0.03%. Where many particles with the same velocity are detected during a measurement interval, this accuracy improves according to the central limit theorem for Gaussian uncorrelated events. For a worst-case noise level derived by observing particles against a background of brilliantly sunlit

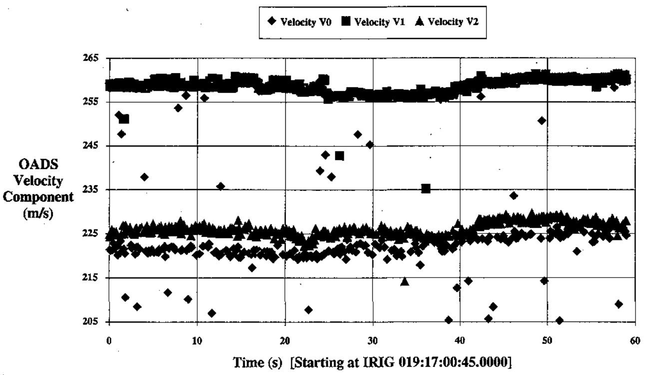

Fig. 1 Fifty ms samples of raw velocity data from each channel for 58 s at 50,000 ft.

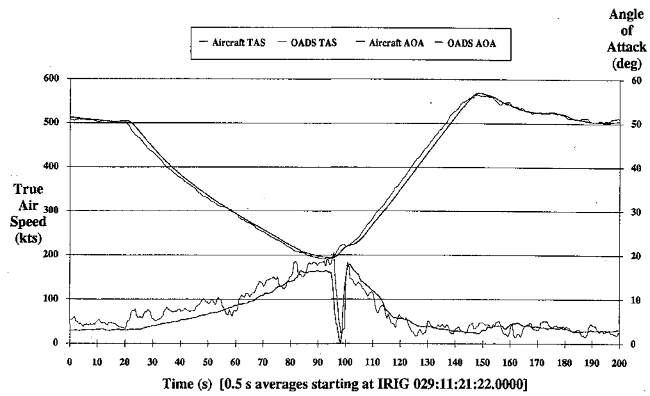

Fig 2 Speed and attack angle comparisons during maneuvers near 17,000 ft.

cloud tops, the accuracy of 0.03% requires a single particle of about 1.7-μm-diameter or several smaller particles.

Design Models

For the described system, a computer model was built to obtain quantitative estimates of expected performance, both in an ideal situation and for diagnostics when not all is as perfect as we might wish, with respect to construction, stability, or operation. The model predicts the signal from the transit of one sheet by a single particle with specified properties and background light levels. It also estimates the accuracy of time measurement with which a transit may be found, given signal and background levels, with proper allowance for optical signal quantization.

We introduce a performance parameter, "discriminability," the signal peak power divided by the standard deviation of the background noise from its mean level, identifying this with the ability to find and measure a single particle in the presence of the inevitable noise. This is more useful when examining the effects of nonlinear processing than the conventional signal-to-noise ratio.

Complete analysis must accommodate all phenomenology. This includes distribution, concentration and scattering characteristics of natural particles, geometrical and physical optics of implementation, optical detection, signal discrimination and timing, correlation to derive velocity estimates, calibration, and consideration of any vehicle specific compensations.

Minimum detectable particle size depends on background light level but in darkness may be as small as 0.2 μm for good measurements. Using the Deirmendjian model for atmospheric aerosols, this suggests a data rate of several hundreds per second up to 50,000 ft, compatible with our flight-test observations, when allowance is made for all the relevant factors.

Flight-Test Results

A former concern about sheet-pair transit-time technology was its potential sensitivity loss at high altitude due to lower concentration of suitable particles.

Figure 1 shows raw velocity data from each of the three velocity channels for 58 s at 50,000 ft. Data rates under these conditions were between 30 and 100/s. Dropouts—data points that are obviously incorrect for whatever reason—are more common on channel 0, presaging the demise of laser 0A, which degraded gracefully throughout the flight test. The two dominant reasons for dropouts are insufficient or inadequate particles and excess background light. Scatter is apparent in these raw data sets, but the change between individual measurements indicates local trends more than scatter of individual samples.

Figure 2 shows maneuvers near 17,000 ft. About 20 s into the record aircraft TAS falls rapidly. At about 93 s, a pushover of AOA to 0 deg is initiated and is almost over at 100 s. OADS reporting of this event is reasonably close to conventional aircraft measurements. OADS leads aircraft TAS throughout and AOA mostly, except during the pushover where it appears to lag. Neither body rate nor aerodynamic compensations were performed on these data. Speed and attitude with respect to the vehicle are obtained from transformation of the nonorthogonal measured components to vehicle frame by a 3 × 3 matrix, based upon geometrical installation factors.

Observations

Simple running averages of both aircraft and OADS data are phase locked to IRIG time to eliminate effects of bus asynchronicity. We consistently observe that the OADS data has a 1–2 s lead over the quantities reported by conventional pneumatic systems to the 1553 bus.

During three supersonic excursions on the last flight, we observed that the OADS velocity was 20–40 kt lower than the aircraft TAS, which showed a step at the Mach 1 transition.

The OADS data are significantly more noisy than the pneumatic data. At first we attributed this to sparse particles, but since it did not worsen with increasing altitude, other sources were suspected. The original software was written in anticipation of lower data rates than those observed and, under the test conditions, discarded most of the good data. With a simple modification, significantly enhanced performance is expected on future flights scheduled for late 1990.

Conclusions

Measurement of aircraft speed and attitude by optical transit-time velocimetry has been shown feasible up to 50,000 ft, with update rates up to 100/s, with latency of a few tens of ms, and up to Mach 1.2 with high reliability. The prototype is sufficiently robust and well understood to permit extension to a production instrument with reasonable size, weight, power demand, and cost. Compared with pneumatic instruments, accuracy is better than 1% of velocity, with attitude accuracy depending on installation and vehicle geometry. Aerodynamic calibration seems feasible and any correction factor small even for the 4-ft throw demonstrated here. There appear to be plenty of suitable particles wherever the system has so far been flown.

References

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