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p. 23

NASA-TM-111259

AIAA 95-3935

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Research Center) 23 p

N96-18437

Unclass

G3/03 0099795

**1st AIAA Aircraft Engineering, Technology,
and Operations Congress
September 19-21, 1995/Los Angeles, CA**

OVERVIEW OF THE PREPARATION AND USE OF AN OV-10 AIRCRAFT FOR WAKE VORTEX HAZARDS FLIGHT EXPERIMENTS

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ABSTRACT

An overview is presented of the development, use, and current flight-test status of a highly-instrumented North American Rockwell OV-10A Bronco as a wake-vortex-hazards research aircraft. A description of the operational requirements and measurements criteria, the resulting instrumentation systems and aircraft modifications, system-calibration and research flights completed to date, and current flight status are included. These experiments are being conducted by the National Aeronautics and Space Administration as part of an effort to provide the technology to safely improve the capacity of the nation's air transportation system and specifically to provide key data in understanding and predicting wake-vortex decay, transport characteristics, and the dynamics of encountering wake turbulence. The OV-10A performs several roles including meteorological-measurements platform, wake-decay quantifier, and trajectory-quantifier for wake encounters. Extensive research instrumentation systems include multiple air-data sensors, video cameras with cockpit displays, aircraft state and control-position measurements, inertial aircraft-position measurements, meteorological measurements, and an on-board personal computer for real-time processing and cockpit display of research data. To date, several of the preliminary system check flights and two meteorological-measurements deployments have been completed. Several wake-encounter and wake-decay-measurements flights are planned for the fall of 1995.

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INTRODUCTION

As part of The National Aeronautics and Space Administration's (NASA) Reduced Spacing Operations (RSO) element of the Terminal Area Productivity (TAP) Program, means are being investigated to safely reduce separations between aircraft landings and departures at major airports. A key area being addressed by the Langley Research Center (LaRC) is the specification of aircraft longitudinal separation to avoid encounters with hazardous wakes from preceding aircraft.¹ Wake hazards (Figure 1), along with runway occupancy times, are currently the primary constraints on minimum safe longitudinal separation for takeoff and landing operations and thus seriously affect airport capacity.

The product of this effort will be the delivery of an Aircraft Vortex Spacing System (AVOSS)^{2,3} near the turn of the century. This system will provide the capability to safely space arriving and departing traffic based on 20- to 30-minute predictions of wake hazards along the terminal-area traffic corridors. The enabling technology of the AVOSS concept is the ground-based prediction and possible real-time measurement of wake strength and location in the airport environment. This information will allow capacity increases in most conditions while preventing the rare encounter of a wake of sufficient strength to cause either an unsafe approach, landing, or departure, or undesired maneuvering (e.g., a go-around). A full-up, optimized system would employ real-time sensor feedback to adjust the predicted separation estimates, and may allow approach/departure traffic to proceed even though nonhazardous wakes exist in the flight corridors.

To meet the AVOSS delivery goal, a multidisciplinary team within NASA is studying and

developing techniques for predicting and measuring aircraft wake-vortex characteristics and predicting the subsequent hazards posed to aircraft encountering these wakes. The Flight Dynamics and Control Division, Research and Technology Group (FDCD/RTG) at LaRC has been tasked, in part, to lead an effort to provide flight data to supplement the ground-based research required for delivery of the AVOSS.

There are four specific objectives of the flight efforts. The first objective is to provide data for the development and validation of computer models to represent the flowfield, decay, and transport of a wake-vortex system in the atmosphere near the ground. The validation of these models requires accurate datasets describing aircraft wake vortices and the meteorological conditions which affect their transport and decay. The second flight objective is to provide key data for the development of wake-encounter hazard models which will be used to define sensor-observable wake-strength thresholds for satisfactory landing/departure operations in the event a wake encounter occurs. Adequate representation of vortex-induced aerodynamic forces and moments on an aircraft and the subsequent dynamics of the encounter are key requirements. The third flight objective is the evaluation of airborne techniques/sensors for detecting nearby wakes. The optimum full-up AVOSS would employ ground-based detection of wakes along the approach corridor, but this does not exclude the evaluation of candidate airborne, in-situ vortex-detection methods which could be considered as potential back-up, early-warning systems for pilots. Finally, the fourth objective is a flight demonstration of the operational utility of the AVOSS in the airport environment.

To facilitate completion of these objectives, a multiple-aircraft flight-test program has been initiated at LaRC. A key test vehicle for this program is a highly-instrumented North American Rockwell OV-10A Bronco. This vehicle became operational as a research aircraft in November 1994, and plans exist to perform several types of missions including (1) flying controlled trajectories near and through the wake produced by another aircraft, (2) tracking the trajectories of the wake of another airplane, (3) performing as a meteorological-measurements platform, (4) assisting in quantifying the trajectory of a typical transport aircraft relative to a wake it encounters, and (5) possibly demonstrating the safety of the new AVOSS reduced-spacing criteria in the terminal area.

This paper presents an overview of the status and development of the OV-10A flight-test program and includes a description of the operational requirements and measurements criteria, the resulting instrumentation systems and necessary

aircraft modifications, the system-calibration and research flights completed to date, and the current flight status.

RESEARCH AIRCRAFT

The OV-10A (NASA 524, Serial No. 67-14687) is a two-seat, twin-turbo-prop, high-wing, high-tail, twin-tail-boom, unpressurized aircraft originally designed and operated as a forward-air-control and observation platform with munitions-delivery capabilities (Figure 2). Basic characteristics of the nominal OV-10A and NASA 524 in its research configuration are presented in Table 1, and a photograph of NASA 524 is shown in Figure 3. Instrumentation and research modifications are discussed in a later section. The OV-10A was selected as a research platform due to its performance envelope, ruggedness, relatively large cargo and aft-cockpit capacity for housing research equipment, and relatively low cost to operate and maintain.

OPERATIONAL REQUIREMENTS AND MEASUREMENT CRITERIA

As previously stated, flight data will support the objectives of wake-vortex characterization, vortex-encounter hazard definition, vortex-detection algorithm development, and AVOSS demonstration. This section presents an overview of the ensuing operational requirements and measurements criteria.

Vortex Characterization

A significant part of the AVOSS development effort is the characterization and prediction of wake-vortex structure and dynamics. Measurements of vortex strength and position made by sensors, when coupled with simultaneous meteorological information, provide data for the development and validation of computer models to predict and quantify vortex behavior. Flight data could be used to augment both the strength and position measurements and the meteorological measurements made from the ground.

Meteorological-Measurements Platform

One sensor, a lidar developed by The Massachusetts Institute of Technology Lincoln Laboratories (MIT/LL), is being used to gather wake strength and transport data at selected airport sites by operating under or near the approach corridor and measuring the wakes of passing commercial aircraft.⁴ The current meteorological-sensor array, which provides data to correlate with the lidar wake measurements, is limited to either

very low altitudes and/or to specific times and spatial positions with respect to the airport. Meteorological flight data has been identified as potentially valuable in extending the range of the current sensor array up the actual airport-area approach/departure corridors and reducing the extent to which other data sources must be extrapolated.

The OV-10A has subsequently been designated as a suitable measurements platform for deployment to these sites and has been tasked with sampling vertical and horizontal profiles of winds, turbulence level, temperature, dew-point, static pressure, and other parameters summarized in Table 2. Because data needs to be collected along both the full approach/departure corridor and across and within the perimeter of the airfield, an array of navigational and air-data measurements is required on the aircraft.

Wake-Decay Prediction Validation

Flowfield measurements made while flying approaches near and through the wakes of other aircraft at altitude have been identified as a means for validating out-of-ground-effect wake-decay models. These models could then be implemented in near-term AVOSS prototypes. Specifically, one prediction methodology⁵ could be validated which requires not only the documentation of ambient meteorological conditions but also the quantification of the trajectory (descent/drift) of the aircraft wake.

These requirements indicate the need for inertial, meteorological, and air-data instruments on the measurement platform (initially identified as the OV-10A) as well as measurements of its state and control positions to enable differentiation between vortex-induced and control-induced aircraft motions. Additionally, a method to track the position of the smoke-marked wake of the vortex-generating aircraft is required. For these experiments, the location of the wake will be determined utilizing a downward-looking, stereo-photographic imaging system installed on the OV-10A (similar to that used in a previous test⁶) coupled with the position measurements of the OV-10A. This method will inherently include measurement of the position of the OV-10A with respect to the wake for documentation of exact wake-encounter geometries. The photographic-ranging scheme entails measurements of the wake from above, which adds the additional potential for measuring the separation of the vortex pair, in part, to characterize the Crow-linking process.⁷ To determine the rate of vortex decay and transport, the position and basic flight conditions of the wake-generating aircraft (currently designated as the NASA C-130 from Wallops Flight

Facility, Goddard Space Flight Center (WFF/GSFC)) are also required.

A typical research scenario could involve the OV-10A first making atmospheric profiles to select the best test altitude of the day (nominally 5,000 ft but potentially much lower). Once at the altitude selected, the wake-generating aircraft would fly at constant altitude and airspeed in a racetrack pattern typically oriented either up/downwind or crosswind. The OV-10A would then begin flying behind the wake-generating aircraft at various separation distances, executing approaches near and through the wake nominally from above, and simultaneously recording both the meteorological conditions and the position of the smoke-marked vortex trails. In-situ measurements of the flowfield made during vortex-core penetrations can provide an independent measure of vortex strength for correlation with the strengths derived from the descent rate of the vortex.

Vortex Encounter Hazard Definition

Perhaps the most challenging aspect of optimizing the AVOSS is defining the threshold of satisfactory-operations for encounters with wakes persisting in the traffic corridors. This entails knowledge of the wake characteristics, an understanding of how the wake affects the aircraft as it passes through, the expected pilot control inputs or automatic control system inputs, a measure of the level of acceptable "upset," and the ultimate application to the aircraft fleet. Simulations of vortex encounters will have to be utilized to address this,^{8,9} and those simulations will have to be validated using a variety of techniques being addressed in a collection of several experimental, numerical, and analytical studies.¹

One process for developing validated models for simulating vortex encounters involves

- developing a simulator math model of a vortex-encounter aircraft
- using measured and/or predicted vortex strengths and vortex-induced aerodynamic forces and moments in a flight simulation to predict airplane motions
- modifying the simulator math model, as necessary, to get correct responses
- extending application of the validated math models to other aircraft for definition of fleet-wide satisfactory-operation thresholds.

Flight data from vortex encounters flown at safe altitudes and approach speeds could facilitate this process. Specifically, measurement of the vortex strength, location, flowfield properties, encounter-airplane states and controls, and relative wake-to-aircraft positions can be used to validate ground-based results. Although wake-encounter flight tests

have been previously conducted,^{e.g., 10, 11, 12} most of the flight work in the past has been aimed at quantifying upset hazards rather than validating encounter models for the ground-based quantification of hazards.

The NASA Boeing 737-100 (NASA 515) has currently been designated as the primary configuration for validation of wake-encounter simulation techniques, and as such may fly approaches near and through the wake of another aircraft. It represents a typical jet-transport configuration, and a large portion of the ground-based simulation, wind-tunnel, and wake-encounter modeling effort at LaRC is centered around it. The B-737 was selected for validation of a wake-encounter simulation since an existing baseline simulation model was already available along with a wind-tunnel database.

For any flight experiments of this type, the OV-10A will be tasked with simultaneously gathering atmospheric data in the vicinity of the wake of interest, photographically recording the trajectory of the B-737 from a nominal standoff distance to quantify its position with respect to the lead-aircraft's vortex pair, and penetrating these vortices in order to obtain quantitative vortex flowfield data. Measurements from the OV-10A similar to those required for wake characterization are therefore needed.

A typical flight will proceed in a very similar fashion to that of the previously-described wake-decay-validation flight, except that selection of the test-altitude would be more restrictive for safety purposes. In general, the B-737 would make several wake penetrations along the leg of the racetrack pattern, then temporarily move out of the vicinity to allow the OV-10A to sample (nearly) the same wake and atmospheric conditions as encountered by the B-737. Longitudinal separation distances would be set to avoid substantial vortex-induced upsets on the vortex-encountering aircraft, since the purpose of flight data is to validate simulation models and not study upset hazard boundaries. The B-737 would be equipped with a nominal instrumentation complement to measure navigation, state, and control parameters. Wake penetrations would be flown from several approach angles to the vortex pair, at typical (and safe) approach speeds and flap settings of interest.

Vortex Detection

An in-situ method for predicting vortex encounters has been suggested^{6, 13} as a candidate early-warning system for pilots. Such a system, relying on measurements of the flow field in the vicinity of the wake coupled with a predictive algorithm, could be very useful in both real-time (in

the cockpit) and in post-flight analysis in computing vortex-pair characteristics as well as the position of an aircraft with respect to that vortex pair.

The unique measurements required to determine these quantities for a near-parallel approach to a vortex include the magnitudes and gradients of the vortex-induced angles of attack (α) and sideslip (β). This technique requires two independent measurements of α and β across the span of the airplane. Similarly, longitudinally-spaced flow sensors are required for non-parallel encounters. Data collected during flights to quantify vortex characteristics in the atmosphere could, with the inclusion of the flowfield-gradient and magnitude measurements, also be used post-flight in the assessment of vortex-detection, location, and strength algorithms.

AVOSS Demonstration

A flight verification of the safety of predicted aircraft spacings will be required during demonstration of the AVOSS near the turn of the century. This demonstration will probably involve one or more test aircraft safely flying approaches in the airport environment using the predicted AVOSS spacings.

OV-10A MODIFICATIONS AND INSTRUMENTATION

Significant modifications to the OV-10A were required to convert it from a stock aircraft into a research platform. The modifications began in the summer of 1992 and were completed in the fall of 1994. This section presents a description of those modifications and the resulting systems.

General System

The custom-built data acquisition system (DAS) acquires analog signals from many sources and converts them into digital form for display, transmission, and recording. Basic requirements of the system include a capability to record approximately two hours of data on one mission and a data rate sufficiently high to characterize high-frequency atmospheric turbulence at values at least as great as the lowest structural frequency of the airframe and instrumentation booms. The major components of the DAS are listed in Table 3 and the basic sensors for each of these systems are listed in Table 4. Figure 4 also shows the system locations relative to the airframe, while Figure 5 depicts the general paths of signals through the DAS. The initial OV-10A data system configuration provides more than 150 flight measurements. The DAS contains six major stages, including sensors, signal conditioning,

pulse code modulation (PCM) data-encoding, tape recording, telemetry, and data display. The sensor outputs are signal conditioned, multiplexed and digitized by a commercial 12-bit PCM subsystem that features functional flexibility, programmability, and the ability to multiplex analog and digital signals into a serial format. Major components of the sensor suite include an IRIG-B time-code generator to provide an accurate time base for all flight measurements, a ring-laser-gyro inertial navigation unit (INU) integrated with a global positioning system (GPS) receiver and a standard central air-data computer (SCADC), a separate package of fast-response rate and attitude gyros, two pitot-static and flow-angle-measurement systems, a 5-hole probe, temperature probes, a dew-point sensor, video/audio cameras/recorders, and several control position transducers (CPTs).

Except for sensors, displays, and control panels, most of the equipment for the DAS system is installed in the OV-10A cargo bay. This space, encompassing approximately 71 cubic feet of usable volume on 22 square feet of flooring, was modified by first removing the floor and side walls, the oxygen bottles, several pieces of avionics equipment plus their mounting shelf, and relocating the VHF radio and the VOR/ILS receivers to the right-hand tail boom. A removable main instrumentation pallet, designed to fit in the aft portion of the cargo bay and roll out onto a cart for system maintenance, was fabricated and populated with equipment (Figure 6). Subsequent major modifications also included installation of a removable metal floor with guide rails to support the main instrumentation pallet in the aft portion of the cargo bay, removable metal plates to hold selected instrumentation and instrumentation-power distribution equipment in the mid- and forward-portion of the cargo bay floor, and shelves in the forward part of the cargo bay to support aircraft power distribution equipment and selected instrumentation (Figure 7). Cargo-bay ventilation was augmented by holes cut in the wing-root fairing and in the honeycomb/fiberglass cargo-bay door. Exhaust fans, operated by the pilot, were installed over the holes in the cargo door.

The instrumentation system is operated with 28-volt DC power. The nominal OV-10A electrical system consists of two DC generators and two AC inverters. Each DC generator is capable of providing a maximum of 300-amperes/28-volts (combined 600-amps/28-volts) to the DC buses, while the inverters each provide 115 volts AC. Single-generator operation is capable of supplying sufficient power for all basic aircraft electrical loads, while the inverters provide 400 Hz power for the aircraft avionics. Two additional instrumentation inverters have been installed to provide 115-volt/400-Hz power for several instrumentation components and 115-volt/60

Hz power for cockpit displays, navigation instruments, and on-board personal computers.

Several of the major DAS system components are described in detail below.

Navigation Systems

Two navigation systems have been added to the OV-10A. The first is a multi-component system that supports the research measurements and includes a Litton LN-93 ring-laser gyro INU integrated with a Honeywell 3A GPS receiver and a CPU-140/A Standard Central Air-Data computer (SCADC), all communicating with the PCM system via a MIL-standard 1553 data bus through an 80486-processor/33-MHz personal-computer bus controller. The INU updates the GPS in the event of satellite signal loss, but the GPS does not update the INU to prevent drift errors in the INU measurements. The INU also is capable of providing aircraft accelerations, velocities, and attitudes, but due to apparent aliasing due to dithering, the linear accelerations and angular rates from the INU must be supplemented by a separate package of fast-response rate gyros and accelerometers. The components of the research navigation system reside in the cargo bay on fixed plates and are not part of the removable instrument pallet. The second navigation system entails a Garmin GPS 100 mounted in the forward cockpit, and enables the pilot to precisely navigate and/or set up research maneuvers.

Although not a pure navigation system, a unique instrument developed at LaRC and installed for precise trajectory control during vortex-measurement maneuvers is the Electronic Vortex Optical Tracking System (EVOTS). This system, composed of a low-power light-emitting diode (LED) coupled with a reflective boresight and mounted on a parallelogram swing-arm mechanism on either side of the forward cockpit, is equivalent to a side-mounted gunsight. When properly calibrated in flight, this instrument gives the pilot some means of quantifying and validating vortex-approach angles. A photograph of the EVOTS instrument is shown in Figure 8.

Air-Data Systems

There are two air-data systems on the OV-10A. One system is the SCADC previously described, which is coupled to the INU/GPS system. The second system is the three-component pitot, static, and flow-direction (α/β) measurement system described here and used to obtain the two flowfield gradients described in the section on vortex-detection measurement requirements.

Air data measurements at both wingtips and the nose are facilitated by sensors mounted on the tips of graphite-epoxy research booms. These

booms fit into aluminum tubes and support brackets, which allow relatively quick boom installation and removal. As is customary, the booms were designed to place sensors as far ahead of the predicted aircraft upwash influence as possible, yet have enough lightness and stiffness (high natural frequency) to prevent unwanted vibration influence on the sensor measurements. Thermally-controlled Setra pressure transducers, located approximately at the base of each respective research boom, provide for enhanced accuracy in pressure measurements. Accelerometers mounted near the tips of these booms provide information on boom vibration.

Sensors at the wingtips provide a measurement of the gradient in angle of attack across the span. At each wingtip, the boom support bracket was attached to the strengthened outer rib, and the fiberglass wingtip fairings were modified to allow each boom to protrude through the leading edge. Thermal-control boxes for the pressure transducers were installed inside a cavity near the tip rib. A standard NACA pitot-static probe with balsa α/β vanes was mounted at the end of each wingtip boom approximately one chord length in front of the wing leading edge. The balsa vanes have a high natural frequency of about 0.18 Hz per knot of indicated airspeed in incompressible flow,¹⁴ so that at a nominal OV-10A airspeed of 120 knots, the natural frequency of the vanes is approximately 22 Hz. Figure 9 shows a boom/probe combination mounted for flight.

A flow-angle measurement at the nose combined with one of the wingtip measurements provide a longitudinal gradient in the flow angles. The longitudinal distance between the nose-mounted sensor and those at the wingtips is approximately 12 feet. At the nose, the fiberglass shell and nearby support structure were modified to accept installation of the research boom on the right side of the aircraft fuselage. (The nose itself was not sufficiently stiff to mount the boom directly at the tip of the nose, and the need to locate instrumentation in the nose wheel well left no room for additional support structure.) A fairing to cover the nose-boom mounting structure was fabricated and installed. Four thermal enclosure boxes for the pressure transducers were installed inside the nose-gear wheel well, while aluminum debris shields were fabricated to protect these boxes. A small fiberglass fairing was fabricated for the upper-left area of the nose cone to externally protect one box that protruded through the nose. A pressure manifold was installed at the base of the nose boom to efficiently route pressure tubing from the pressure ports in the boom to the transducers in the wheel well. Finally, a small box housing power converters

for the pitot-static instruments was installed inside the aft end of the nose boom mounting tube.

A commercial, heated Rosemount 5-hole probe (Model 858 AJ) was mounted at the end of the nose boom. The Rosemount probe provides the required pressure ports for determining α , β , airspeed, and altimetry measurements at the nose, and also provides a rugged instrument housing. The tip of the mounted probe is located approximately 6 feet in front of the aircraft nose and approximately 2 feet right of the longitudinal centerline (Figure 10). The probe was connected to the Setra pressure transducers by approximately 17 feet of 3/16-inch inside-diameter flexible tubing. A one-inch-long restrictor with a 0.067-inch hole (#51 drill) was placed inside the tubing near the probe to reduce resonant overshoots in the response. Ground-based tests at sea-level indicated the total system had a natural frequency of approximately 20 Hz with good damping.

A pair of Rosemount Model 102 non-deiced total temperature probes (one for the SCADC and one for the research system) and a General Eastern 1011 Aircraft Dew-Point Sensor were also integrated into the air-data system. The temperature probes are located on the underside of the wing approximately midway between the engine and wingtip on each side (Figure 11), and the dew-point sensor is mounted on the left side of the forward fuselage.

Airborne Video/Audio Systems

The research instrumentation includes a video/audio system consisting of three miniature lipstick-size Elmo video cameras and three recorders. One camera is located at the tip of the left vertical tail, pointing in the general direction of flight, and includes the top of the wing and fuselage in its field of view. This camera provides a good, qualitative means of reviewing the highlights of a flight in preparation for data reduction and analysis. The top, left vertical fin cap fairing was modified to include this camera plus a small, clear-plastic window (Figure 12). The other two cameras are mounted near the tip of each wing and are pointed vertically downward through "peepholes" bored out of the wingtip fairings (Figure 11). Algorithms are being developed to use the stereo effect of the synchronized frames from the two downward-looking views to calculate the relative distance between vortex smoke trails and the OV-10A, and the relative distance between the smoke trails and the B-737. Audio channels on the video/audio system enable the pilot and FTE to record verbal data during maneuvers.

The sponsons are small pods attached to both the left and right sides of the fuselage near the waist position (front view of Figure 2), and were originally used to carry part of the OV-10A weapons system.

Both sponsors on this aircraft were modified extensively to house equipment associated with the research video/audio system (e.g., Figure 13). Additionally, aerodynamic/cosmetic fairings were fabricated and installed on their exterior to cover the voids created by the removal of the machine guns, the ammunition-discharge system, and the bomb racks.

L-Band Telemetry system

The telemetry system provides L-Band transmitters for data transmission and C-Band Beacon transmitters for aircraft radar tracking, and includes associated miniature antennas which are mounted externally to the aircraft structure.

Flight-Test Engineer's (FTE) Station

Although the nominal OV-10A can be safely operated by a single crew member, most flight experiments for this project require two crew members. The pilot occupies the front cockpit and has responsibility for the overall safe conduct of the flight, which includes guiding the aircraft to and through the test maneuvers and overriding research instrumentation systems in the event of an emergency. The flight-test engineer (FTE) occupies the aft cockpit and operates instrumentation, monitors research measurements, directs and evaluates test maneuvers, and maintains audio contact with ground-based researchers.

The FTE research station is, therefore, a major part of the DAS system and encompasses the entire aft-cockpit area. Modification of the nominal aircraft in this area required removal of

- the control stick, rudder pedals, power levers, landing-gear lever, and map case
 - the observer's instrument panel, including the attitude indicator, the landing-gear warning light, the fuel-low and fuel-feed lights, the radio magnetic indicator (RMI), and the microphone select switch
 - the oxygen regulator panel
- and subsequent installation of
- side consoles on either side of the seat to house research equipment, including the hygrometer control/indicator unit, the video/audio system control panel, a data-computer-display keypad, and the DAS system control panel
 - an intercom/microphone switch on the throttle console
 - a new instrument panel, housing two video displays; a flat-panel, 640-by-480-pixel monochrome VGA computer display; and the nominal ship's airspeed indicator, altimeter, torque indicators, fire handles, and a fire-extinguisher switch
 - extensive instrumentation wiring.

The flat-panel computer display is driven by a second 80486-processor/33-MHz personal computer (located in the cargo bay directly behind the FTE) dedicated for real-time calculation and presentation of selected research parameters to the FTE. The FTE has the ability to request any one of several display pages for inspection, but cannot modify these pages nor control the calculations in flight. A depiction of the aft-cockpit configuration is shown in Figure 14 and the components are described in Table 5.

Pilot's Station

The forward cockpit was modified to allow partial instrumentation control and video display. Modification included removal of

- HF radio control
- one VHF radio control
- armament-control panel
- map case
- missile control panel

and installation of

- instrumentation and video/audio system control panels
- a video display directly in front of the pilot on top of the control panel
- the Garmin GPS navigation unit to the left of the video display
- α/β indicators to the right of the video display
- a battery-temperature monitoring system
- a master power-interrupt switch for all video and experimental equipment
- the EVOTS instruments.

The new panel presents the pilot with the capability of controlling data-recording, but does not allow the flexibility to selectively shut down certain systems (e.g., telemetry) nor evaluate data (other than video) in real time. However, the limited control is useful for certain flights (e.g., flutter clearance) where the FTE cannot occupy the back seat. The new forward-cockpit configuration is shown in Figure 15 and the components are summarized in Table 6.

FLIGHT TEST PROCEDURES

Scope

Flight experiments with the OV-10A entail the proposed research missions discussed in the introduction plus a substantial preliminary test program to calibrate the research systems. The preliminary test program has included clearing the modified OV-10A flight envelope for flutter, calibrating the pitot-static and flow-angle measurement systems, validating the meteorological-measurement algorithms, calibrating the stereo video system, and practicing photographic tracking techniques for three-ship wake-encounter flights. With the exception of two completed

deployments, the preliminary flights have entailed most of the program to date and, therefore, are summarized in this section along with an overview of the deployments. Specific technical results from the aircraft calibrations may be presented in a later report.

Aircraft Test Limitations

Research modifications resulted in the establishment of four artificial limits to the nominal OV-10A performance envelope. First, NASA 524 is no longer capable of all-weather performance, since flight into "wet" clouds or in rain could expose the α/β vanes to moisture and possible warpage. Planned future replacement of these vanes with heated 5-hole probes, upon further satisfactory experience using the nose-mounted probe, could ease this constraint. Second, even though the nominal OV-10A was designed for landings on unprepared strips, a landing sink rate of less than 4 ft/sec has been recommended for NASA 524 to avoid excessive vertical accelerations and subsequent stresses on the wingtip booms and mounting hardware. Accelerometers have been placed on the booms to monitor these accelerations on landing, and required inspections are conducted following any firm landings. Third, avoidance of roll rates exceeding 140 deg/sec during loaded maneuvers exceeding 4g has been recommended for the same purpose (although this is an unlikely condition for research experiments). Finally, the aircraft is limited to an altitude of 12,500 ft MSL due to the removal of the oxygen system.

In terms of natural performance limits, there is an approximately 25-30 KIAS (about 15%) reduction in the maximum attainable level-flight airspeed at 10,000 ft MSL. The additional drag caused by the three research booms/fairings is the suspected cause. No additional significant handling-quality and performance differences between the unmodified and modified versions of NASA 524 have been noted. Neither roll performance nor pitch-rate capability were perceptibly affected. The center of gravity was shifted from a near aft limit with the instrumentation pallet (only) installed, to a near forward limit with the addition of the nose boom and associated equipment in the nose wheel well. This forward shift in the center of gravity results in a slight tendency for the nose to rotate sluggishly on takeoff. The OV-10A's docile stall characteristics were not affected.

Wake turbulence tends to persist and be most hazardous during relatively "benign" weather conditions, when winds, convective activity, and precipitation are relatively light. Hence, with a few exceptions, most of the operations associated with collection of wake-decay data, encounter upset dynamics, and meteorological profiles occur during fair-weather conditions coupled with typical pattern approach speeds and nominal "g" loading. Required flight conditions are, therefore, not generally affected

by the limitations described above, except for the "wet" cloud/rainshower avoidance. High-altitude operations requiring the oxygen system are not necessary.

Flight Operations -- Preliminary Calibration & Check Flights and Deployments

Flutter clearance

An available flutter analysis for an OV-10D indicated a sensitivity of the horizontal tail to vibration modes. Because no flutter data were available for the OV-10A, and because the effect of the significant modifications to the nose and wingtips of NASA 524 on the flutter modes were unknown, a flutter and envelope expansion flight test program¹⁵ was completed in the fall of 1994. A summary of the operational procedures used in that flutter flight-test program is presented here.

As the extent of the required nose and wingtip modifications to the OV-10A became apparent, aeroelastic specialists at LaRC were consulted to determine the scope of a flutter flight-clearance requirement. A comprehensive plan was developed which included a series of ground vibration tests and envelope expansion flights. The ground vibration tests were accomplished for both the baseline aircraft and the fully modified aircraft for purposes of comparison. Analysis of these data did not indicate a strong possibility of flutter within the full aircraft envelope, prompting the decision to proceed to a full envelope expansion flight series.

NASA 524 was fully instrumented with the DAS and telemetry system previously described, except for the addition of accelerometers attached to the forward and aft left-wingtip spars. A high-speed taxi test was completed prior to the first flight. This test showed no undamped vibratory modes, even though the wingtip booms exhibited large-amplitude oscillations due to runway roughness and the natural frequency of the aircraft during taxiing. Airborne testing was completed in two flights in November 1994. The test maneuvers included incremental airspeed increases from a straight-and-level condition, aileron raps on condition to act as a frequency-sweep method, stick-free rudder doublets to examine coupled lateral/directional excitations on the nose boom, and dives to maximum attainable airspeeds (330 KEAS) accompanied by aileron raps on condition. After these flights, the envelope was cleared for all flight operations with no evidence of flutter modes having been detected.

During flutter testing, data were being telemetered to the LaRC Flight Control Center (FCC) and analyzed in near-real-time by aeroelastic specialists. An FTE was not allowed to fly in the OV-

10A because of the hazardous nature of the flutter tests and because an FTE could not assess vibration data from the aft cockpit. However, a crew, which included a trained safety observer, chased the OV-10A in a NASA T-34C turbo-prop aircraft. Progression through the test card was controlled by the flight-test director in the FCC with required inputs from the analysts.

Air-Data System Calibrations

Prior to delivery of recorded research data, a variation of the tower flyby method was executed in February 1995, for position-error calibration of the three installed research booms and the Rosemount temperature sensor using the unique capabilities of Wallops Flight Facility. At WFF the basket of a 100-ft-tall "cherry picker" was instrumented with a spare OV-10A pressure transducer and a radiosonde instrumentation pod measuring pressure and temperature. Both the basket and the OV-10A were also each outfitted with a laser-reflector cube, enabling precise position tracking of either by a laser tracker mounted to one of the WFF radar installations.

The flight profiles included multiple passes at incrementally increasing airspeeds flown abeam the cherry-picker basket at 100 feet above ground level (AGL), oriented along the centerline of WFF runway 04. Laser-tracking acquisition of the OV-10A occurred approximately 5,000 feet from the cherry picker. Several combinations of landing gear position (up/down) and flap setting (up/intermediate/down) were flown. At set intervals during these passes, as the OV-10A was in the pattern, the basket was lowered and raised to obtain atmospheric profile data while being simultaneously tracked by the laser tracker. At the start and conclusion of the pitot-static calibration flights, the OV-10A was taxied to the cherry-picker location on the airport and 30 seconds of on-board data were recorded next to the lowered cherry-picker basket so that calibrations of the respective pressure transducers could be made at the same altitude.

During operations, data from all three research booms were recorded and video-tracking signals, pressure, and temperature data from the cherry picker were time-stamped, recorded, and telemetered along with the OV-10A data to the LaRC FCC via satellite. The LaRC FCC was configured to receive the multiple data streams and accomplish partial real-time processing and display of selected parameters for evaluation. Laser-tracking data was post processed along with on-board recorded data to give the final position-error corrections for the research instruments. The onboard FTE was responsible for controlling progress through the test card, although a flight-test director was assigned to the LaRC FCC to suggest changes based on real-time analysis of data.

The flights were scheduled for early morning in order to obtain the calmest atmospheric conditions.

Since the flights occurred during the winter months, obtaining the proper weather conditions became problematic and resulted in several aborts. Both flights for this procedure occurred on the same day. The second flight was conducted during a period of changing wind conditions at the established limit of 10 knots.

Meteorological-Measurements Validation

Several flights were completed in February 1995, to gather data for validation of the meteorological measurements and algorithms needed for further research flights, particularly turbulence algorithms and the computed winds.

Flight test maneuvers included constant-speed/altitude/angle-of-bank 450-degree turns; constant-heading/speed/altitude passes combined with elevator, aileron, rudder, and throttle doublets; constant-speed/altitude box patterns; and level-flight acceleration/decelerations. Constant-speed spiral ascents and descents were used to validate temperature and dew-point measurements against weather-balloon measurements. Additionally, an airspeed calibration using GPS-derived data was attempted using constant-air-speed/-altitude and constant angle-of-bank 450-degree turns and constant-air-speed/altitude/heading passes on reciprocal headings.

These flights demonstrated some of the shortcomings of the aircraft, including the inability to hold a constant airspeed with a standard deviation of less than one knot, and the continuous small lateral-directional oscillations of the aircraft. The former was a result of the weak speed stability of the aircraft, while the latter was principally a result of, the constant variation of engine torque of ± 25 -50 ft-lb characteristic of the installed Garret T-76 turboprop engines. Additionally, the aircraft is characterized in both the gear/flaps up and down configurations by a divergent spiral mode, a lightly damped Dutch-roll mode, and high positive dihedral effect. The combination of all of these effects results in "sloppy" lateral-directional characteristics in the context of precise tracking required for these maneuvers. Maintaining zero sideslip requires constant attention, and non-zero sideslip conditions excite the nuisance lateral-directional modes.

Due to these aircraft characteristics, the calibration maneuvers were not trivial. Even the slightest amount of atmospheric turbulence caused airspeed, heading, and angle-of-bank deviations. Modifications to the original test plan included constant-throttle passes to mitigate the speed instability and nuisance lateral-directional modes.

Video System Calibrations

The on-board stereo-video system, entailing the pair of downward-looking wingtip cameras,

required flight data to tune the automated ranging algorithms used in post-flight processing. As previously described, the stereoscopic range information provided by this system is used to determine aircraft-to-vortex distance for vortex-characterization and vortex-encounter flights.

The two cameras initially were aligned on the ground and the lens distortion characteristics were determined using a target grid. Next, the geometry of the camera orientations with respect to each other was determined by comparing right and left camera images of the runway from an altitude of 12,000 feet where the stereo effect was a minimum. Finally, data passes were flown over the markings on runway 04/22 at WFF at various lower altitudes. Subsequent post-processing was used to compare the GPS-measured altitude with altitude values derived from the cameras. Specifically, the system was validated using data from passes ranging from approximately 100 feet to 600 feet AGL. A range accuracy of approximately 13 feet (1σ) at a nominal range of 500 feet was determined. Flights for these purposes were completed in February 1995, and then again in June 1995, following relocation of the cameras to facilitate instrumentation maintenance in the wingtip areas.

Tracking Assessments

Perhaps the most challenging pilot aspect of the proposed vortex-encounter flights will be the photographic coverage provided by the OV-10A from directly overhead the wake-encountering aircraft. The complicating factors include the need to acquire and maintain position by using the pilot's video display from the downward-facing wingtip cameras. The installed video system complicates the task because the display reverses typical formation-flight cueing. For example, with the image of the target moving aft on the display, the pilot may be induced to make a nose-down pitch input to keep the target centered in the display. The aircraft then begins to accelerate, further exacerbating the problem, and the nose-down pitch input causes a descent below the altitude selected to maintain the desired nominal standoff distance. Furthermore, since the wingtip cameras are rigidly fixed to the aircraft, every attitude change by the OV-10A results in a dramatic shift in the observed focal plane.

In recent practice flights, the OV-10A first tracked the T-34C and then the B-737. These flights demonstrated the difficulty of this task, but techniques were developed which simplified the problem. With the camera lenses currently installed, the B-737 (with a span of 93 ft) covers roughly one-fifth of the focal plane at a 500-ft separation, and a roll-angle or pitch-attitude change of only 5 degrees shifts the coverage area approximately 45 feet and causes track crossing-angle problems. Similarly, a speed differential of only

10 knots results in movement of the image across the video display in the longitudinal direction of 170 feet in 10 seconds. One significant technique developed was to place the B-737's ground track over a relatively straight-line ground reference such as a railroad or coastline, which had the added effect of mimicking a vortex smoke trail. This technique dramatically decreased the lateral control problem by providing a pseudo-roll-attitude reference in the video display. Since the OV-10A lacks speed stability, power changes to correct airspeed errors require a relatively long time to accomplish, and the image is often seen moving out of the field of view while power adjustments are slowly taking effect. To mitigate this difficulty, it was found that holding constant power settings and using S-turn maneuvers to slow downrange travel was preferred to making large power corrections. Obviously, however, this technique decreases the time in which there is a steady image in the fields of view of both cameras, a necessity for stereoscopic measurements.

In another tracking test, the other tracking system aboard the OV-10A (the EVOTS) was evaluated. Early tests in which this system was flown against ground-based targets were very positive and tracking along precise trajectories should be possible.

Vortex Characterization--

Meteorological Measurements Platform

The first field deployment for the MIT Lincoln Laboratories lidar vortex-tracking experiment occurred at Memphis International Airport, TN, during late November and early December 1994.⁴ A second deployment was recently completed in August 1995. Accurate measurements of atmospheric data by the OV-10A were required to correlate balloon, sodar, radar profiles, and tower-measured meteorological data. In order to support the complex multi-agency experiment, the OV-10A deployed the first time prior to the completion of the air-data and atmospheric calibration flights previously described. The recorded data were not processed until the calibration flights were completed and the correction factors were derived, although data-quality checks were performed in the field.

A variety of both vertical and horizontal passes were made along the approach/departure corridors and runways and in the area surrounding the airport at Memphis to document the atmospheric conditions. Vertical profiles were used primarily to sample temperatures and dew-points through the planetary boundary layer (PBL), while horizontal profiles provided sufficient sampling intervals for calculating atmospheric turbulence and winds at discrete altitudes within the PBL. Operations were always attempted for the same runway as used by the

lidar in making its measurements of vortex decay and transport (Figure 16).

Two basic profiles were flown on the first deployment, examples of which are depicted in the sketches in Figure 17. Typically, the first, middle, and last passes on any flight were vertical sampling profiles (Figure 17(a)). These profiles involved flying the instrument approach from the outer marker to the runway threshold, starting at about 1,200 feet above ground level (AGL), followed by a 3-degree climbout to 1,000-1,500 feet AGL at the upwind end of the runway. The second type of profile consisted of sets level-flight, horizontal samples at four or five discrete altitudes. The sampling duration at each altitude averaged about one minute, and was highly dependent on the need to avoid landing and departing traffic (especially on the perpendicular runways at Memphis) and to clear ground obstacles. These passes were established from either a tight, closed pattern (Figure 17(b)) or were integrated with abbreviated approach/departure vertical profiles starting/ending at about 1200 feet AGL (Figure 17(c)), depending upon the traffic situation.

On the second deployment, the passes described above were augmented with horizontal passes similar to those shown in Figure 17(b) but on a runway perpendicular to that of lidar operations; 10-nm-leg box patterns flown near the airport at altitudes approximating one-third, two-thirds, and the top of the PBL to gather winds and turbulence data; 33-nm-leg box patterns surrounding the airport with either a spiral climb or descent at each corner to gather temperature/dew-point data from approximately 1,000 to 10,000 ft MSL; and weather-balloon chases starting at the airport and continuing up to 12,500 ft MSL for aircraft/balloon data correlation. Selection and conduct of these additional maneuvers were based on the day-to-day weather, the status of the ground-based instruments, and the time remaining in a flight following the completion, if any, of the nominal maneuvers shown in Figure 17.

Elaborate coordination with the Memphis approach control and tower was required for the OV-10A to be sequenced with the steady flow of arriving traffic, especially during times of peak airport operations when the largest number of vortices was available. The excellent maneuverability of the OV-10A contributed to being able to quickly fly horizontal passes (Figure 17(b)) in between arriving traffic. Many variations of these basic profiles were completed as dictated by a variety of conditions.

A total of nine research missions were completed over the course of the first eight-day deployment in November-December 1994. On two occasions, two missions were flown on the same day. Data were collected primarily during mid-day hours, although changing conditions during one sunrise and

one sunset were also captured. Approaches were flown in both instrument meteorological and visual conditions. A summary of the flights from the first deployment is presented in Table 7.

A total of seventeen research missions were launched over twenty-one days during the second deployment in August 1995. Data were collected during sunrise, mid-day, late afternoon, and midnight traffic pushes. All operations were conducted in visual meteorological conditions. A brief summary of the flights from the second deployment are presented in Table 8; a summary of data-passes was not available at the time of this writing due to the recent completion of the second deployment.

STATUS AND SCHEDULE

Flutter-clearance and preliminary calibration flights have been completed. Additionally, the first deployment to Memphis in support of lidar wake measurements was completed in December 1994, while the second was completed in August 1995. Current plans for the OV-10A include

- a series of vortex-decay-validation flights with the WFF C-130 in the fall of 1995
- a series of vortex-encounter flights with the B-737 and C-130 in the fall of 1995
- third and fourth deployments to a selected airport site in 1996 and 1997 in support of further lidar wake measurements
- participation in AVOSS validation flights in 1998.

SUMMARY

The development, use, and current flight-test status of a highly-instrumented North American Rockwell OV-10A (Bronco) as a wake-vortex-hazards research aircraft have been discussed. A description of the operational requirements and measurements criteria, the resulting instrumentation systems and aircraft modifications, system-calibration and research flights completed to date, and current flight status were included. These experiments are being conducted by the National Aeronautics and Space Administration as part of an effort to provide the technology to safely improve the capacity of the nation's air transportation system, and specifically to provide key data in understanding and predicting wake-vortex decay and transport characteristics and the dynamics of encountering wake turbulence. The OV-10A performs several roles, including meteorological-measurements platform, wake-decay quantifier, and trajectory-quantifier for wake encounters. Extensive research instrumentation systems include multiple air-data sensors, video cameras with cockpit displays, aircraft

state and control-position measurements, inertial aircraft-position measurements, meteorological measurements, and an on-board personal computer for real-time processing and cockpit display of research data. To date, several of the preliminary system check flights and two meteorological-measurements deployments have been completed. Several wake-encounter and wake-decay-measurements flights are planned for the fall of 1995.

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Table 1 : OV-10A Basic Characteristics

<u>GENERAL</u>	<u>NOMINAL OV-10A</u>	<u>NASA 524 IN RESEARCH CONFIGURATION</u>
<u>Geometry</u>	<u>Weights:</u>	
Span: 40 ft	Approx range: 8,000 to 14,400 lb	
Wing Area: 291 sq ft	Max expected: ----	12,500 lb ^a
Wing Chord: 7.27 ft	Typical takeoff: ----	11,000 lb
Aspect Ratio: 5.5	<u>Speeds:</u>	
Length: 39.7 ft	Level range: 60 to 230 knots	60 to 180 kt ^b
Height: 15.1 ft	Dive limit: 350 kt	330 kt ^b
<u>Engines:</u>	Typical cruise: 180 kt	150 kt ^b
Garrett 715 SHP	Approach: 110 kt	110 kt
Left: T76-G-10	<u>Ceiling:</u>	
Right: T76-G-12	25,000 ft MSL	12,500 ft MSL ^c
<u>Load Factors:</u>		
Normal: -1.0 to +6.5 g		
Rolls: 0.0 to +4.0 g		

a) with the addition of the optional wing external fuel tanks

b) suspected effect of drag due to modifications

c) oxygen system removed from NASA 524 for installation of research equipment

Table 2: Required meteorological measurements.

Date/Time	Rate of climb	Virtual potential temperature
Aircraft weight	Pitch attitude	Inertial wind speed
Flap position	Roll attitude	Inertial horizontal wind components
Landing-gear position	True heading	Inertial vertical wind component
Runway in use	Aircraft angle of attack	Inertial wind direction
Altitude, MSL	Aircraft angle of sideslip	Static outside air temperature
Static pressure	Aircraft X, Y, Z *	Dew point temperature
True airspeed	Localizer deviation	Potential temperature
Ground speed	Glide-slope deviation	

* with respect to the runway threshold

Table 3: Instrument System Summary

System	Components	Location	Figure
DAS	Electronics/Pallet	Cargo bay	6a, 7
	Basic Sensor Suite	See Table 4	—
FTE Station	See Fig. 14 & Table 5	Aft cockpit	14
Pilot's Station	See Fig. 15 & Table 6	Forward cockpit	15
Navigation System	Integrated INU/GPS/SCADC	Cargo bay	7
	Garman GPS	Forward cockpit	15
	EVOTS	Forward cockpit	8
Air-data systems	Booms	One each wingtip One at nose	9 10
	NACA probes	End of wingtip booms	9
	5-hole probe	End of nose boom	10
	Balsa vanes	End of wingtip booms	9
	Pressure transducers	Wingtips and nose wheel well	Not shown
	Thermal control	FTE station	14
L-Band telemetry system	2 transmitters	Cargo bay	6a
	2 antennas	Top/bottom of fuselage	Not shown
Airborne video/audio system	Electronics and recorders	R & L Sponsons	13
	2 cameras	Wingtips	11
	1 camera	Top of left vertical tail	12
	Monitors	FTE/pilot stations	14, 15

Table 4: OV-10A basic measurements and sensor locations

Measurement	Number	Sensor	Location
Airspeed & Altitude	3	Pitot-static with variable-capacitance ceramic pressure sensors	Booms at wingtips and nose
Angle of attack and sideslip	2	Balsa vanes with synchro/DC converter	Booms at wingtips
Angle of attack and sideslip	1	Differential pressure probe with variable-capacitance ceramic pressure sensors	Boom at nose
Linear accelerations	3	Servo accelerometers	Near c.g. in cargo bay
Control positions	10	Potentiometers	At each surface
Angular rates	3	Mechanical rate gyros	In cargo bay
Engine speed	1	Tachometer	At engine
Total air temperature	1	Platinum resistance	Under wing
Dew-point temperature	1	Cooled mirror	Left side of forward fuselage
Boom vibration	3	Piezoelectric vibrometer	Near boom tips
Position	1	GPS receiver	Antenna on top of fuselage
Inertial velocities	1	Ring-laser INU	Cargo bay
Attitude angles	1	Ring-laser INU	Cargo bay

Table 5: Components of the FTE station.

Key to Figure 14	Component	Key to Figure 14	Component	Key to Figure 14	Component
A	Communications switch	F	Flight card mounting bracket	K	Control panel for video/audio display/recording systems
B	Communications panel	G	Setra pressure transducer thermal control switch	L	Computer-display keypad
C	Dew-point sensor control/indicator unit	H	Basic (retained) OV-10A cockpit instruments (airspeed, altimeter, engine torque, fire extinguisher, emergency IFF)	M	Control panel for DAS and telemetry
D	Video monitors	I	Altimeter for hygrometer calibration		
E	Flat-panel monochrome computer display 640 x 480 pixels (glare hood not shown)	J	Video display select panel		

Table 6: Research components in the pilot's cockpit.

Key to Figure 15	Component	Key to Figure 15	Component
A	Garman GPS	E	Master instrumentation switch
B	Video monitor (glare hood not shown)	F	Video/Audio/DAS control panel
C	Video display select panel	G	Cargo bay cooling fan switch
D	α/β indicators		

Table 7: Summary of first Memphis field deployment.

Flight	Flight Time (hours)	Time of Day	Vertical Profiles	Horizontal Passes
1	1:32	sunset	10	10
2	2:11	late morning	13	14
3	1:24	sunrise	8	15
4	1:08	late morning	7	13
5	0:51	sunrise	8	4
6	1:16	late morning	11	2
7	2:21	late morning	4	16
8	1:15	mid afternoon	4	15
9	<u>2:14</u>	late morning	<u>14</u>	<u>8</u>
Totals:	14:12		79	97

Table 8: Summary of second Memphis field deployment.

Flight	Flight Time (hours)	Time of Day	Flight	Flight Time (hours)	Time of Day
1	2:18	early afternoon	10	1:13	early afternoon
2	1:50	late afternoon	11	2:04	sunrise
3	2:38	late afternoon	12	1:21	late afternoon
4	1:38	early evening	13	0:52	midnight
5	2:51	early afternoon	14	2:00	midnight
6	1:27	sunrise	15	1:14	late afternoon
7	2:30	midnight	16	2:22	late morning
8	2:16	midnight	17	2:35	late afternoon
9	0:56	early evening	Totals:		32:05

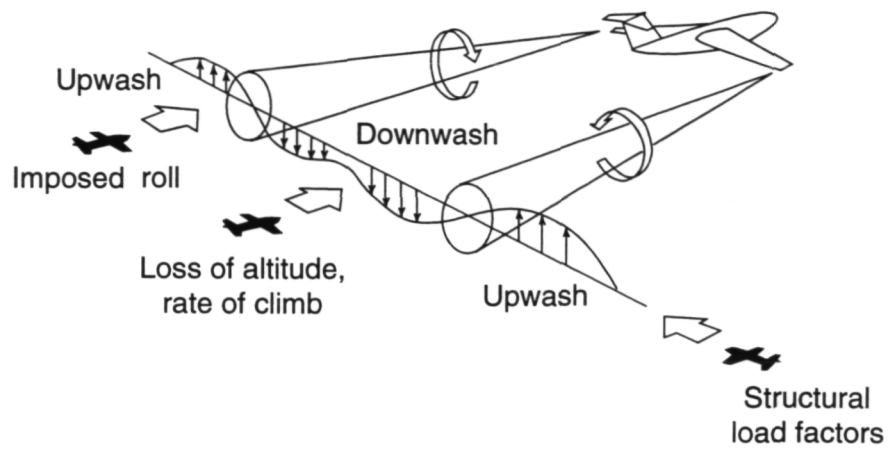


Figure 1: Wake-vortex hazards.

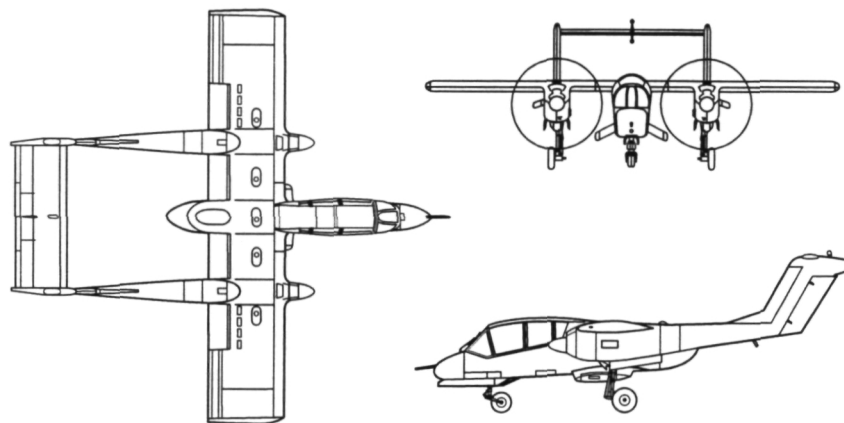


Figure 2: Three-view of a stock OV-10A.



Figure 3: Photograph of NASA 524.

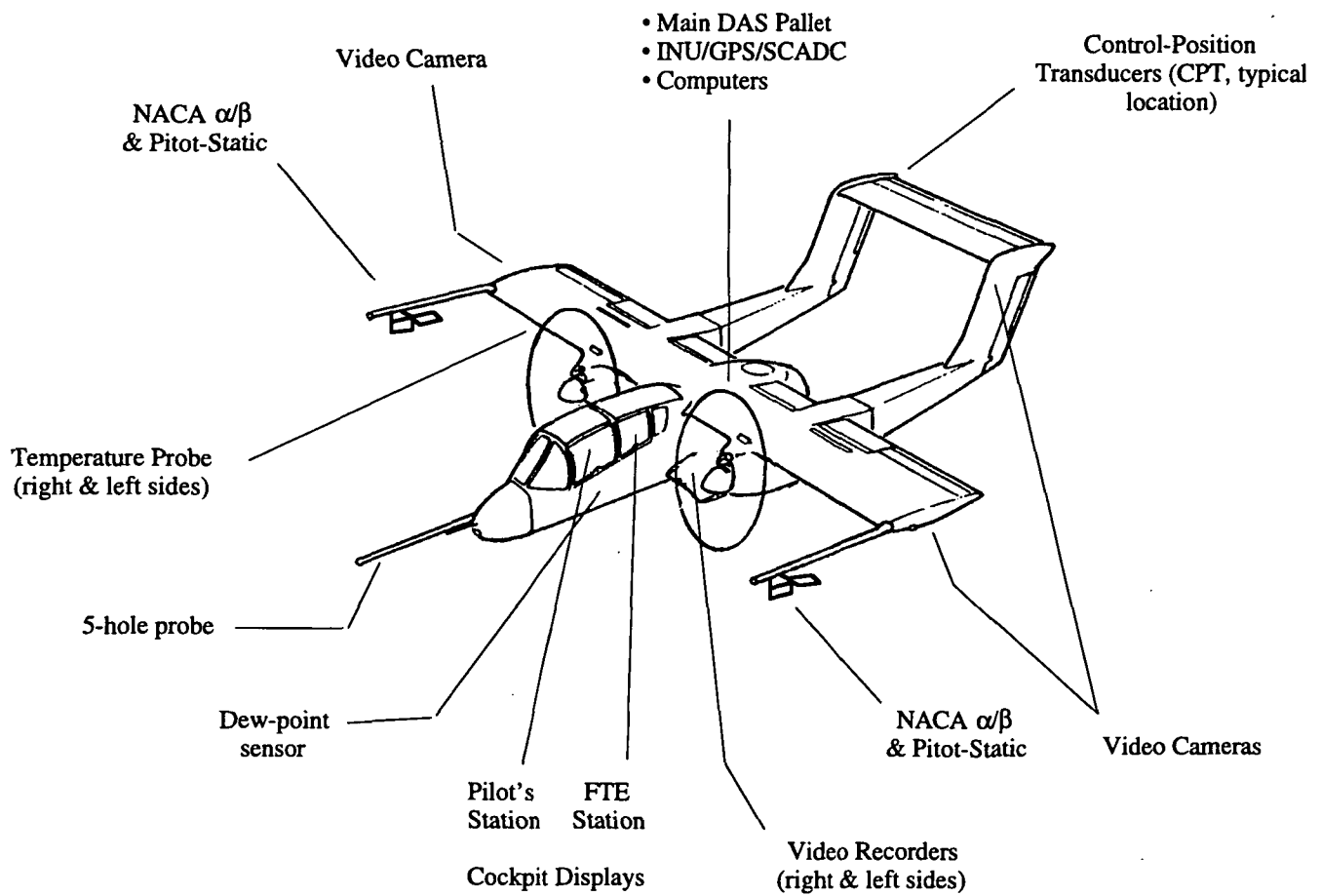


Figure 4: Location of major instrumentation systems.

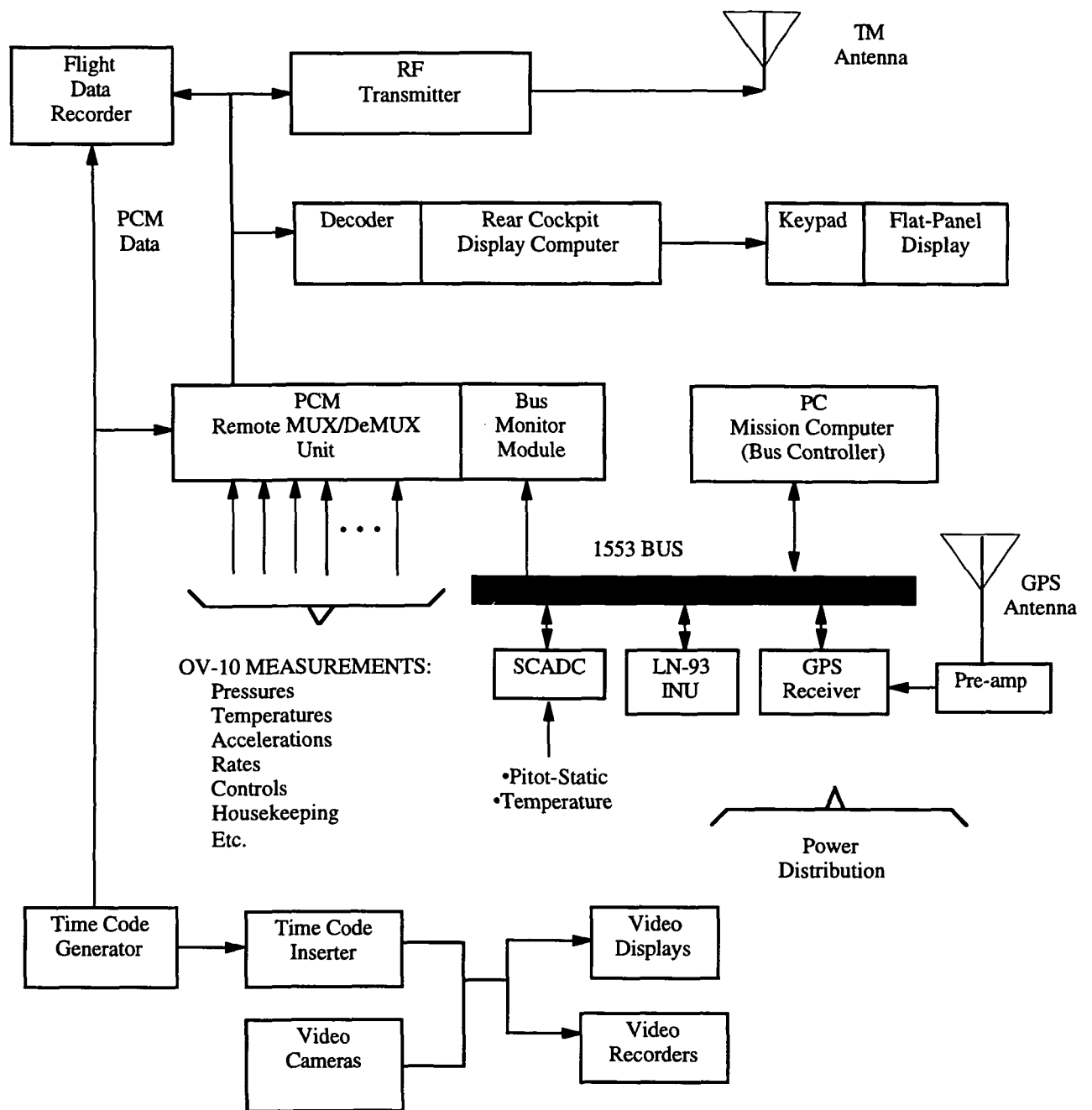
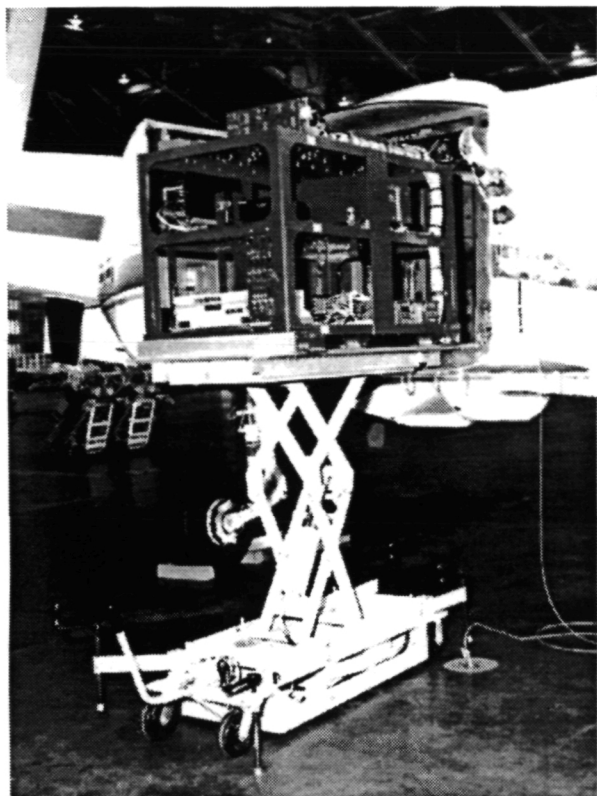
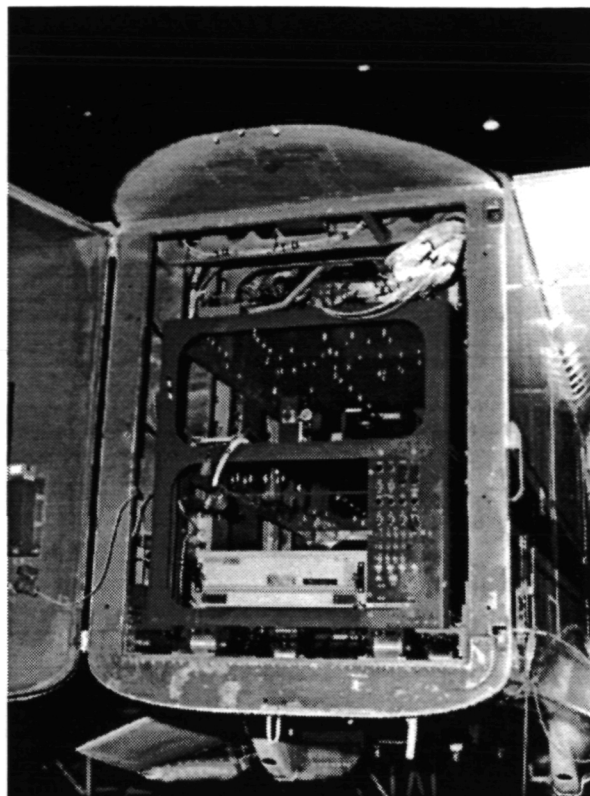


Figure 5: Schematic of data-acquisition system.



(a) Pallet outside of cargo bay.



(b) Pallet installed for flight.

Figure 6: DAS research pallet.

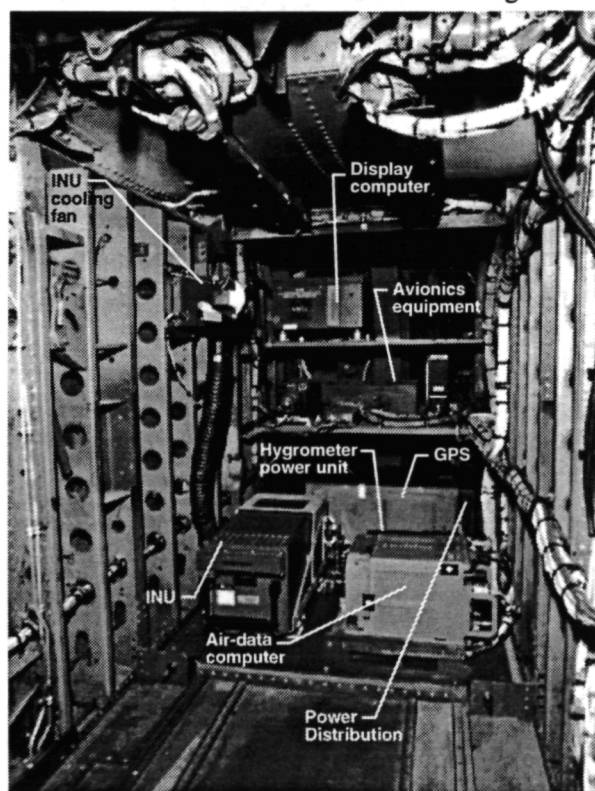


Figure 7: Research equipment in the forward cargo-bay area.



Figure 8: EVOTS instrument.

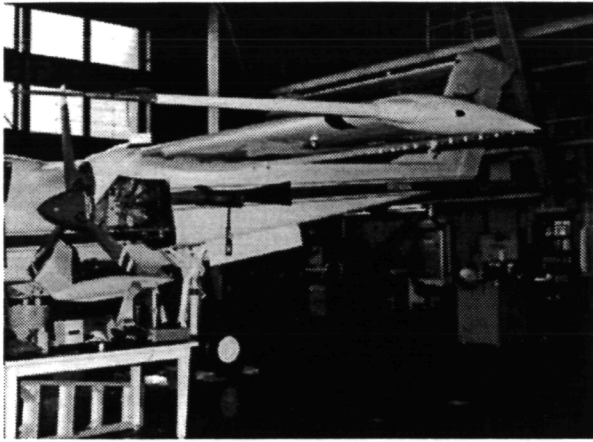


Figure 9: Wingtip boom and NACA probe (typical).

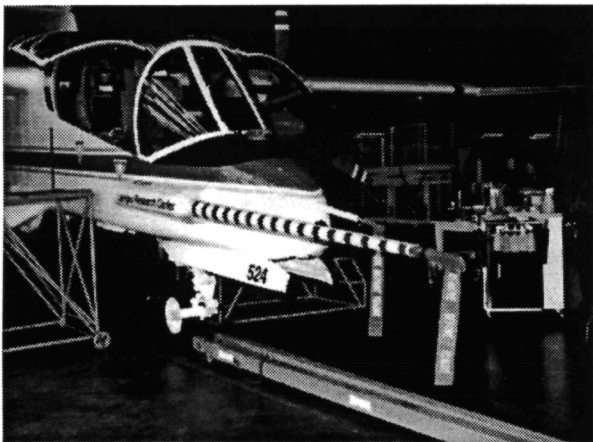


Figure 10: Nose boom and covered 5-hole probe.

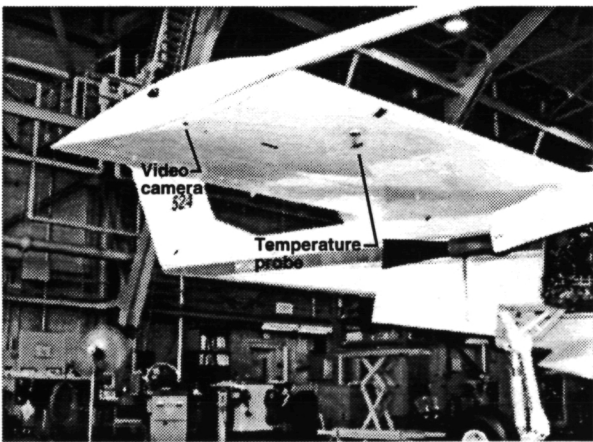


Figure 11: Wingtip video camera and total-air-temperature probe (typical).

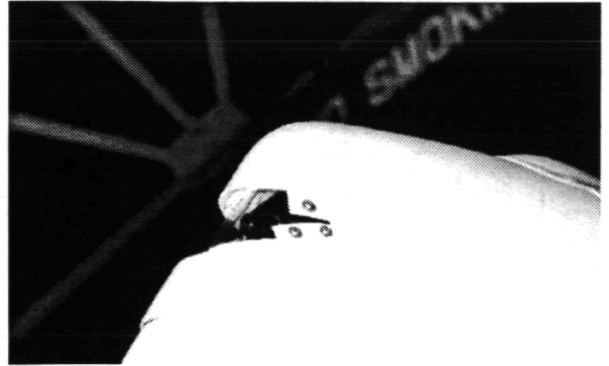


Figure 12: Camera mounted to top of left vertical tail.

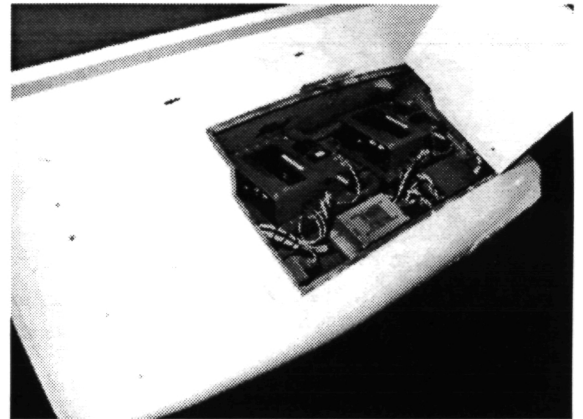


Figure 13: Right-sponson video equipment (typical).

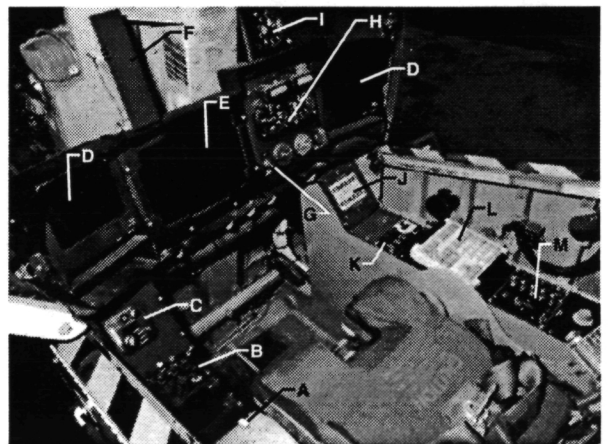


Figure 14: Flight-test engineer's research station (aft cockpit).

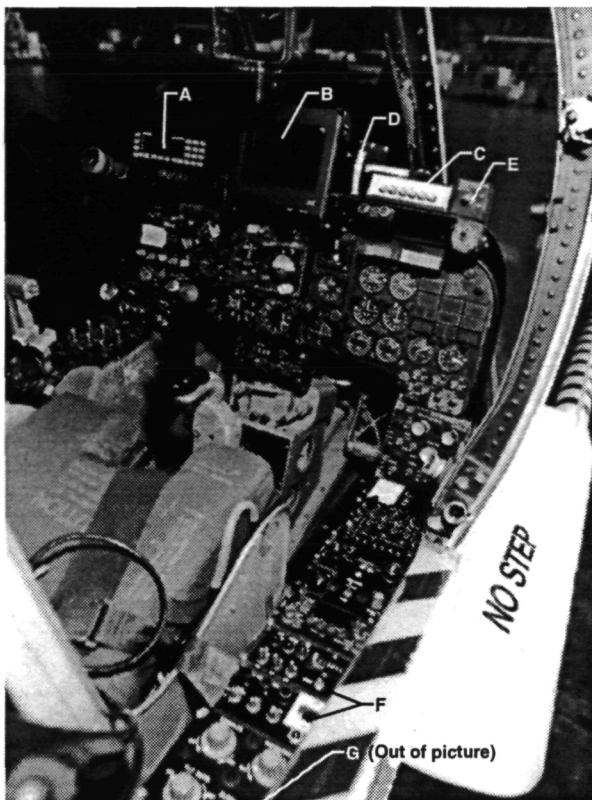


Figure 15: Pilot's research equipment (forward cockpit).

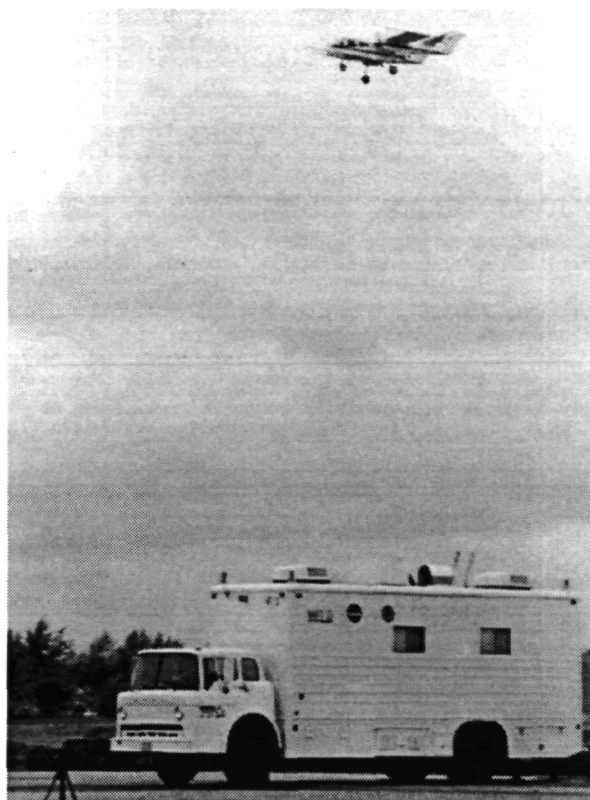
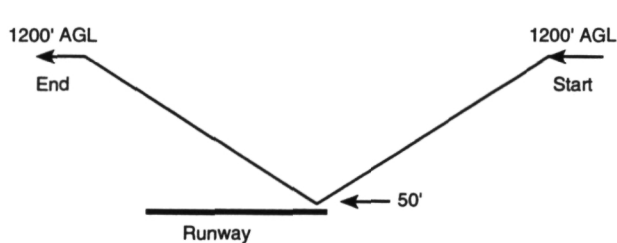
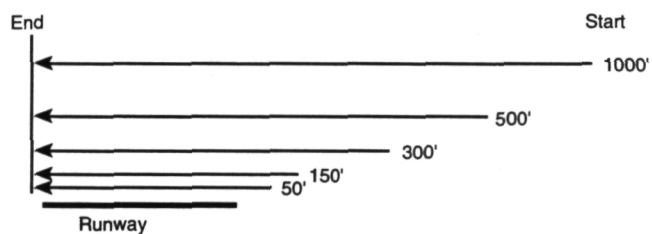


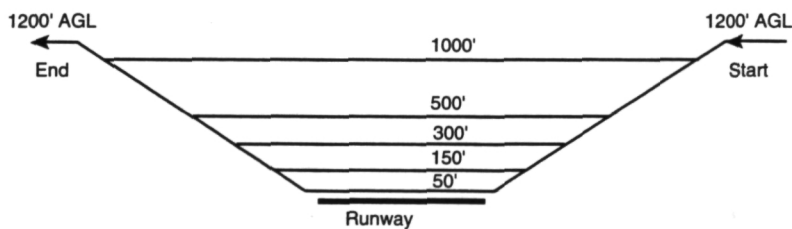
Figure 16: Typical OV-10A operation with MIT L.L. lidar van at Memphis, TN.



(a) Vertical profiles.



(b) Horizontal profiles at typical altitudes.



(c) Horizontal profiles coupled with abbreviated vertical profiles.

Figure 17: Examples coupled with abbreviated vertical profiles.