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SUMMARY

The Langley Research Center has been operating variable-stability helicopters since 1953 to explore a wide variety of navigation, guidance, control, and display problems associated with low-speed flight. The current research vehicle is a CH-47B helicopter which has been modified to provide a general-purpose variable-stability capability for the VTOL Approach and Landing Technology (VALT) Program. This report describes the functional aspects of the hardware of the VALT CH-47 research system and discusses the capabilities of the overall system. Data from automatic decelerating approaches to a touchdown, flown in various wind conditions, are presented to illustrate the performance of the overall system.

INTRODUCTION

The Langley Research Center has been operating variable-stability helicopters since 1953. The first variable-stability helicopter used by Langley was an HO3S-1 (fig. 1) which had been modified so that electrical-input signals could move the aircraft's control system through parallel electrical actuators in pitch, roll, and yaw. The evaluation pilot moved controls connected to rheostats, the outputs of which were wired to a modified autopilot through potentiometers permitting variable gains. The safety pilot, on the other hand, remained connected to the basic mechanical control system. Although crude by today's standards, this variable-stability helicopter served as an invaluable tool for gathering handling-qualities data (e.g., ref. 1) that were eventually incorporated into documents such as those detailing handling-qualities requirements for all military helicopters (ref. 2).

In 1962 the Langley Research Center initiated studies with a replacement variable-stability helicopter, the YHC-1A (fig. 2). This aircraft, later redesignated a CH-46C, represented a major advance in variable-stability capability at Langley. It had four controllable degrees of freedom (pitch, roll, yaw, and collective) through full-authority, electrohydraulic actuators mounted in parallel with the basic mechanical control system, an onboard analog computer, and an extensive set of sensors. The vehicle was used to develop the so-called "model-following" method of airborne simulation (ref. 3), one of the first known applications of this technique. The YHC-1A served as a "workhorse" in expanding the handling-qualities data base (refs. 4, 5, and 6, for example) initiated with the HO3S-1. In 1968, Langley initiated the VTOL Approach and Landing Technology (VALT) Program to investigate the zero-visibility, zero-ceiling, decelerating approach problem. The YHC-1A was employed as the primary flight-test vehicle in this program and was used in 1972 to perform the world's first fully automatic decelerating approach and landing to a predetermined spot (ref. 7). This aircraft was retired in 1974 after 12 years of service.

The replacement for the YHC-1A was a CH-47B helicopter (fig. 3) which had been modified for the U.S. Army's Tactical Aircraft Guidance Systems (TAGS) program. This program, described in reference 8, was aimed at developing and demonstrating an advanced flight-control concept using a triply redundant digital fly-by-wire system. In order to support the VALT program, the aircraft was subsequently modified by the Langley Research Center to a general-purpose variable-stability research helicopter. The purpose of this report is to describe the VALT CH-47 helicopter, the airborne research system, and related ground-based facilities and also to discuss the capabilities of the overall system.

Use of trade names or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

SYMBOLS AND ABBREVIATIONS

Values are given in both the International System of Units (SI) and U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units.

Symbols

a_x, a_y, a_z	body-mounted accelerometer outputs, m/s^2 (ft/s^2)
g	gravity constant, 9.8 m/s^2 (32.2 ft/s^2)
K_1, K_2	system gains
s	Laplacian operator
X,Y,Z	displacement in runway-reference coordinate frame, m (ft)
θ	pitch attitude, rad
τ	time constant, s
ϕ	roll attitude, rad
ψ	yaw attitude, rad

A dot over a symbol indicates a derivative with respect to time. A circumflex ($\hat{}$) denotes an estimated value.

Abbreviations

ADF	automatic direction finding
ARRC	Aeronautical Research Radar Complex

CDU	control-display unit
CRT	cathode-ray tube
DIU	digital interface unit
DME	distance-measuring equipment
DSC	discrete signal conditioner
ECS	electronic control system
FDRS	Flight Display Research System
FM	frequency modulation
HOME	hardover monitoring equipment
HRTVC	high-resolution television camera
ICS	intercommunication system
J-box	junction box
LTS	laser tracking system
PCM	pulse-code modulation
SAS	stability-augmentation system
TAGS	Tactical Aircraft Guidance System
TANS	terminal area navigation system
TDS	transponder data system
TIU	transponder-data-system interface unit
TV	television
UHF	ultra high frequency
VALT	VTOL Approach and Landing Technology
VOR	VHF omnirange
VHF	very high frequency
VTOL	vertical take-off and landing
WFC	Wallops Flight Center

OPERATIONAL CONCEPT

The VALT CH-47 research system was designed to be a general-purpose facility for the investigation of navigation, guidance, control, and display concepts applicable to a wide range of VTOL aircraft. The primary research mode includes both an airborne system and ground-based facilities as depicted in figure 4. The system functions in a typical operation are as follows: Aircraft position relative to the desired touchdown point is determined by the radar-laser tracking system and sent to the aircraft over a digital data link. The incoming position signals are processed in an onboard computer and, along with various other parameters, are used to derive guidance and control outputs. (The guidance in this case is relative to stored speed, altitude, and horizontal-path profiles.) Pertinent parameters, such as pitch and roll attitude, are sent to the ground over the digital data link and then to an interactive graphics terminal located in the Flight Display Research System (FDRS) trailer. The graphics terminal creates the cathode-ray-tube (CRT) displays which are transmitted to the aircraft via a wide-band video link and displayed to the evaluation pilot on his instrument-panel monitors.

The remainder of this report describes the elements of the VALT research system. Optional research modes not using the primary system are also noted. Finally, the capabilities of the system are illustrated by presenting data from fully automatic, decelerating approaches to a hover landing.

RESEARCH AIRCRAFT

General Description

The VALT research system was installed in the CH-47B helicopter shown in figure 3. This helicopter is a twin-turbine-engine, tandem-rotor aircraft designed for the transportation of men and equipment. The overall dimensions are given in figure 5. The allowable gross weight is 177 929 N (40 000 lb), and the vehicle has a top speed of approximately 160 knots.

The helicopter was loaned to the NASA by the U.S. Army for use in the VALT program. It had been modified previously for the Army TAGS program (refs. 8 to 11), and included a pseudo fly-by-wire control system. Many elements of this system were retained during the subsequent VALT modifications and are described herein.

The pitot-static system of a standard CH-47B includes a pitot tube mounted on the forward transmission fairing (see fig. 6) and static pressure sources on either side of the fuselage. The research system employs a second pitot-static system which includes a pitot tube mounted on the left side of the nose (see fig. 6) and static pressure sources on either side of the fuselage just aft of the standard static pressure sources. The pitot tube and static pressure sources were TAGS program modifications (ref. 9) which were retained during the VALT modifications.

A significant modification made to the aircraft during the VALT system installation involved a structural rework of the right side of the nose compartment to accommodate dual CRT displays. The only external visible evidence of this modification is the small fairing shown in figure 6.

Flight Control System

The flight control system of the aircraft had been extensively modified for the TAGS program. Triplex, full-authority, parallel, electrohydraulic actuators had been added to each control axis (pitch, roll, yaw, and collective). The actuators were connected to the mechanical control system of the aircraft through rotary clutches which were held closed by hydraulic pressure while the system was engaged. Additional TAGS modifications included reworking the mechanical linkages between the pilot's controls and the stick-boost actuators to reduce friction and hysteresis. The foregoing modifications are documented in reference 9.

In implementing the VALT system, two of the three actuators in each channel were removed to obtain a simplex, or single channel, system. The rotary clutches, as well as the mechanical linkage modifications, were retained. The right-hand set of conventional cockpit control was disconnected from the left-hand set, control-position transducers were added, and an independent force-trim system was installed. The mechanical characteristics of the evaluation pilot's (right-hand) control system are given in table I.

Figure 7 is a simplified diagram of the final VALT CH-47 control system. The stability-augmentation system (SAS) was not modified except for the addition of a transducer mounted on each SAS actuator to measure the position of the extensible link. This transducer was added during the TAGS modification and retained in the VALT system. The application of this transducer will be covered in a subsequent section.

Cockpit Modifications

In the VALT CH-47 research-system configuration the safety pilot occupies the left-hand cockpit seat and the evaluation pilot occupies the right-hand seat. All critical switches and gages were located to make them accessible to the safety pilot. The safety pilot's display panel, shown in figure 8, included a sideslip indicator (the edge meter in the lower left corner of the panel) driven by a sideslip vane located on a post below the nose of the aircraft. (See fig. 6.)

The center console was completely revised to incorporate the VALT navigation and communication equipment and research-system control and monitoring units as shown in figure 9.

Navigation and Communication Equipment

The navigation and communication equipment installed in the VALT CH-47 helicopter are listed in table II. As indicated in the table, some of this equipment was wired to provide outputs for the research system.

The interphone system was modified to provide an air-to-ground transmitting capability from the jump-seat station and research-system operator's station. In addition, the six observer stations shown in figure 10 have been provided with a monitoring capability.

An audio-warning (passenger-address) system was wired to the safety-pilot, evaluation-pilot, research-system operator, and jump-seat interphone stations to provide an audio cue (an airline-type chime tone) any time that the research control system is engaged or disengaged. The signal to sound the chime is generated by the electronic control system (ECS).

Operating Limitations

The VALT research-system modifications, as well as the previous TAGS modifications, have not resulted in any additional operating limitations on the aircraft. As such, the standard CH-47B operating limitations summarized in table III apply. At the present time, however, the aircraft is being operated only up to 120 knots with the research system engaged. This is an arbitrary, self-imposed limit established for an initial period until operating experience can be accumulated with the overall research system. To date, over 100 flight hours have been accumulated with this research system.

RESEARCH SYSTEM

Components

Figure 11 is a simplified block diagram of the primary VALT CH-47 flight system. The major subsystems include the digital computing system, analog computing system, electronic control system (ECS), hardover monitoring equipment (HOME), the instrumentation system, discrete signal conditioner (DSC), the transponder data system (TDS), and the display system. The subsystems are mounted on pallets (tables) in the cabin area as shown in figure 10. Control of the subsystems is accomplished from the research-system operator's console described in the next section.

Operator's Console

Design of the research-system operator's console was initiated by establishing the following ground rules:

(1) The entire airborne research system would be controlled and monitored by a single operator from a fixed station (except arming and engaging the control system).

(2) Controls and displays would be grouped according to priority.

(3) Switch positions would indicate system state, and the use of status lights would be minimized.

(4) Use of lights, where justified, would employ the following color scheme:

Green - indicates a normal condition that requires no response.

Amber - indicates a condition that requires awareness and possibly a later response.

Red - warns of a condition that requires immediate attention and/or action.

By using these ground rules, the research-system operator's console was designed and implemented as shown in figure 12. The console was organized by ordering control and monitoring functions according to their importance and frequency of use.

The primary panel (see fig. 13) includes the displays used in monitoring the ECS, a remote HOME system monitoring and control panel, a control and display unit for the digital computer, data-system controls and displays, and a communication control box. Although the analog-computer controls and displays are not located on the primary panel, they are located within the research-system operator's primary viewing area.

The secondary panel is used for monitoring flight conditions and is located immediately above the primary panel.

The tertiary panel, shown in figures 12 and 14, is located above the analog computer and contains the ECS configuration switches, power switches, and other miscellaneous controls and displays which are generally set and remain set during the course of a flight. The guarded emergency-disengage switch was intentionally positioned at the extreme end of the tertiary panel.

The toggle switches that control the research system are set up such that they are all down when the system is shut off and all up in the primary in-flight research configuration. In addition, all the switches, except the data and camera on-off switches, are of the pull-to-set type to preclude unintentionally actuating them.

Twelve indicator lights have been incorporated into the final design: 9 are green status lights, 2 are amber, and 1 is red. The red light indicates that the HOME system has automatically disengaged the ECS and must be reset before the ECS can be reengaged. One of the amber lights indicates that the ECS is engaged, whereas the other amber light indicates that one channel of the triplex HOME system has failed.

Digital Computing System

The digital computing system installed on the aircraft consists of a general-purpose Sperry 1819A digital computer, a pair of control-display units (CDU), a digital interface unit (DIU), and a transponder-data-system interface unit (TIU). The computer and DIU are mounted on a pallet as shown in figure 15. The TIU is rack mounted on the same pallet. One of the control-display units is mounted on the cockpit center console (fig. 9), whereas the other is mounted on the research-system operator's primary panel (fig. 13).

Digital computer.- The general-purpose digital computer was specifically designed for airborne applications. It has 16 384 words of 18-bit, magnetic core memory; 1024 words of 18-bit, solid-state, read-only memory; 7 input-output channels; and a built-in test routine. A write-protect feature is provided for 2048 consecutive storage locations.

Digital interface unit.- The interface between the digital computer and the analog signals employed in the VALT system is provided by the digital interface unit (DIU). The DIU performs analog-to-digital conversions for 30 input channels and digital-to-analog conversions for 30 output channels. In addition, the DIU provides the capability to input 12 discretes into the computer and accept 12 discretes from the computer. All of these 84 channels are wired directly to dedicated terminals in the VALT signal junction box (J-box).

Transponder-data-system interface unit.- The TIU is a digital-to-digital converter which connects the digital computer to the transponder data system, the two-way air-to-ground digital-data-link subsystem. The TIU provides the level shifting, logic sequencing, and memory buffering required to accept uplink data from the TDS and transmit it to the computer and, also, to accept data from the computer and transmit it to the TDS.

Control-display units.- The man-machine interface with the digital computing system is provided by control-display units (CDU), one of which is shown in figure 16. Each CDU consists of 15-momentary unlighted pushbuttons, 11-momentary lighted pushbuttons, a 12-position rotary switch, and an 11-digit gas-tube indicator divided into one 6-digit group and one 5-digit group. All of the functions such as lighting the pushbuttons and display blanking are completely under software control. As such, the CDU's are general-purpose interfaces. Besides software, only the legends on the buttons and rotary switch need to be changed to suit the specific experiment at hand. The present VALT configuration utilizes two of these CDU's, each of which is connected to a dedicated input-output channel so that they can perform entirely separate functions. Additional details of the digital computing system are given in reference 12.

Analog Computing System

The analog computer installed in the VALT CH-47 aircraft is shown in figure 12. This is a general-purpose analog computer composed of solid-state computing components. Each component has input and output terminations on a prepatch panel for interconnection by patch cords. The monitoring and control panel includes a digital voltmeter, a multirange voltmeter, and a pushbutton signal-selector system. Computer mode control, such as operate or reset, can be controlled manually through a series of mode-control pushbuttons or automatically. The automatic mode-control results in the computer being in "reset" when the ECS is disengaged and in the "operate" mode when the ECS is engaged.

Additional or modified mode control over selected integrators can be implemented through the patch panel.

The computer configuration includes 48 operational amplifiers (14 of which can be implemented as integrators), 60 potentiometers, and 14 nonlinear components, including comparitors, function switches, multipliers, and variable-diode-function generators. The computer is connected to the VALT signal junction box via 42 trunks which may be utilized as either input or output lines.

As noted earlier, all programming is accomplished by interconnecting components with patch cords on a prepatch panel. In order to reconfigure the analog-computer program between experiments, therefore, the prepatch panel is replaced with one containing the alternate program.

Electronic Control System

The electronic control system (ECS) contains the signal conditioning necessary to convert an electrical input signal from the research system to an electrohydraulic actuator position and, hence, a mechanical control-system input. The system contains four channels: pitch, roll, yaw, and collective. Since all channels are essentially the same, only the pitch channel will be described herein.

Figure 17 is a simplified block diagram of the pitch channel of the ECS. There are three operating states: disengaged, armed, and engaged. In the disengaged state, the electrohydraulic actuator is depressurized and, hence, does not respond to electrical inputs. In addition, the rotary clutch is depressurized and held open by internal springs.

When the system is armed, the clutch remains open but the actuator is pressurized and begins tracking the actuator command signal. In this state, the ECS track-and-hold circuitry tracks an incoming signal; therefore, the actuator command signal is equal either to zero or to the safety pilot's stick position depending on the position of the preengage actuator mode switch at the computer-operator station. In the center mode, the actuator drives to its center position prior to engaging. In the synchronization mode ("sync") the clutch faces are aligned in an open-loop manner prior to engaging. Synchronization is required to insure that the ECS actuator and safety pilot's control reach their respective full-travel stops at approximately the same time.

When the system is engaged, the rotary clutch is closed by hydraulic pressure. At the same time, the track-and-hold circuitry holds the incoming signal, thus allowing the ECS input signal to pass and, hence, drive the control system. The source of the input signal is controlled by the position of the computer-control mode switch and the SAS canceling switch, both of which are located at the computer-operator station.

The computer-control mode switch is used to select either a computer-derived signal or the evaluation-pilot stick-position signal as the input source. Selecting the evaluation-pilot stick-position signal (computer control mode off) as the source simulates the standard, dual-control, mechanical system since the safety pilot's controls will track the evaluation pilot's controls on a one-to-one basis.

The aircraft is normally flown with dual SAS. With the SAS canceling switch off, the research system drives the augmented aircraft; the final control input is the sum of the research-system input and the dual SAS inputs.

In general, there are advantages in driving the unaugmented aircraft with the research system. Although it is possible to turn the SAS off, this is not an acceptable procedure from a safety-of-flight standpoint. Therefore, the method of SAS canceling used by TAGS was adopted where the total SAS input is measured and canceled by an equal and opposite input to the ECS actuator. This mode is obtained with the SAS canceling switch on.

To operate the system, the computer operator selects the engage configuration by setting the preengage actuator mode switches, SAS canceling switches, and computer-control mode switches to their appropriate positions. The evaluation pilot then arms and engages the system.

Arm process.- Arming one or more channels with the magnetically held closed switches causes the research-system operator's appropriate arm lights to illuminate. The engage light remains off indicating the clutch is open. At this time the computer operator can press the preengage test button, which provides an artificial engage signal to the track-and-hold circuitry to check its function and to allow computer or evaluation pilot's stick signals to drive the actuator. (Since the clutch is not closed, the actuator will not be driving the control system in this mode.) The test button is spring loaded so that, when released, the system reverts to the normal mode.

Engage process.- The engage switch is a spring-loaded, slide switch located on the evaluation pilot's collective lever. When the switch is momentarily actuated, clutches corresponding to the armed axes close, the engage lights illuminate, and an audio chime tone is sounded. Relay logic prevents the evaluation pilot from arming additional channels once the system is engaged. This is necessary since the unarmed actuators would generally not be aligned with the safety-pilot controls; therefore, simultaneous alignment and clutch closure could cause control-system transients.

Disengage process.- The ECS requires 28 volts dc to engage and remain engaged. The 28-volt engage line can be momentarily "broken" by the safety pilot's collective disengage button, the safety pilot's center-stick disengage button, or the evaluation pilot's center-stick disengage button. Any momentary power interruption causes the magnetically held arm switches to release, thereby permanently opening the circuit. In addition to the three disengage switches, the circuit can be opened by physically pulling the arm switch off, which disengages that particular channel, or by the HOME system, which disengages all channels automatically. The computer operator also has a guarded switch which can be used to open the circuit.

Since the ECS requires power to remain engaged, cutting power to the entire research system will also cause it to disengage. Two switches in series, one in the cockpit on the center console and one at the computer-operator station, control power to the entire research system.

In addition to the electrical disengage modes, there are several backup safety features designed into the actuator-clutch system. These features were designed into the TAGS system and retained by the VALT system. The clutch requires utility-system hydraulic pressure to remain engaged. Any failure causing loss in pressure will disengage the clutch. By assuming that the clutch remains engaged (a dual failure), the pilot can then back-drive the depressurized hydraulic actuator by overcoming the forces given in table IV. In the unlikely event that both the actuator and clutch remain pressurized following a disengagement (this requires three unrelated failures), the safety pilot can fly the aircraft by slipping clutches using forces given in table IV.

Hardover Monitoring Equipment

As noted in a previous section, the VALT CH-47 research system employs full-authority, parallel, electrohydraulic actuators driven by nonredundant electronics in each of the controlled degrees of freedom. Failure detection and correction is the responsibility of the safety pilot who monitors the research-system output through his controls (which are back-driven by the research-system actuators). When the research system is engaged, the safety pilot keeps his hands and feet on the controls to aid in detecting failures and to minimize his reaction time in the event that one occurs. Inadvertent control inputs by the safety pilot are prevented by employing suitable clutch slip-force levels.

In order to enhance safety, the VALT CH-47 research helicopter is equipped with a hardover monitoring equipment (HOME) system (see fig. 12) which automatically disengages the ECS any time that a hardware or software failure results in a runaway control input. The system, described in reference 13, was originally designed and built for the CH-46 variable-stability helicopter. The system was subsequently installed in the VALT CH-47 aircraft with certain modifications as described herein.

Functionally, the HOME system samples the safety pilot's control positions at specified intervals and compares them to the previous samples. Whenever one of the channels (pitch, roll, yaw, or collective) exceeds a preselected amplitude difference within a given sample period, the system disengages the ECS. Since the HOME system is a digital device operating at a fixed sample rate in each channel, the system, in effect, tests the rate of the mechanical control motions. In the VALT CH-47 application, the HOME system is programmed to disengage the ECS whenever the mechanical control input by the ECS actuator exceeds 80 percent of its maximum rate capability.

In applying the HOME system to the VALT CH-47 aircraft, the iteration rate was converted to a split-cycle mode wherein the pitch channel was sampled twice as often as the remaining channels. In addition, first-order lags were added to the pitch, roll, and yaw control-position inputs to minimize nuisance disengagements.

The characteristics of the HOME system installed in the CH-47 aircraft are given in table V. These characteristics were selected to yield acceptable control transients following hardovers while, at the same time, minimizing nuisance disengagements. During qualification tests, hardovers and slowovers (control-input rates less than 80 percent of the maximum rate) were inserted into the control system from the research system at aircraft speeds up to 120 knots. In all of the hardover cases, the aircraft motions following the automatic disengagements were mild and recovery was easily executed. In the case of the slowovers, the safety pilot was able to detect the runaway, disengage the sytem, and execute a recovery without encountering unacceptable transients in the ensuing aircraft motions.

Power Distribution

The design philosophy for the power-distribution system in the VALT CH-47 helicopter was based on the following criteria:

(1) The ac and dc power to the research system could be shut off via a single switch.

(2) The research subsystems would not incorporate separate power switches unless otherwise justified.

(3) A single, dedicated, power-distribution box would be utilized.

The tie-in between the power-distribution box and the standard electrical system of the aircraft utilized the circuit-breaker boxes which were installed during the TAGS modification. (It should be noted that the circuit breakers were resized based on an electrical loads analysis of the VALT research system.) The word "standard" is used in quotes since the TAGS modification included replacing the B-model generators with CH-47C units having a higher power output plus several other refinements which are not standard on CH-47B aircraft. All of the modifications made in the TAGS program pertaining to the basic CH-47B electrical system were retained.

To meet the first design criterion noted previously, the incoming power was routed through two series relays: one controlled by a switch on the center console in the cockpit, and the other controlled by a switch at the computer-operator station. As indicated in figure 18, both master-power switches must be closed in order to provide power to the research system. A power-monitoring panel was installed at the computer-operator station so that the ac and dc voltage levels and ac frequency could be checked prior to applying power to the research system.

The second criterion was established to eliminate unnecessary switching requirements. Although almost all the subsystems were found to require individual power switches, it was possible to locate them at the computer-operator station. In the present research-system configuration, power to all the subsystems, except for the evaluation pilot's two CRT monitors, can be controlled from the computer-operator station.

The power-junction box is located on the aft end of the digital-computer pallet as shown in figure 10. This box contains all of the power-switching circuits, circuit breakers, and the single point-power ground for the VALT research system. The box was designed to allow growth, since the area behind the avionics pallet (see fig. 10) had been reserved for other systems which would be flown from time to time.

VALT Signal Junction Box

The overriding goal of the VALT system design was to create an airborne system that could be readily configured to meet the requirements of a wide variety of experiments. This goal was obtained by employing a master-signal junction box (J-box) through which all analog and discrete signals passed on their way to and from each subsystem. The layout of the J-box is shown in figure 19. All of the subsystems are connected to the J-box from the left side. The incoming and outgoing signal lines from each subsystem are fanned out and connected to dedicated terminals within the box. From this point on, the system configuration is controlled by attaching jumper wires between appropriate terminals within the J-box. In a sense, the signal J-box is a patch panel in that any subsystem output can be connected to the input of any one or more subsystems merely by installing the proper jumper wires. All subsystem outputs, including sensor signals from the instrumentation system, are buffered to prevent altering signal characteristics when adding additional loads.

A single-point-signal ground concept was employed in the system to minimize ground-loop problems. All incoming and outgoing signals to the VALT signal J-box are single ended relative to a common ground. The ground bus is located in the bottom of the signal J-box and consists of a heavy copper bar which is tied directly to the aircraft structure.

Instrumentation System

The instrumentation system, excluding some sensors and the position transducers, is contained on a pallet (fig. 20) located in the cabin area. The system provides fully buffered output signals to the VALT signal J-box which can be used as inputs to one or more subsystems. It is important to note that the sensor outputs sent to the signal J-box and used as control-system inputs are also recorded. (Oftentimes a separate set of sensors are employed for recording purposes.) The recording filters are implemented so as not to affect the signals sent to the J-box. A list of the sensor signals is given in table VI.

The data system includes a magnetic tape recorder which is set up to record both pulse-code-modulation (PCM) and frequency-modulation (FM) data. Input signals to the recorder, which include both computer-generated signals and the buffered sensor output signals, are sent to a signal conditioner which provides the capability to prefilter the PCM data. The frequency response of the recorded PCM data is a function of several variables which can be selected to satisfy the requirements of a specific experiment. By assuming one sample per frame, the frequency response of the PCM data is determined by the PCM frame (sampling) rate. Higher rates (hence, higher frequency response) require faster tape speeds resulting in lower recording times. Table VII shows two of the options available with the present system which is capable of recording 104 channels of PCM data.

Another option available to the user involves supercommutating particular channels. This reduces the number of channels available but doubles the frequency response of the supercommutated channels.

Ten channels for recording FM data are also provided. The frequency response is 200 or 400 Hz, depending on the type of voltage-controlled oscillator employed. All external inputs to the recording system are connected via jumper wires in the VALT signal J-box.

Discrete-Signal Conditioner

The VALT research system contains a variety of output discrete-signal levels such as switch closures, computer-generated discretes from 0- to 5-volt dc, and discretes from 0- to 28-volt dc generated by the ECS. Similarly, the input discrete-signal requirements for the subsystems also vary. For example, the digital computer accepts 0- to 5-volt dc input levels, whereas some indicator lights at the computer-operator console require an input of 28-volt dc. In order to provide the proper discrete-signal characteristics throughout, a discrete-signal conditioner (DSC) was designed and fabricated. The DSC accepts input discretes at one level from the VALT signal J-box and returns them at one or more other levels. The DCS is currently configured to process 26 input discretes and to return 37 outputs. Additional channels are available for growth.

Display System

The evaluation-pilot instrument panel in the VALT CH-47 research aircraft can be configured four ways, as shown in figure 21. The cathode-ray-tube (CRT) displays are generated on the ground and sent to the aircraft over a wide-band video link. The electromechanical displays, on the other hand, are driven by onboard systems via the VALT signal J-box. The signals used to drive various elements of these displays from the VALT signal J-box pass through an avionics J-box which utilizes jumper wires similar to the signal J-box. As such, the signal J-box input can be disconnected from the instrument at this point and replaced by an appropriate navigation-system signal.

AIR-GROUND INTERFACE

Radar-Laser Tracking System

As noted earlier, the VALT CH-47 airborne research system was designed to operate in conjunction with a radar-laser tracking system located at the Wallops Flight Center (WFC) on Virginia's Eastern Shore. This tracking system is part of an Aeronautical Research Radar Complex (ARRC) and consists of an FPS-16(V) radar system with an integrated laser tracking system (LTS), a Honeywell 316 computer, a Honeywell 735G computer, and peripheral equipment.

The laser is the primary tracker in VALT operations; it provides automatic range tracking and supplies azimuth and elevation error signals to the FPS-16 radar servo system for automatic angle tracking. The LTS is designed to acquire and track targets in the range interval from approximately 106.7 m (350 ft) to 9144 m (30 000 ft) and at all azimuth angles and elevation angles between -10° and 90°. The VALT CH-47 utilizes two completely passive targets for the LTS, one on each side of the aircraft. These targets are 15-element, hemispherical, retroreflector arrays employing open-faced, first-surface, mirror elements. (See fig. 22.) Since each retroreflector provides slightly more than hemispherical coverage, the LTS can always "see" one of the arrays regardless of the vehicle attitude.

In the event that the LTS loses the target, the system automatically reverts to the radar tracking mode. The radar is always in a state to resume tracking since it is employed in the two-way digital data link with the aircraft (i.e., the TDS).

The range, azimuth, and elevation signals obtained from the radar-laser tracking system are sent to the Honeywell 316 computer as shown in figure 23. These signals are processed to obtain range (X), crossrange (Y), and altitude (Z) of the aircraft relative to the touchdown point. The position data in X, Y, and Z Cartesian coordinates are computed every 100 ms and sent to the Honeywell 735G computer which formats the data and sends it to the TDS for transmission to the aircraft.

The radar-laser tracking system is a portion of the overall Aeronautical Research Radar Complex located at WFC. Reference 14 provides a description of the entire ARRC site and includes additional details of the radar-laser tracking system.

Transponder Data System

The digital-data link between the aircraft and the ground is provided by the C-band transponder data system (TDS). The TDS is composed of a ground subsystem and an airborne subsystem installed on the digital-computer table (fig. 15). The ground subsystem accepts digital data from the Honeywell 735G computer, formats the data (including address and check words), and transmits the data to the aircraft via the FPS-16 radar system. The data are transmitted one word at a time prior to each radar ranging pulse using a pulse-position coding scheme. There are four types of words transmitted: a frame synchronization word, proportional words (with 10 bits resolution), discrete words, and an error code word. These words are grouped together in a preset manner to form a data frame. Once the data are received onboard the aircraft, the decoder checks them and, depending on the security mode selected in the airborne receiver, either inhibits it or transfers it to the TIU described previously.

The downlink portion of the system works exactly the same as the uplink portion except that the data pulses making up a word are transmitted after the transponder ranging pulse.

The system is effectively "transparent" in that whatever digital-data word is inserted at one end, it (the input) appears at the other end (the output) bit for bit. The number of uplink and downlink channels transmitted can be varied between the limits shown in table VIII. Some control over frame rate also exists since frame rate depends on the radar pulse rate and the number of words transmitted, both of which can be varied. The frame rate is defined by the relationship:

$$\text{Frame rate} = \frac{\text{Radar pulse rate}}{\text{Number of words per frame}}$$

The radar-pulse-rate options are 1024, 640, or 160 pulses per second.

The system offers a variety of security modes; however, in the VALT research system only the maximum security mode is utilized. In this mode the entire frame of data is checked for errors and is transferred to the TIU only if found to be free of errors.

The TDS includes many other features which are not presently utilized in the VALT CH-47 research system. These features are discussed in reference 14.

Flight Display Research System

The Flight Display Research System (FDRS) provides a generalized display-generation capability using a ground-based interactive graphics terminal in conjunction with a televised display technique as shown in figure 24. The parameters used to drive various elements of a given display are sent to the ground via the TDS. These inputs are used to create real-time dynamic displays which are converted into television (TV) format by using high-resolution television cameras (HRTVC). Once the images are converted to television formats, they can be processed and mixed by using studio television equipment to enhance the basic, interactive, graphics-system image.

In the primary research mode, two independent displays are generated by the interactive graphics system in the FDRS and sent to separate transmitters, one operating at 2.22 GHz and the other at 2.32 GHz. The transmitter outputs are combined in a diplexer and fed to an auxiliary video antenna on the FPS-16 radar antenna (see fig. 4) through a rotary joint. The combined signal is received at the aircraft, split into the original frequencies by a diplexer, and then fed to the appropriate receivers which, in turn, drive the cockpit and research-system operator's monitors. (See fig. 11.) In the course of flight tests, CRT pictures have been received at a range of 35 n. mi. from the transmitter.

RESEARCH-SYSTEM APPLICATION

Data Source

The research-system capabilities can be illustrated by considering some results from the initial flight investigation using the VALT CH-47 research system. The investigation was conducted to establish a data base of performance and handling qualities for decelerating approaches to a hover landing under zero-visibility, zero-ceiling conditions. The baseline navigation, guidance, control, and display concept was a refined version of the concepts developed on the CH-46C variable-stability helicopter reported in reference 7. This baseline configuration included a high-gain attitude-command control concept, a three-cue electromechanical attitude-director indicator, and a moving-map display. Manual, split-axis, and fully automatic approach modes were provided in which speed was controlled through pitch, the horizontal path through roll and yaw, and the vertical path through collective. The automatic approach performance obtained during this investigation will be used to illustrate the capabilities of the VALT research system.

Hardware

The hardware configuration used during these tests was the same as that shown in figure 11 except that the 25.4-cm (10-in.) CRT monitor in the cockpit was replaced by an electromechnical attitude-director indicator driven by the digital computer. The digital computer performed the navigation, guidance, and control functions; whereas the analog computer was used to obtain the high-gain-feedback control-loop closures employed in the model-following technique. (See ref. 3.)

The digital-computer control and display units were labeled as shown in figure 25. The automatic approach mode was obtained by engaging the system and selecting "auto appr." Since this is the only mode discussed in this report, the functions associated with the remaining mode buttons are not described.

Software

Navigation.- In order to perform the baseline task, namely, a 6° decelerating approach to a hover at an altitude of 15 m (50 ft) followed by a vertical landing, the position of the aircraft relative to the touchdown point must be known with a high degree of accuracy. The exact requirements in terms of accuracy, resolution, update rate, and signal-to-noise ratio are not presently known; however, for the baseline configuration, the best information obtainable was desired. Previous flight tests indicated that adequate position and rate of change of position information could be obtained by using a technique referred to as the terminal area navigation system (TANS) and reported in reference 15. This technique is illustrated in figure 26. In essence it is a complementary filter wherein onboard body-mounted accelerometers are resolved by using a full Euler transformation to obtain accelerations in a runway-referenced coordinate frame. These accelerations are high-passed through a fixed-gain Kalman filter and combined with low-passed position information from the ground which is also in a runway-reference coordinate frame. The final outputs are best estimates of aircraft position and rate relative to the touchdown point.

In the baseline configuration, the TANS was implemented in the digital computer as a subroutine (of approximately 200 instructions) which was called every 50 ms (once per cycle). The radar-laser position information was calculated on the ground every 100 ms and transmitted to the aircraft at a rate of approximately 30 samples per second. Once received, a reasonableness test was performed on the data in a separate subroutine. Tests indicated that the TANS concept could lose updates (i.e., go open loop) for periods of up to 20 seconds and still provide reasonably accurate position and rate outputs.

Guidance.- The flightpath used in the baseline configuration included the following: a straight horizontal path from 3048-m (10 000-ft) range to the touchdown point at zero range and a vertical path consisting of a level portion at 244-m (800-ft) altitude, a 6° descent starting at 2175-m (7136-ft) range and terminating in a 15-m (50-ft) hover, and a vertical letdown. The speed profile was based on a "constant attitude" deceleration and was programmed in terms of ground speed as a function of range as shown by the dashed line on figure 27. The control laws commanded the aircraft to fly a constant 80-knot airspeed until the stored ground-speed profile was intercepted. From this point on, the control laws commanded the aircraft to follow the deceleration profile. The horizontal, vertical and speed profiles were stored in the computer by using the methods described in reference 12. Guidance laws programmed in the digital computer provided outputs for both control and display computations. The guidance software also included capture logic to insure that the system was flying the desired course, heading, and altitude prior to reaching to 3048-m (10 000-ft) range point inbound.

Control.- The automatic-approach modes included a horizontal-path coupler, a glide-path coupler, and a speed coupler. These were fully automatic modes and could be obtained by selecting the automatic-approach mode.

The attitude and heading commands resulting from the automatic control computations were satisfied by using a high-gain model-following technique. The high-gain loop closures were performed in the analog computer and employed a complementary filter on the rate closure as described in reference 16.

System Performance

A composite of 14 approaches flown over a 6-day period in a variety of wind conditions is shown in figure 27. During these approaches, the recorded surface winds ranged from 2 to 18 knots with the crosswind components ranging from 2 to 14 knots. Nine approaches were made with crosswinds from the left and five with crosswinds from the right. Figure 27 includes crossplots of ground speed as a function of range, crossrange as a function of range, and altitude as a function of range.

The plot of ground speed against range provides an indication of the winds encountered at 244 m (800 ft) during the initial portion of the approaches. As noted previously, the aircraft is commanded to fly at an airspeed of 80 knots until it intercepts the ground-speed deceleration profile. As indicated in figure 27, the initial ground speeds ranged from a high of approximately 85 knots, implying a slight tailwind component at 244-m (800-ft) altitude, to a low of approximately 55 knots, indicating a headwind component on the order of 25 knots at altitude.

Following ground-speed profile intercept, the approach tracks converge to the programmed deceleration profile. The performance of the automatic pitch control loop was examined by performing a statistical analysis of the ground-speed error from intercept to touchdown. The results were as follows:

Mean, knot	0.2 (fast)
Standard deviation, knots	1.4
Maximum error, knots	5.7 (fast)
Minimum error, knots	4.5 (slow)

Although the maximum errors may be considered somewhat large, the overall performance appears to be good and indicates that the navigation, guidance, and control system operates satisfactorily.

The crossrange tracking performance, shown in figure 27, was examined by performing a statistical analysis of the crossrange error from 3048-m (10 000-ft) range to touchdown. The results of this analysis yielded the following:

Mean, m (ft)	1.5 (4.8)
Standard deviation, m (ft)	2.9 (9.5)
Maximum error, m (ft)	11.1 (36.5)
Minimum error, m (ft)	-10.8 (-35.5)

where a positive value indicates that the vehicle was to the right of the center line. Since the performance indicated by this analysis was based on approaches with crosswinds up to 14 knots, the overall system was considered satisfactory.

The navigation, guidance, and control performance in the vertical degree of freedom is illustrated by the altitude approach tracks plotted at the bottom of figure 27. As illustrated in the figure, the glide-slope capture was very smooth with no apparent overshoot. A statistical analysis of the glide-slope error between the glide-slope capture and the 15.2-m (50-ft) hover point yielded the following results:

Mean, m (ft)	-1.0 (-3.3)
Standard deviation, m (ft)	2.2 (7.2)
Maximum error, m (ft)	7.2 (23.7)
Minimum error, m (ft)	-7.5 (-24.7)

where a positive value indicates that the vehicle was above the glide slope. Here again the data indicate that the system was performing satisfactorily with no apparent navigation, guidance, or control-system anomalies.

As noted at the beginning of this section, the purpose in presenting the foregoing automatic approach data was to illustrate the overall research-system performance. The data indicate that the overall research system operates as designed and that the navigation, guidance, and control concepts employed provide a satisfactory baseline for conducting simulated zero-visibility, zero-ceiling, decelerating approach and landing studies.

CONCLUDING REMARKS

This report has described the VALT (VTOL Approach and Landing Technology) CH-47 general-purpose variable-stability research helicopter. The general-purpose aspect of the system stems from the fact that the navigation, guidance, control, and cathode-ray-tube display concepts are programmable by using ground-based and airborne computers. In addition, signal routing between airborne subsystems can be reconfigured for specific tests by means of jumper wires in a central signal junction box.

The capability of the overall system has been discussed in terms of the capabilities of the major subsystems involved. The automatic approach performance illustrated indicates that the subsystems perform satisfactorily, thus providing a viable research system.

To date, over 100 flight hours have been accumulated with the VALT CH-47 research system in the conduct of a variety of research investigations. All of the goals established during the initial design phase have been met or exceeded by the VALT CH-47 research system described herein. In particular, the capability to reconfigure the system rapidly between such diverse experiments as an in-flight simulation of the rotor-systems research aircraft and the decelerating approach baseline configuration has been accomplished.

Langley Research Center
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Hampton, VA 23665
June 21, 1979

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TABLE I.- EVALUATION PILOT'S CONTROL CHARACTERISTICS

Control	Travel		Breakout		Gradient	
	cm	in.	N	lb	N/cm	lb/in.
Pitch	±14.0	±5.5	4.45	1.0	2.63	1.5
Roll	±9.4	±3.7	2.22	0.5	1.23	0.7
Yaw	±8.3	±3.25	8.9	2.0	7.88	4.5
Collective	±13.2	±5.2	(a)	(a)	(a)	(a)

[a]The collective lever is held in position by a magnetic brake. The forces are negligible when the magnetic brake is released to make collective inputs.

TABLE II.- NAVIGATION AND COMMUNICATION EQUIPMENT

System	Remarks[a]
Interphone	See text.
UHF radio	Can transmit from pilot's station, jump-seat station, and research-system operator's station.
VHF radio	Same as UHF.
VOR	Output to A, B, C, and D.
Localizer	Output to A and D.
Glide slope	Output to A and D.
Marker beacon	Output to A.
DME	Range output to A, C, and D.
Compass	Output to A, B, C, and D.
ADF	Output to A, B, C, and D.
Transponder	No output to research system.
Radar altimeter	Output to A and D.
Passenger address	Audio tone (chimes) wired to pilot's interphone, jump-seat interphone, and research-system operator's interphone.
Voice recorder	Records selected interphone channels on magnetic tape cassette. Employs voice-operated relay.
Attitude-director indicator	Optional instrument for evaluation of pilot's panel. Indicator can be driven by either avionics system or research system.
Horizontal-situation indicator	Same as attitude-director indicator.

[a]Signal destinations:
- A - Safety pilot's indicator
- B - Evaluation pilot's indicator
- C - Research-system operator's indicator
- D - Research system

TABLE III.- STANDARD CH-47B OPERATING LIMITATIONS

Maximum airspeeds:	
Forward flight, knots	160
Sideward flight, knots	35
Rearward flight, knots	30
Maximum allowable accelerations:	
Positive, g units	3.0
Negative, g units	0.5
Maximum bank angles:	
At 160 knots, deg	25
At 145 knots or less, deg	40
Center-of-gravity limits:	
Forward of datum line between rotors, cm (in.)	68.6 (27)
Aft of datum line between rotors, cm (in.)	35.6 (14)
Maximum speeds at landing:	
Sinking speed, m/s (ft/s)	2.5 (8.2)
Forward speed, knots	60
Conditions:	
Density altitude	Sea level
Gross weight, N (lb)	133 447 (30 000)
Rotor speed, rpm	225

TABLE IV.- PILOT STICK FORCES WITH ECS FAILURES

Axis	Back-drive forces		Clutch slip forces	
	N	lb	N	lb
Pitch	27	6	71	16
Roll	45	10	67	15
Yaw	67	15	196	44
Collective	53	12	116	26

TABLE V.- HOME-SYSTEM CHARACTERISTICS

Channel	Sample interval, ms	First order lag, τ, s	Control displacement[a]	
			cm	in.
Pitch	42.5	0.055	3.6	1.4
Roll	85.0	0.140	4.6	1.8
Yaw	85.0	0.065	2.5	1.0
Collective	85.0	-----	1.5	0.6

[a]Control displacements resulting from hardover failures assume that actuator is driving at its maximum rate.

TABLE VI.- INSTRUMENTATION SENSOR SIGNALS

Number of signals	Source
4	Evaluation pilot's control positions
4	Safety pilot's control positions
4	ECS actuator positions
4	Upper boost actuator positions
6	SAS actuator positions (two each in pitch, roll, and yaw)
3	Body-axis linear accelerations
3	Angular rates
2	Attitudes (pitch and roll)
1	Magnetic heading
1	Airspeed
1	Barometric altitude
1	Radar altitude
1	Vertical speed
2	Engine torques
1	Rotor rpm
1	Glide slope
1	Localizer
1	DME range
1	VOR bearing
1	ADF bearing

TABLE VII.- RECORDING OPTIONS

	Option 1	Option 2
Frequency response,[a] Hz	5	10
PCM frame rate, frames/s	40	80
PCM bit rate, kb/s	44.8	89.6
PCM bandwidth required (nominal), kHz . .	89.6	179
Tape speed, cm/s (in./s)	19 (7.5)	38 (15)
Tape bandwidth, kHz	93.5	187
Recording time, hr	2	1

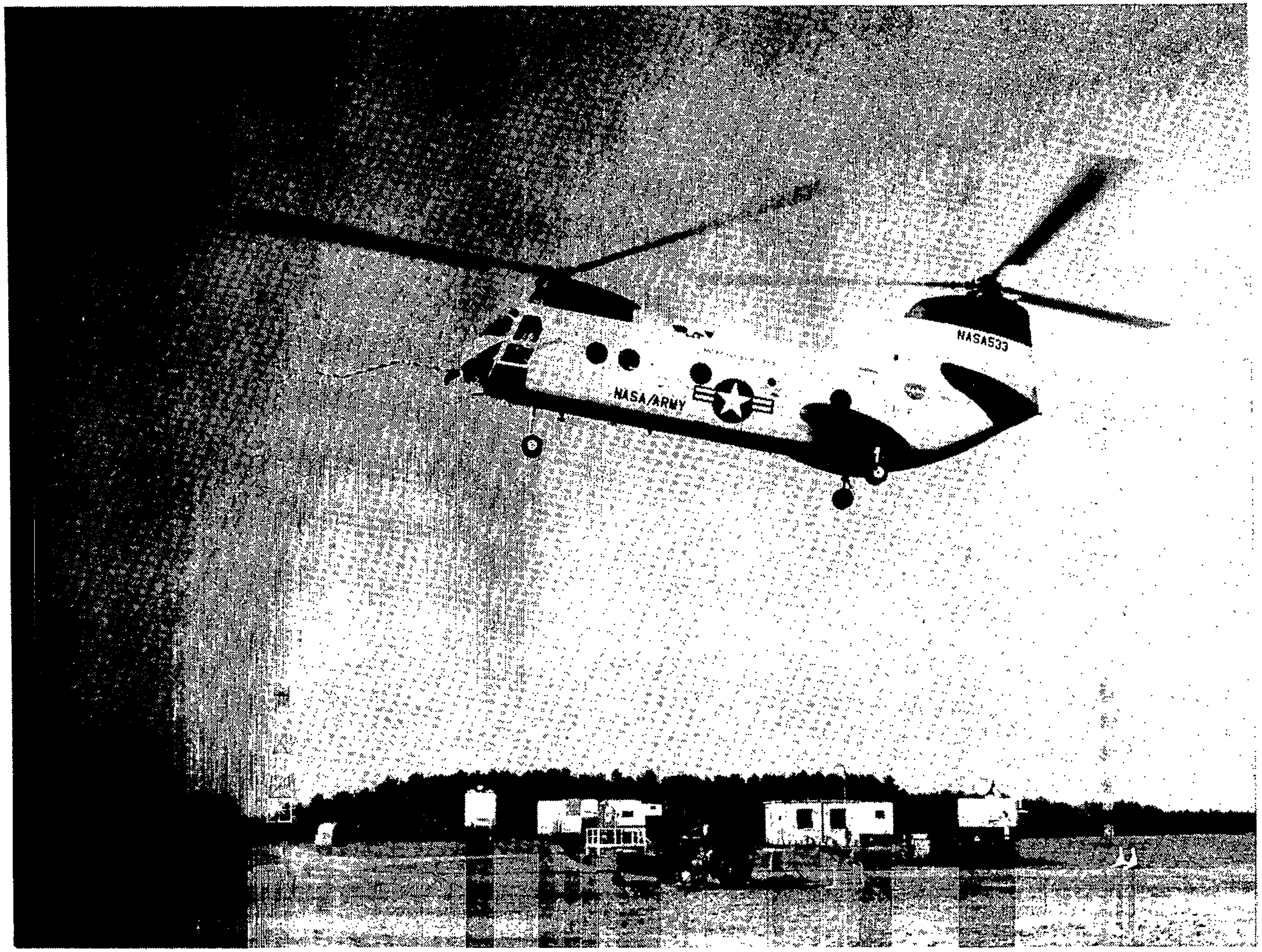
[a]Assumes eight samples per cycle.

TABLE VIII.- TDS CHARACTERISTICS

Word type	Uplink data frame	Downlink data frame
Frame synchronization word . .	1	1
10-bit data words	0 to 16	0 to 48
Word groups of four discretes each	1 to 16	1 to 16
Error check code word	1	1
Minimum frame words	3	3
Maximum frame words	34	66

LAL 88302

Figure 1.- HO3S-1 variable-stability helicopter.

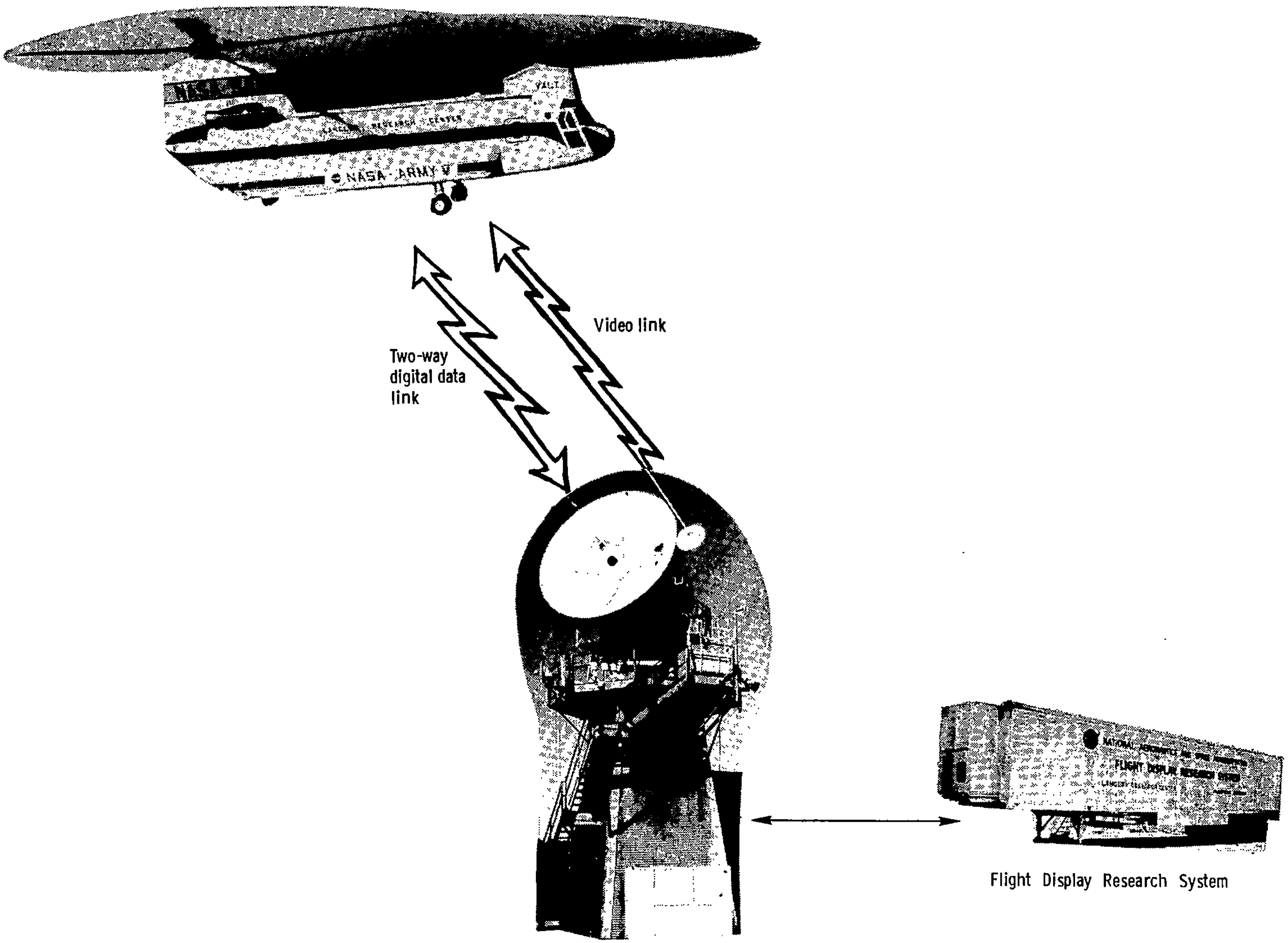


L-72-7

Figure 2.- YHC-1A variable-stability helicopter.

L-78-323

Figure 3.- VALT CH-47 research helicopter.



L-79-192

Figure 4.- Primary research mode facilities of the VALT CH-47 helicopter.

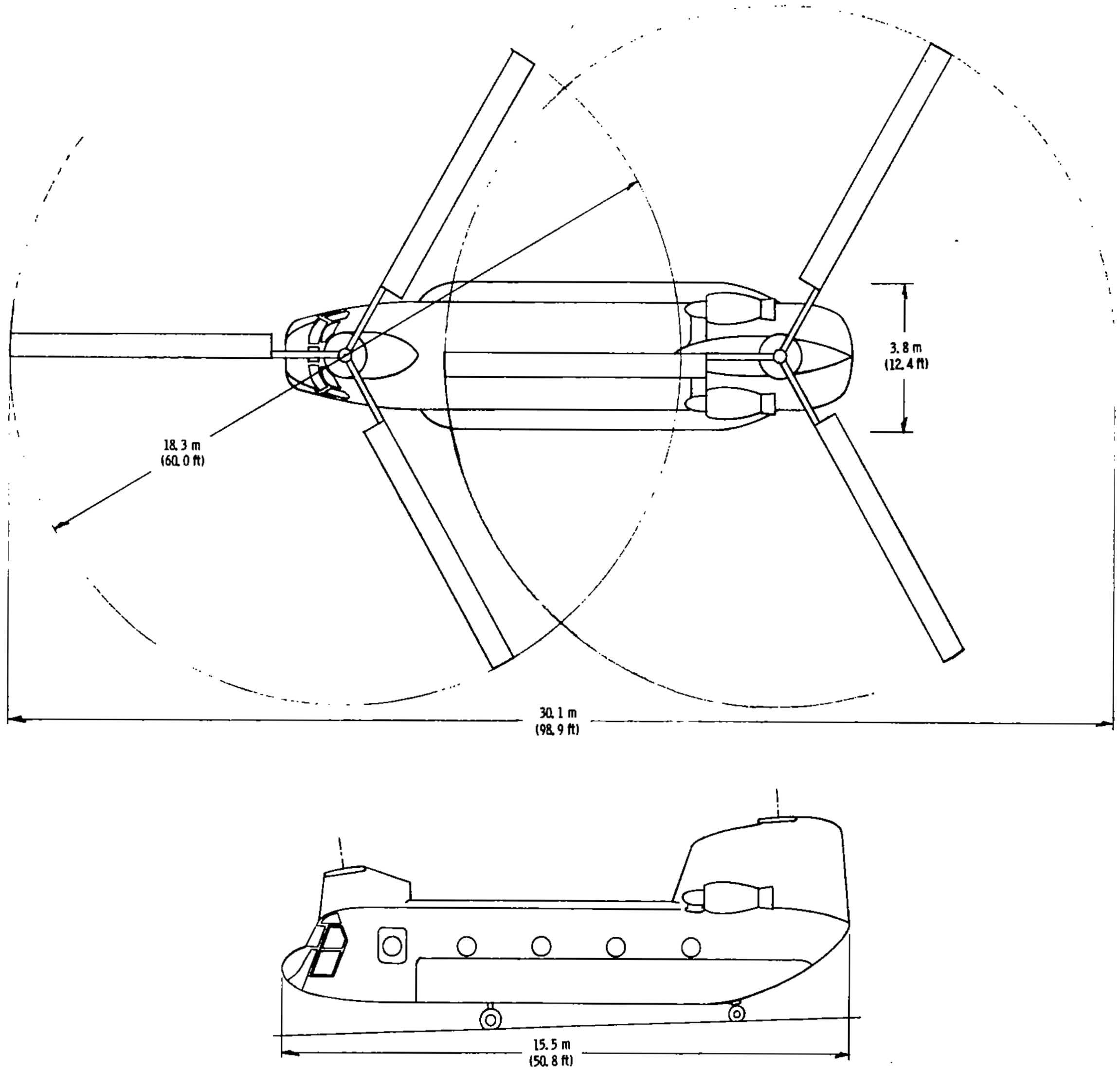
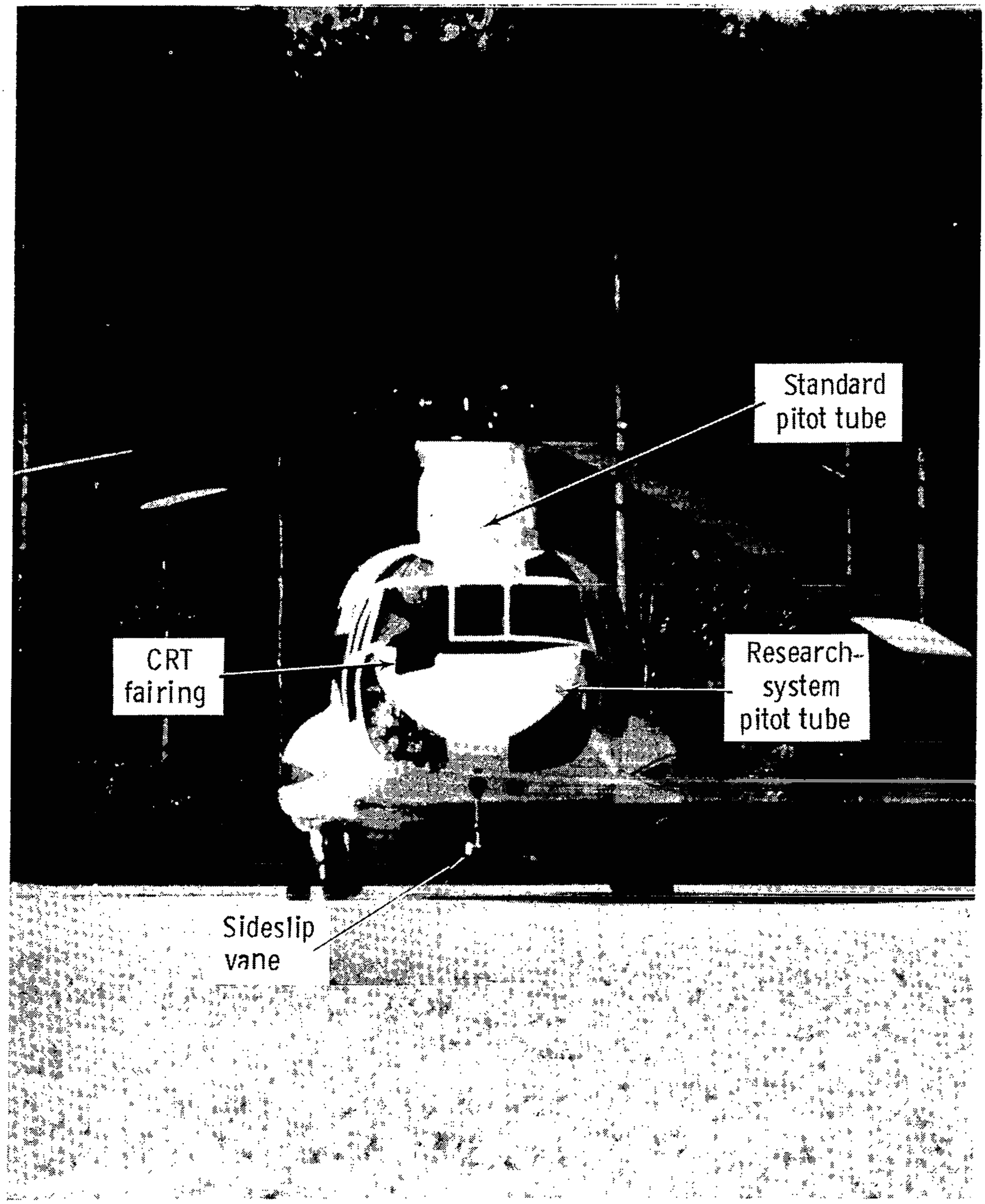


Figure 5.- Overall dimensions of the CH-47 helicopter.



L-78-322.1

Figure 6.- Front view of the VALT CH-47 helicopter.

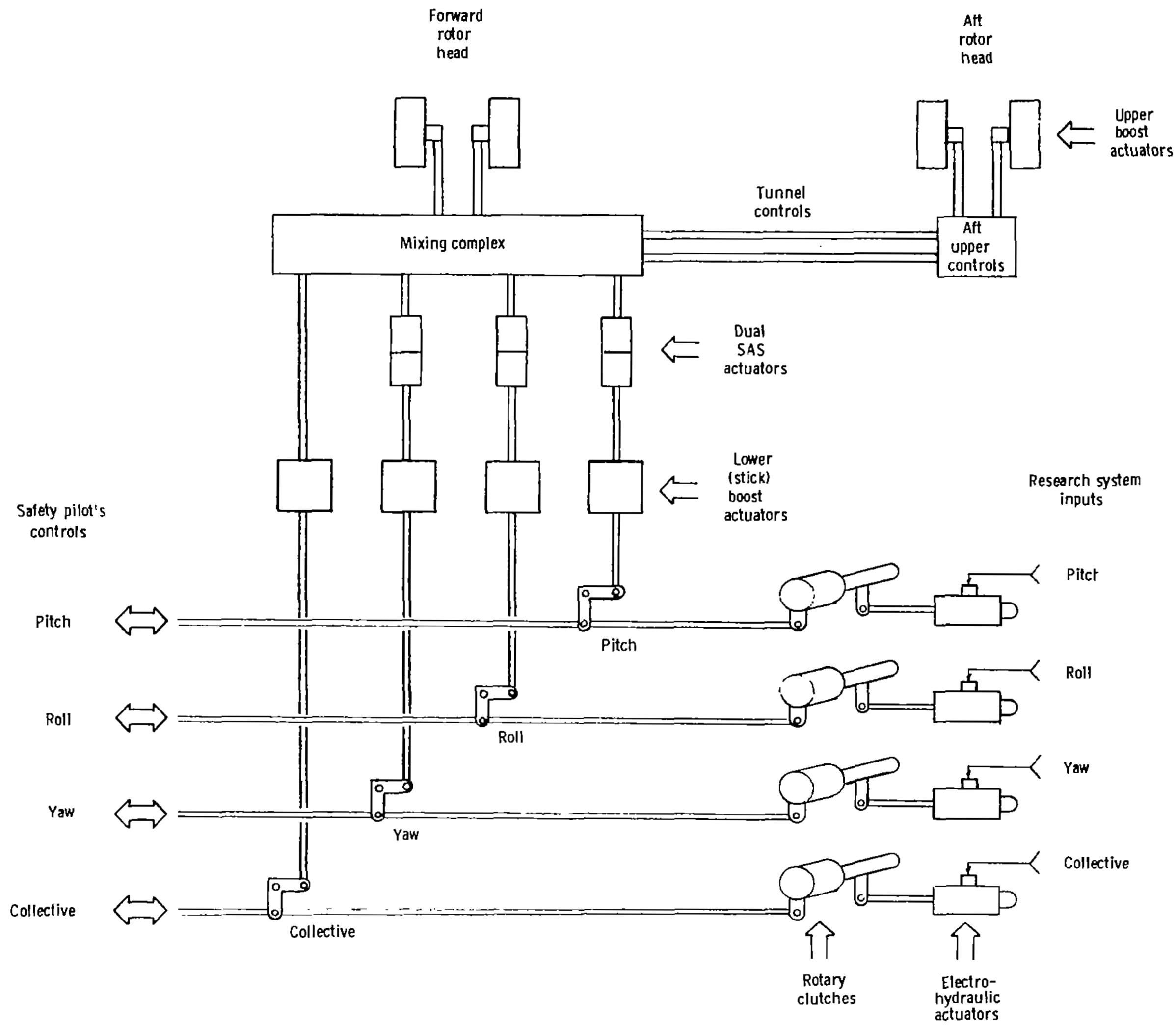
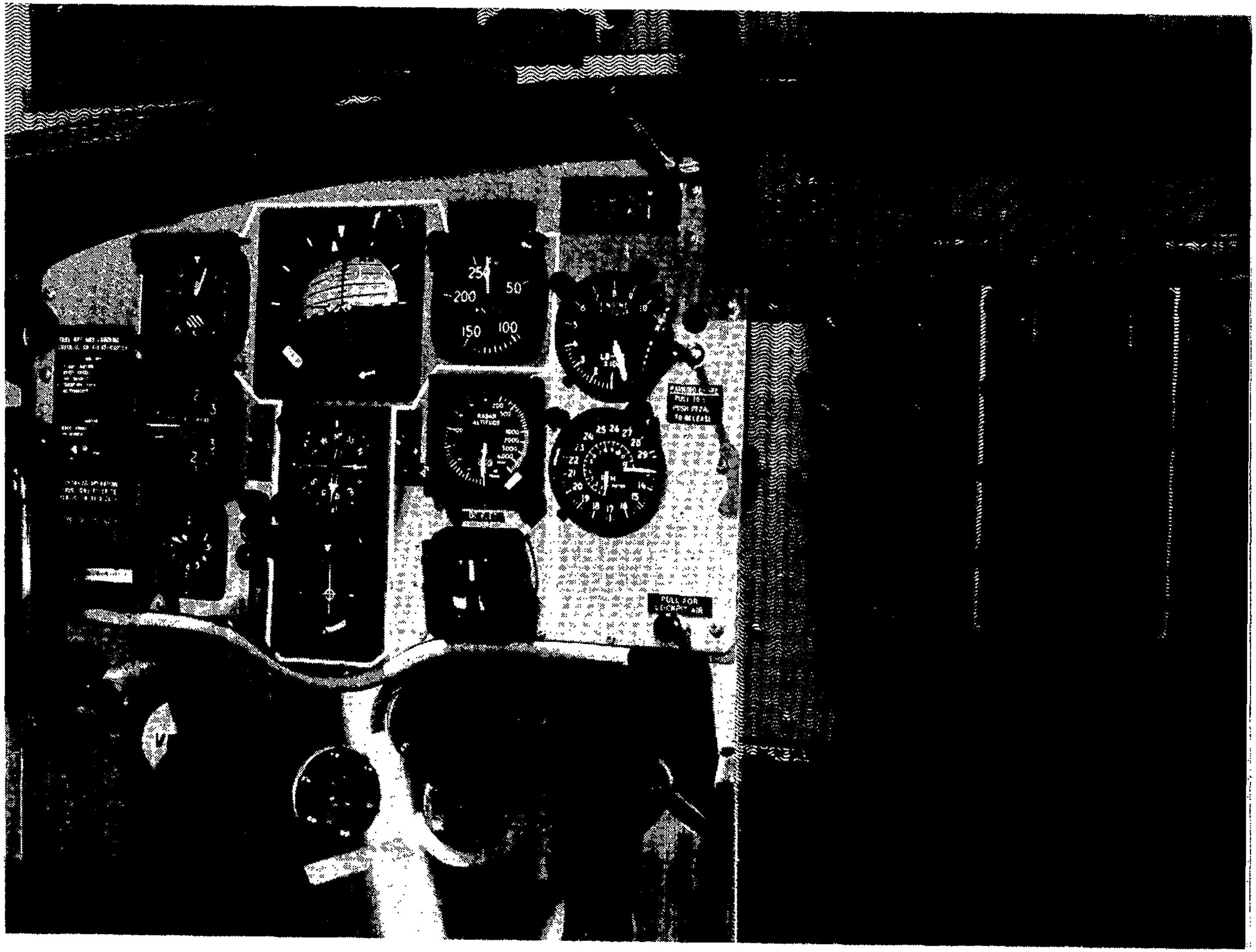
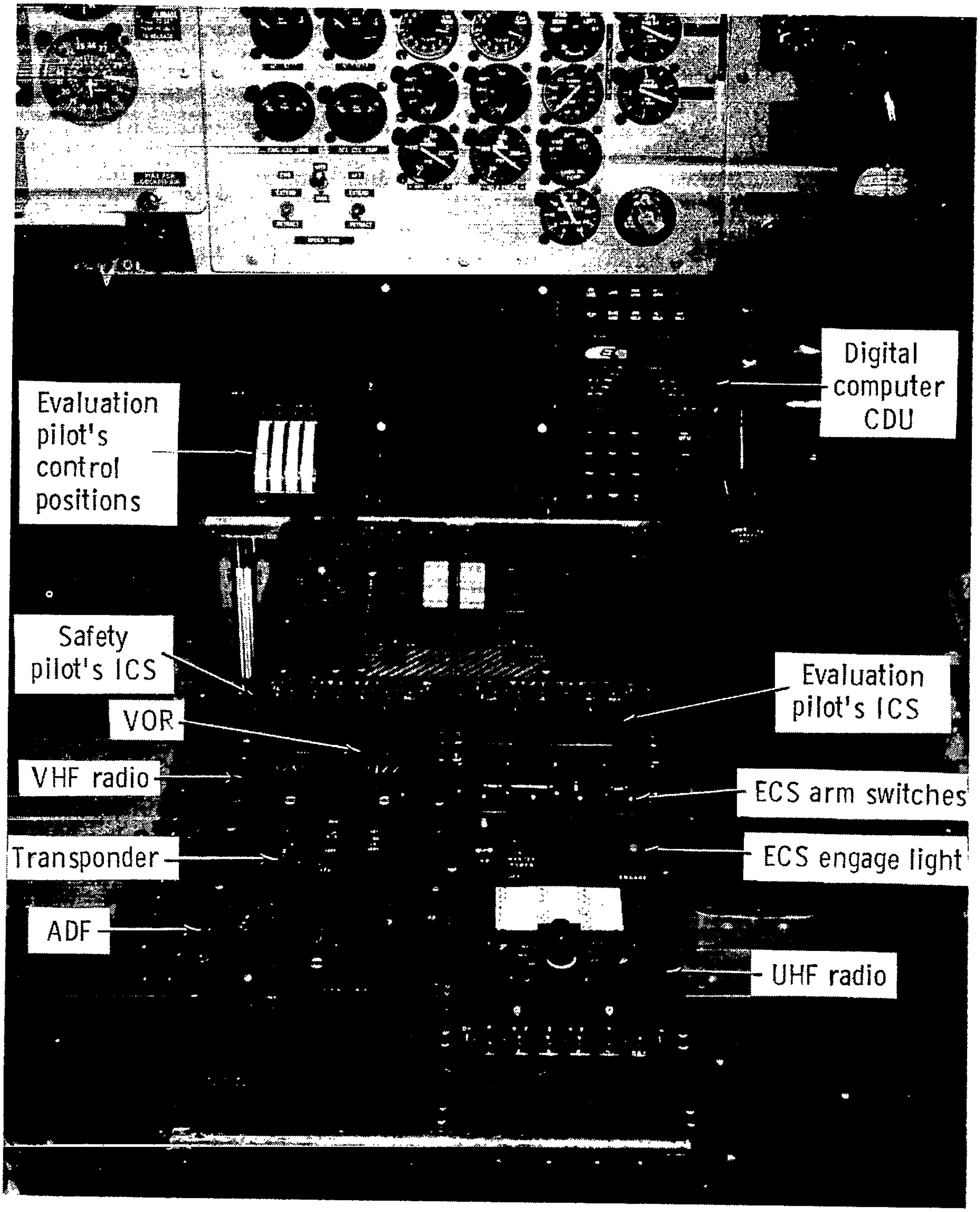


Figure 7.- Flight control system of the VALT CH-47 helicopter.



L-76-23

Figure 8.- Safety pilot's display panel.



L-77-4672.1

Figure 9.- Cockpit center console.

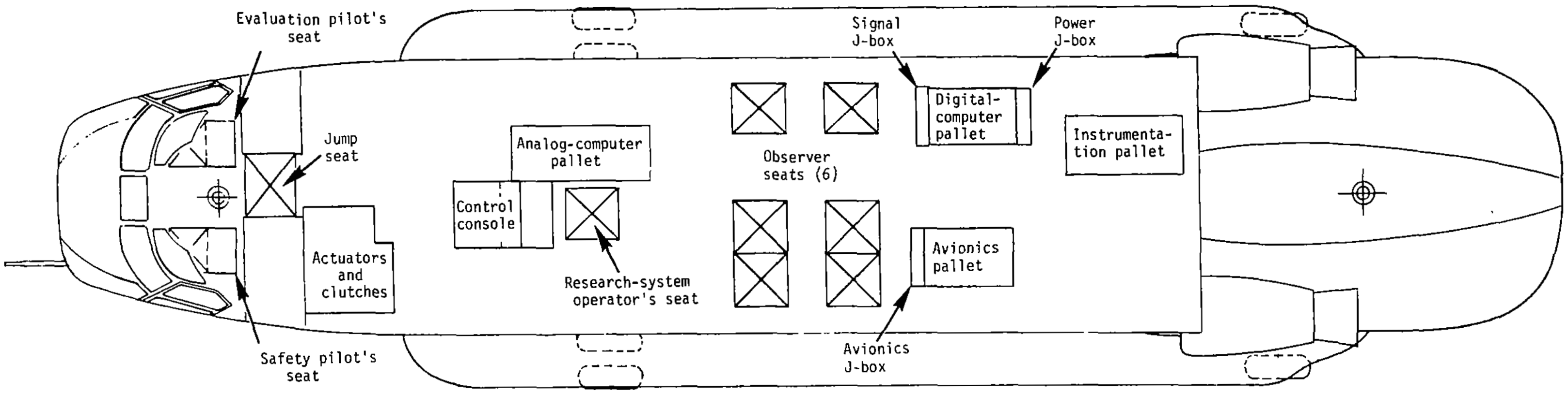


Figure 10.- Cabin layout.

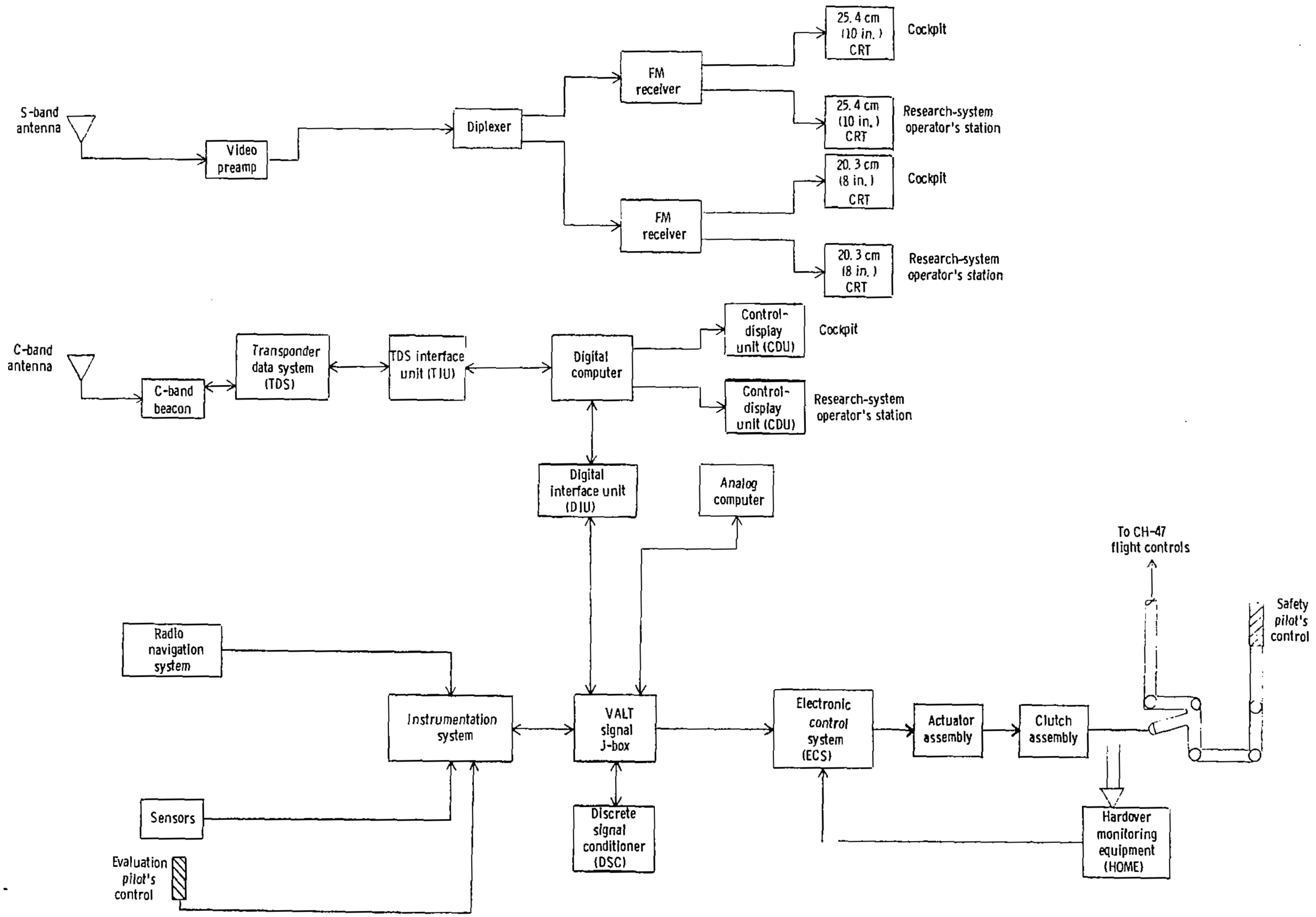
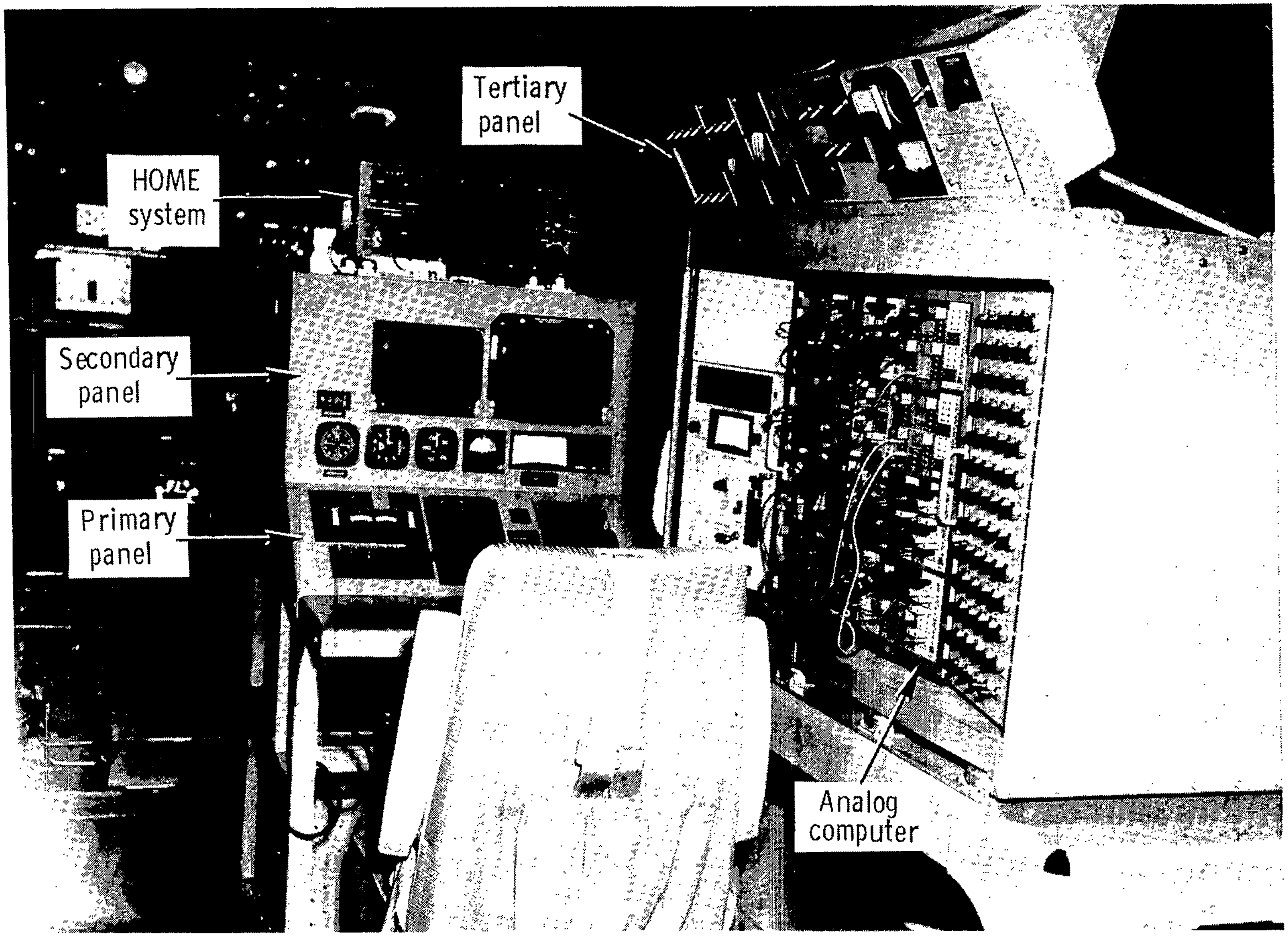


Figure 11.- Primary VALT CH-47 flight system.



L-78-325.1

Figure 12.- Research-system operator's station.

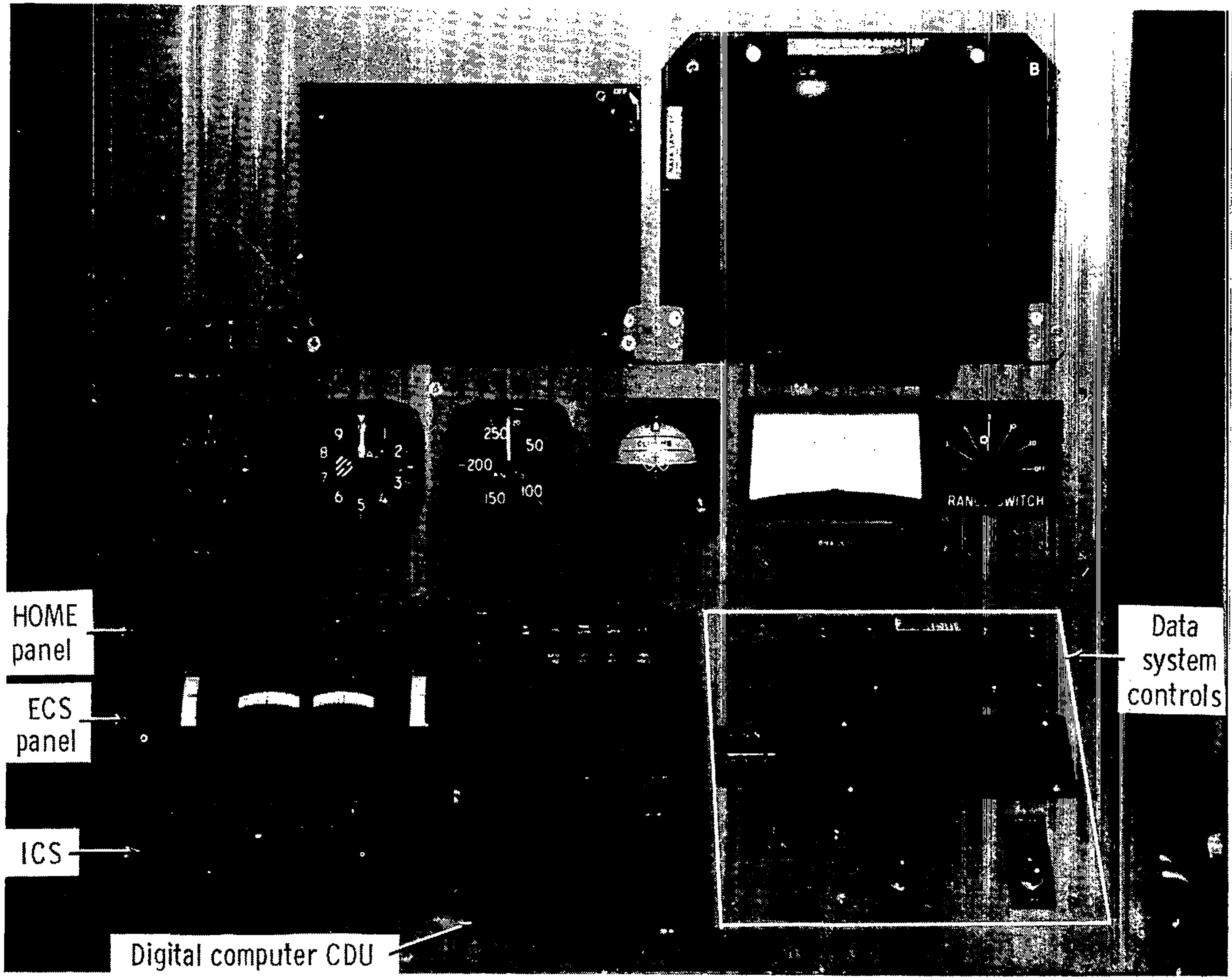


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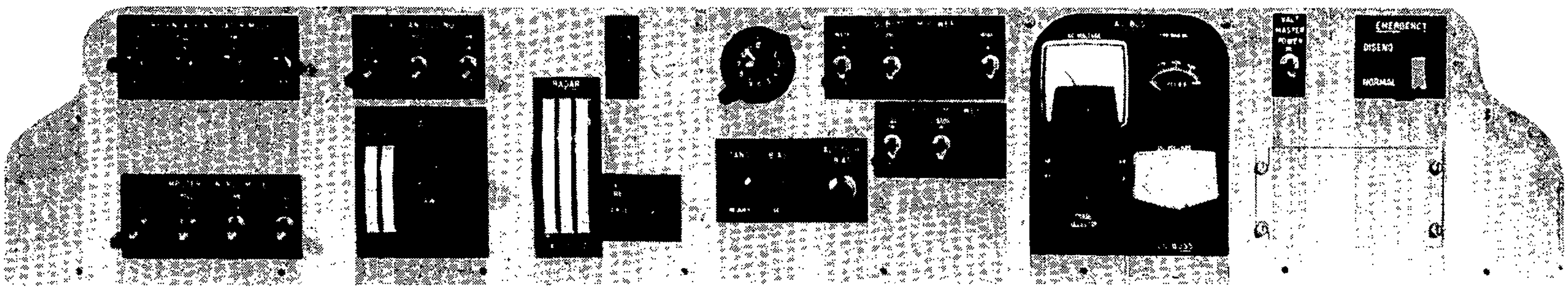
Figure 13.- Research-system operator's primary and secondary panels.



L-79-193

Figure 14.- Research-system operator's tertiary panel.

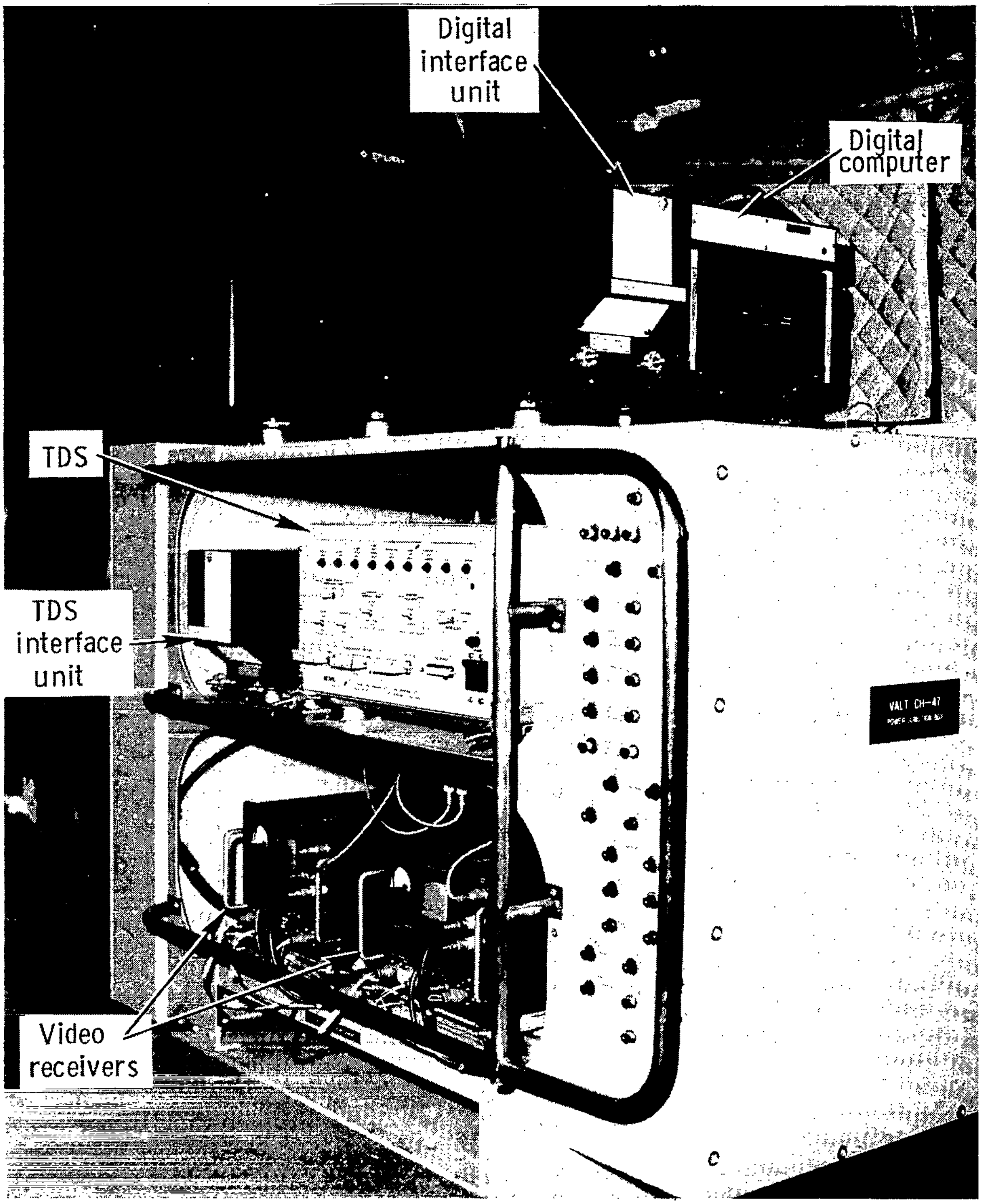


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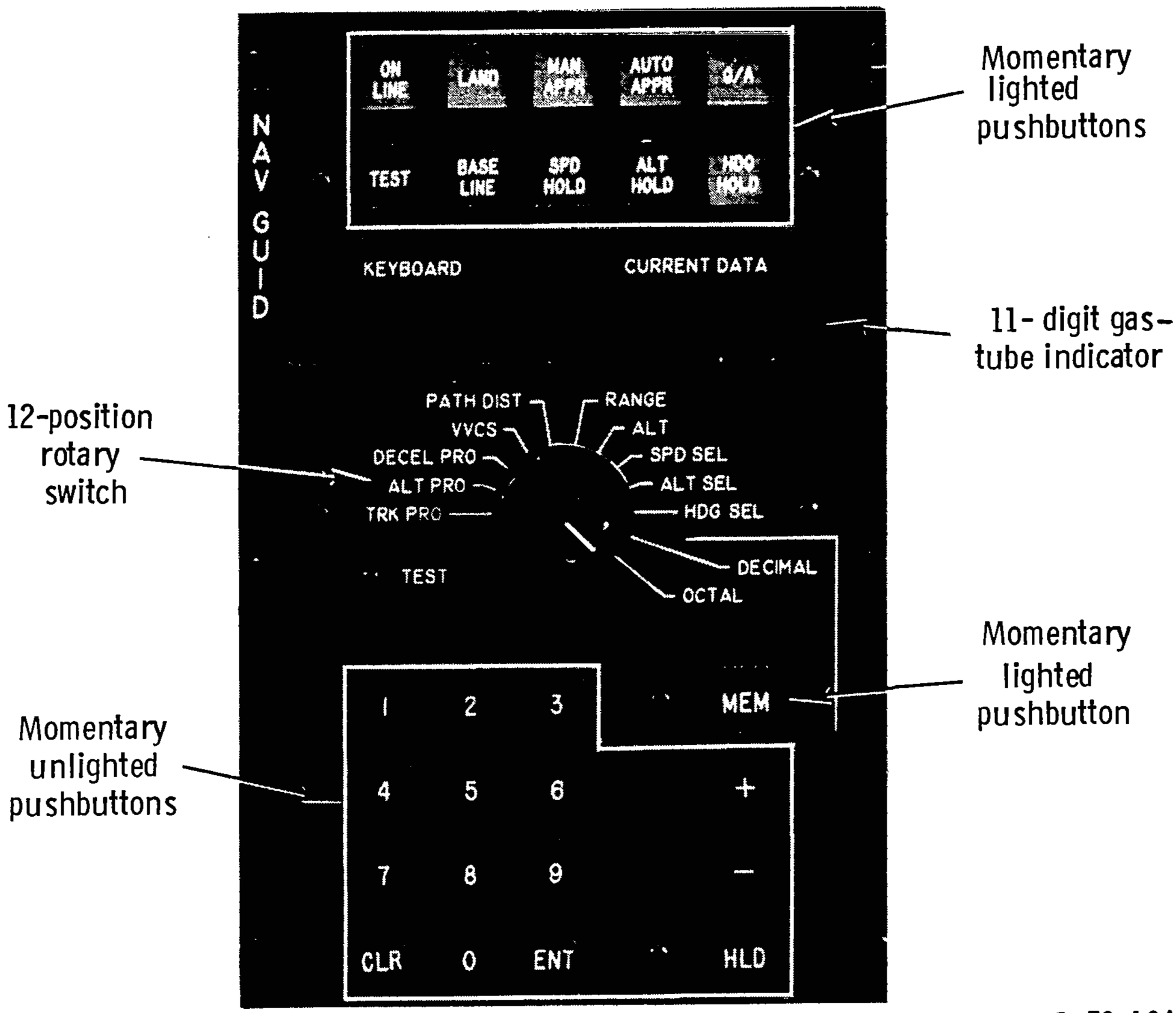
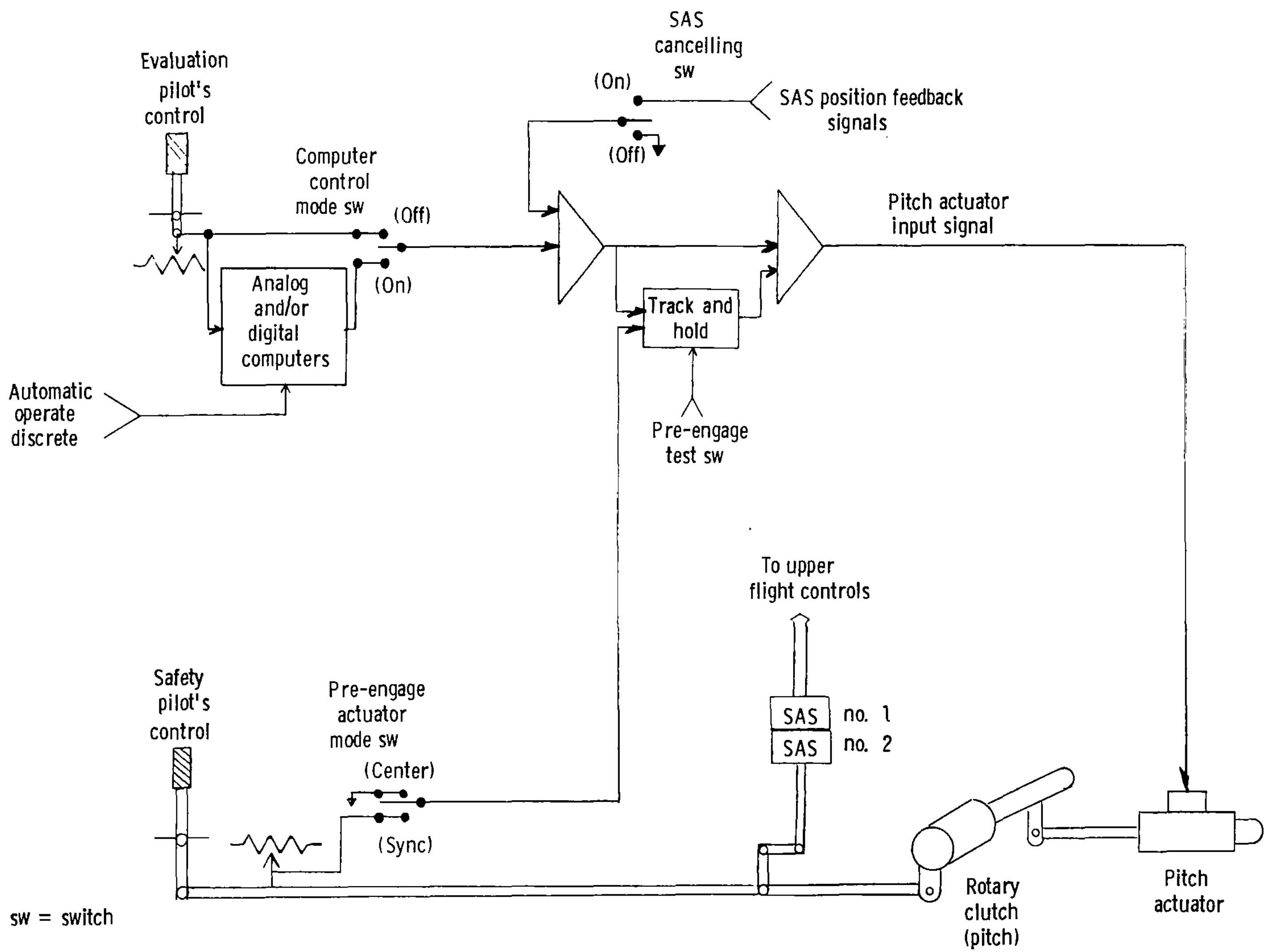
Figure 15.- Digital-computer pallet.



L-79-194

Figure 16.- Digital computer CDU.



sw = switch

Figure 17.- ECS pitch channel.

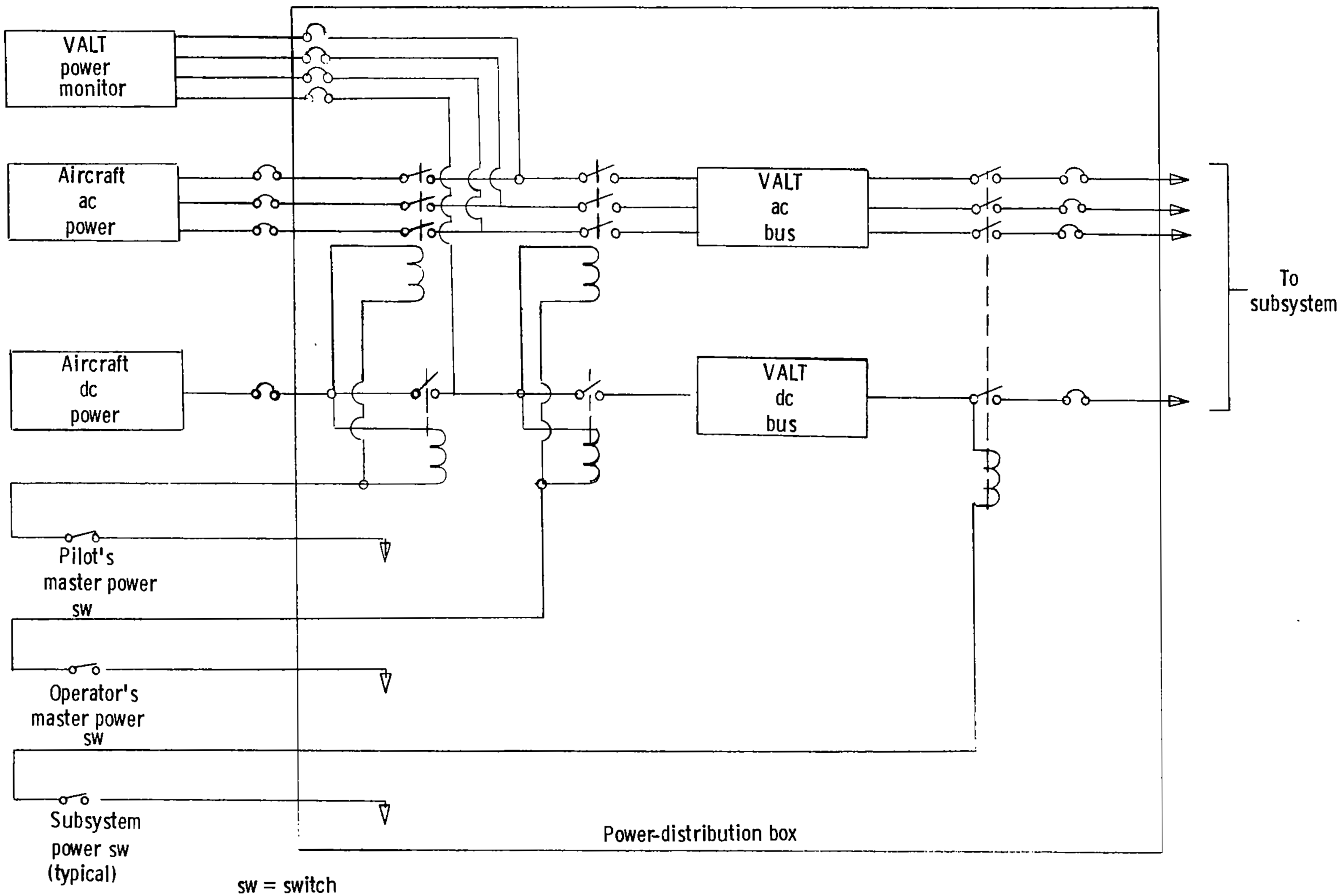


Figure 18.- Power-distribution system.

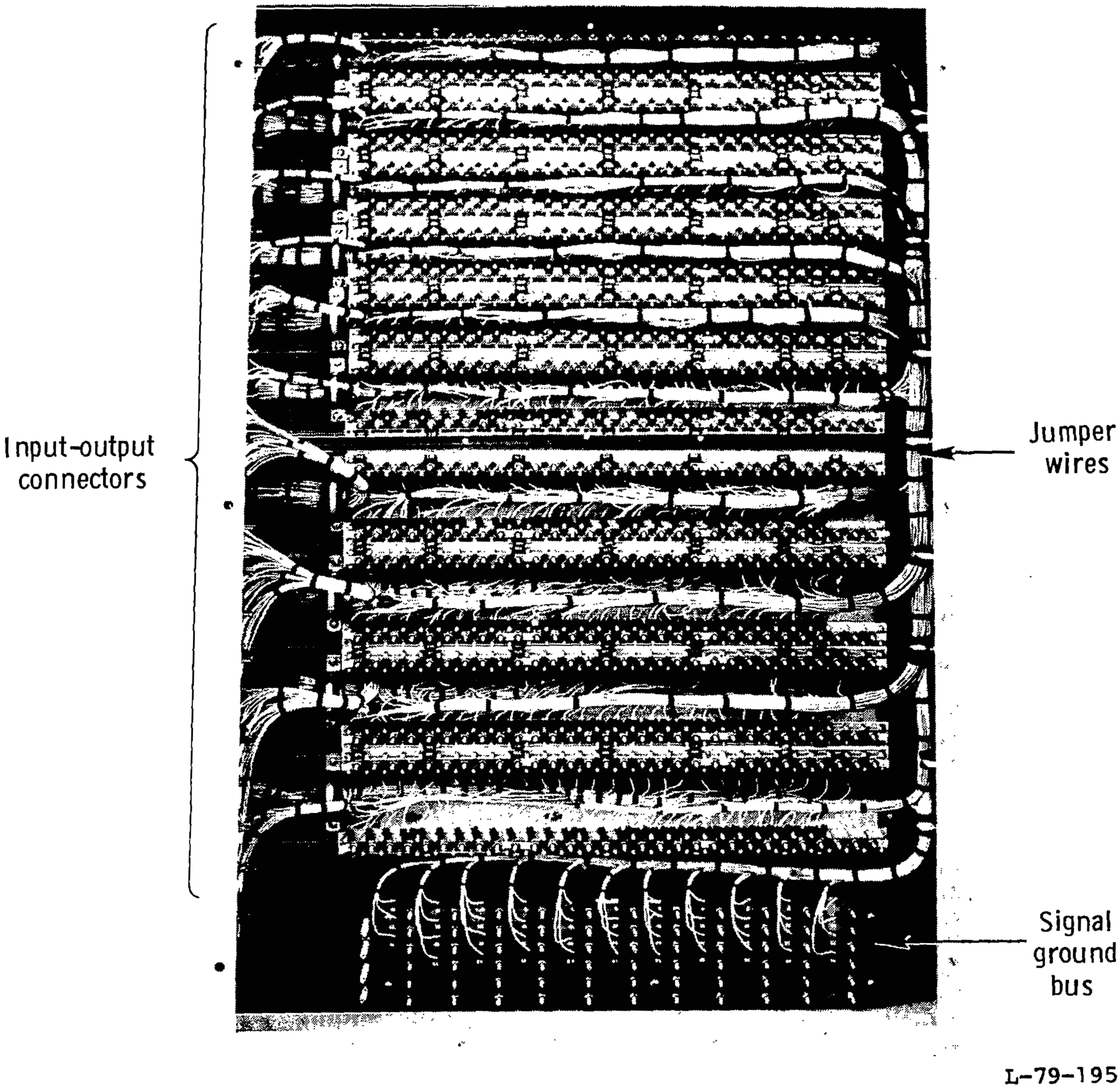
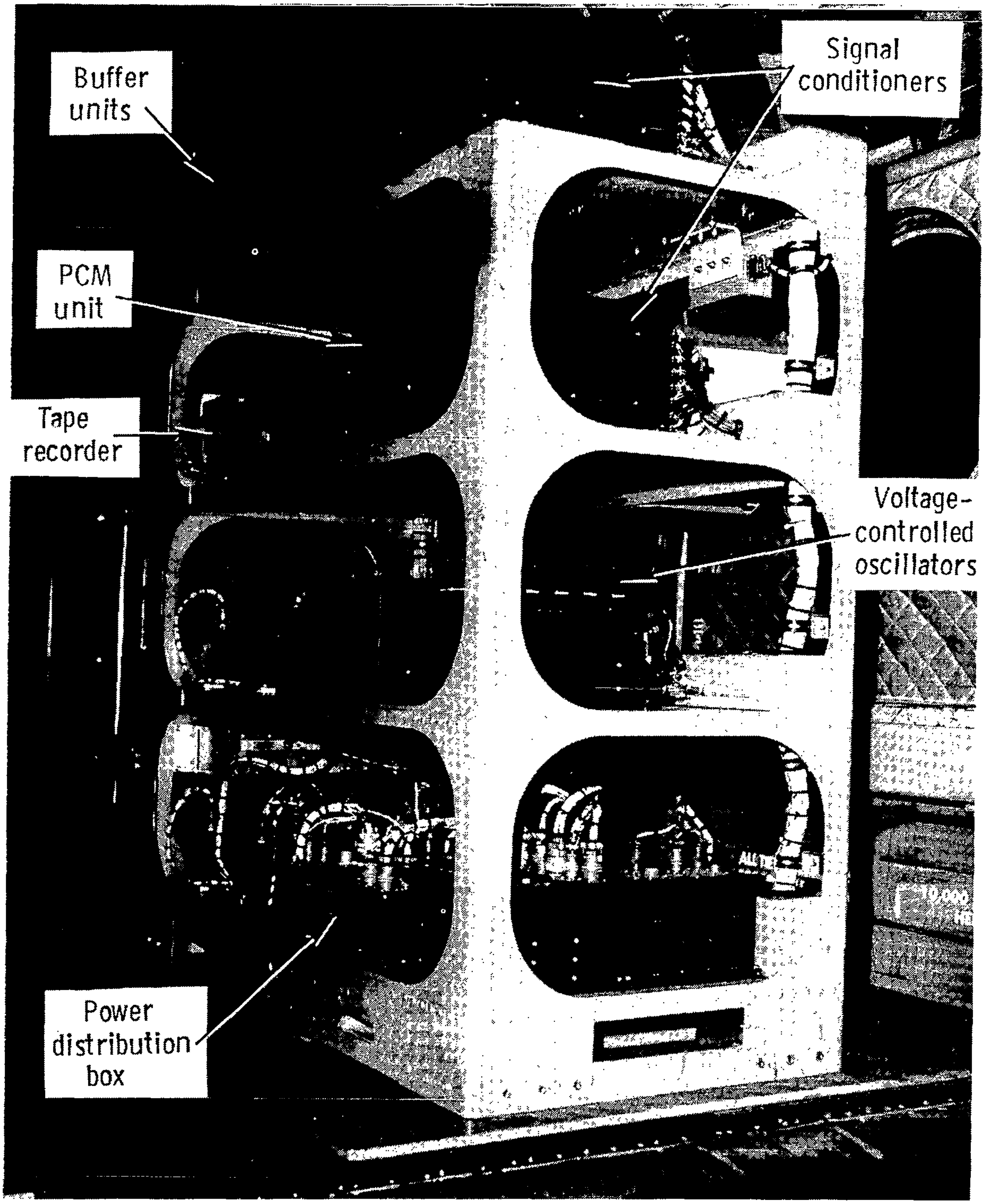


Figure 19.- VALT signal J-box.



L-78-327.1

Figure 20.- Instrumentation system.

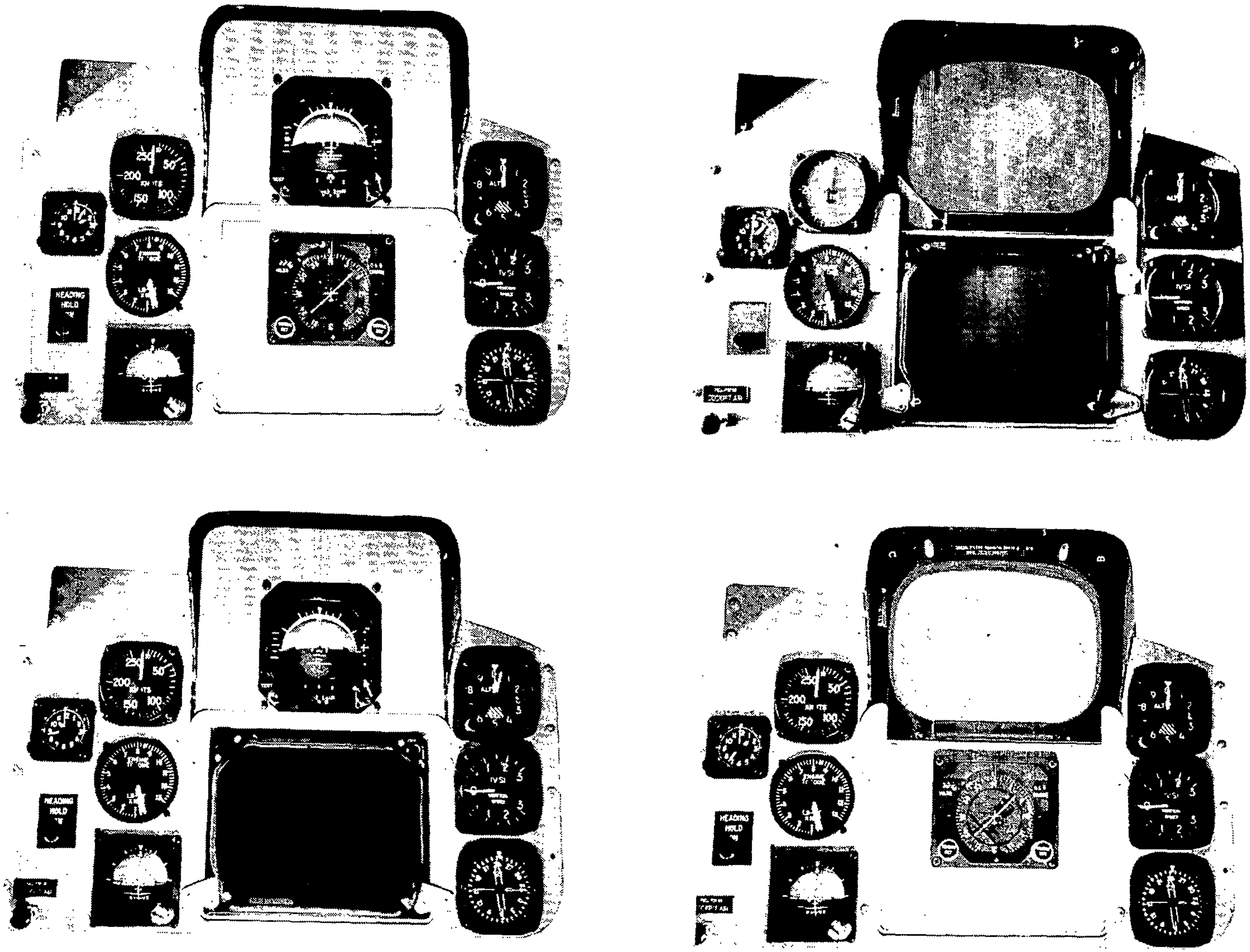
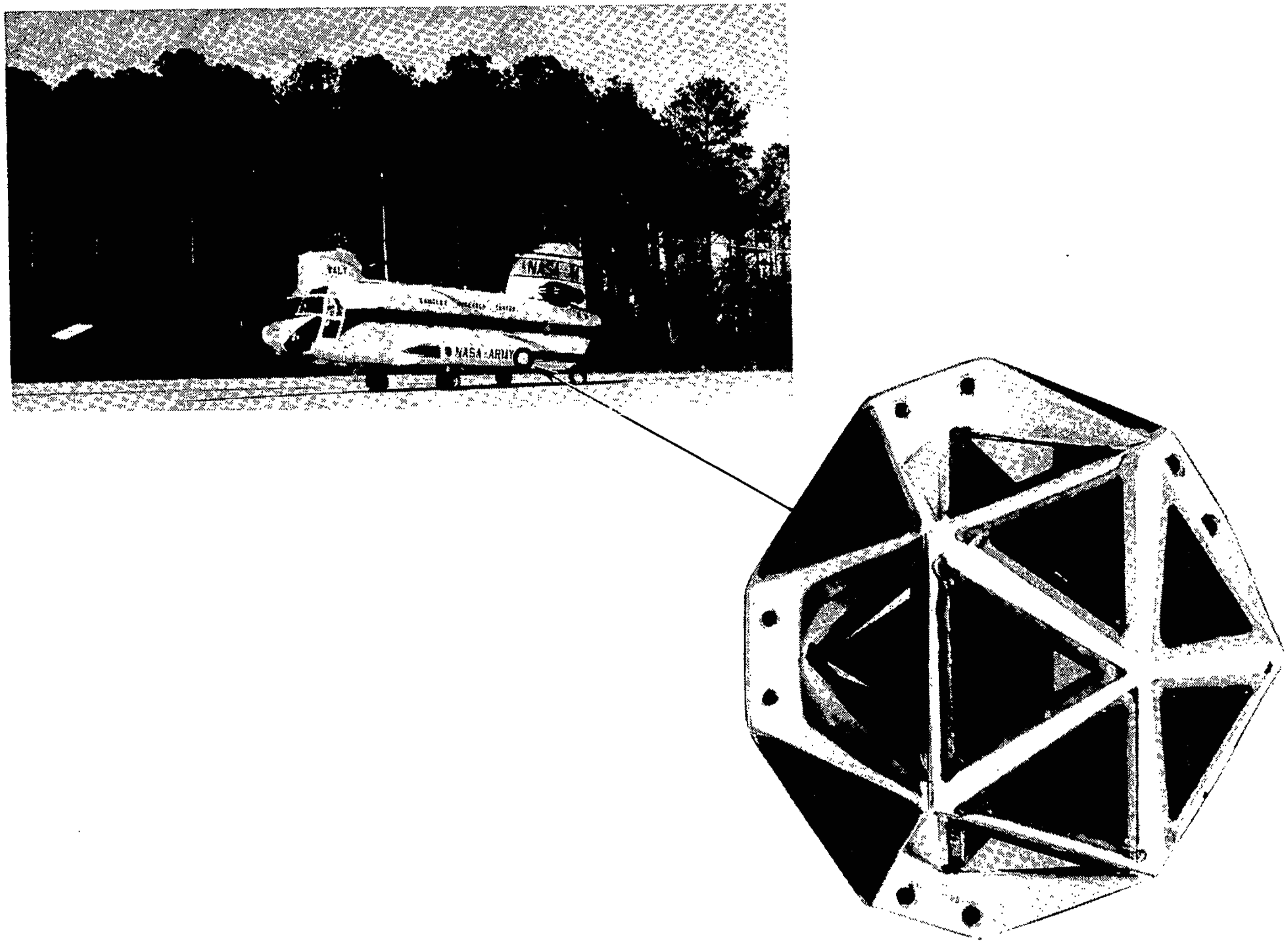


Figure 21.- Evaluation pilot's instrument-panel configurations.

L-79-196



L-79-197

Figure 22.- Retroreflector array.

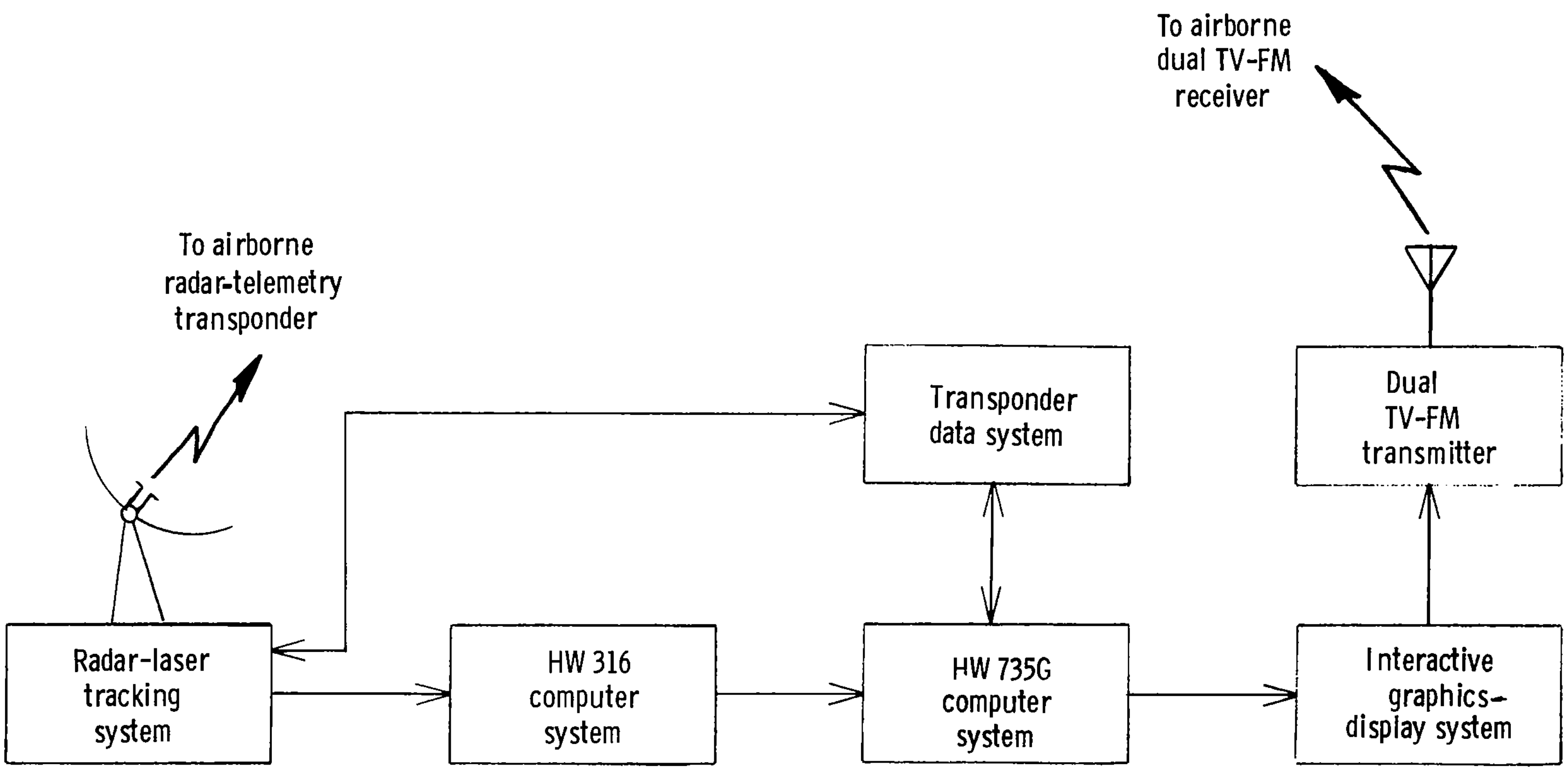
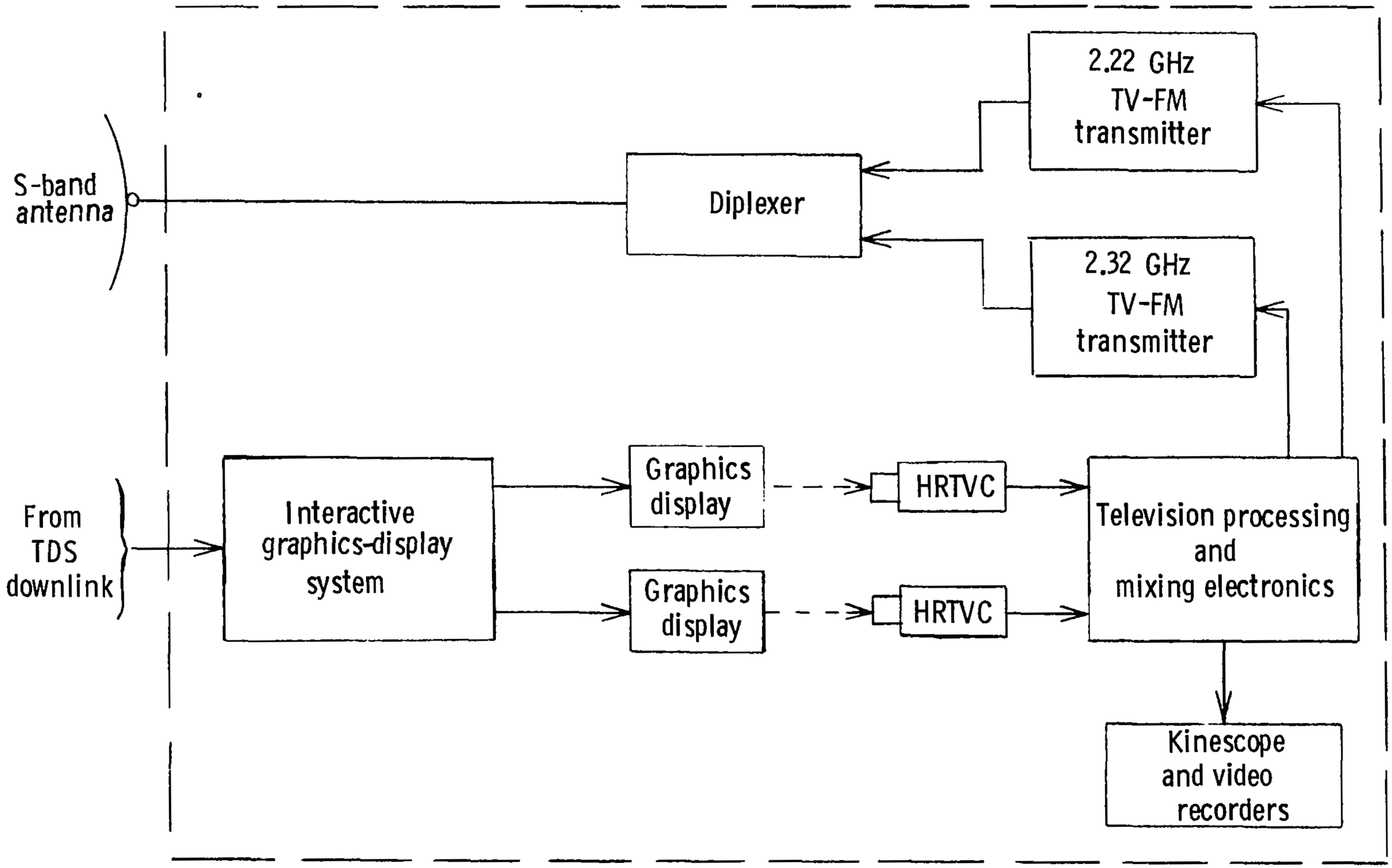


Figure 23.- Simplified diagram of ground-based system.



HRTVC - high-resolution television camera

Figure 24.- Simplified block diagram of flight-display research system.

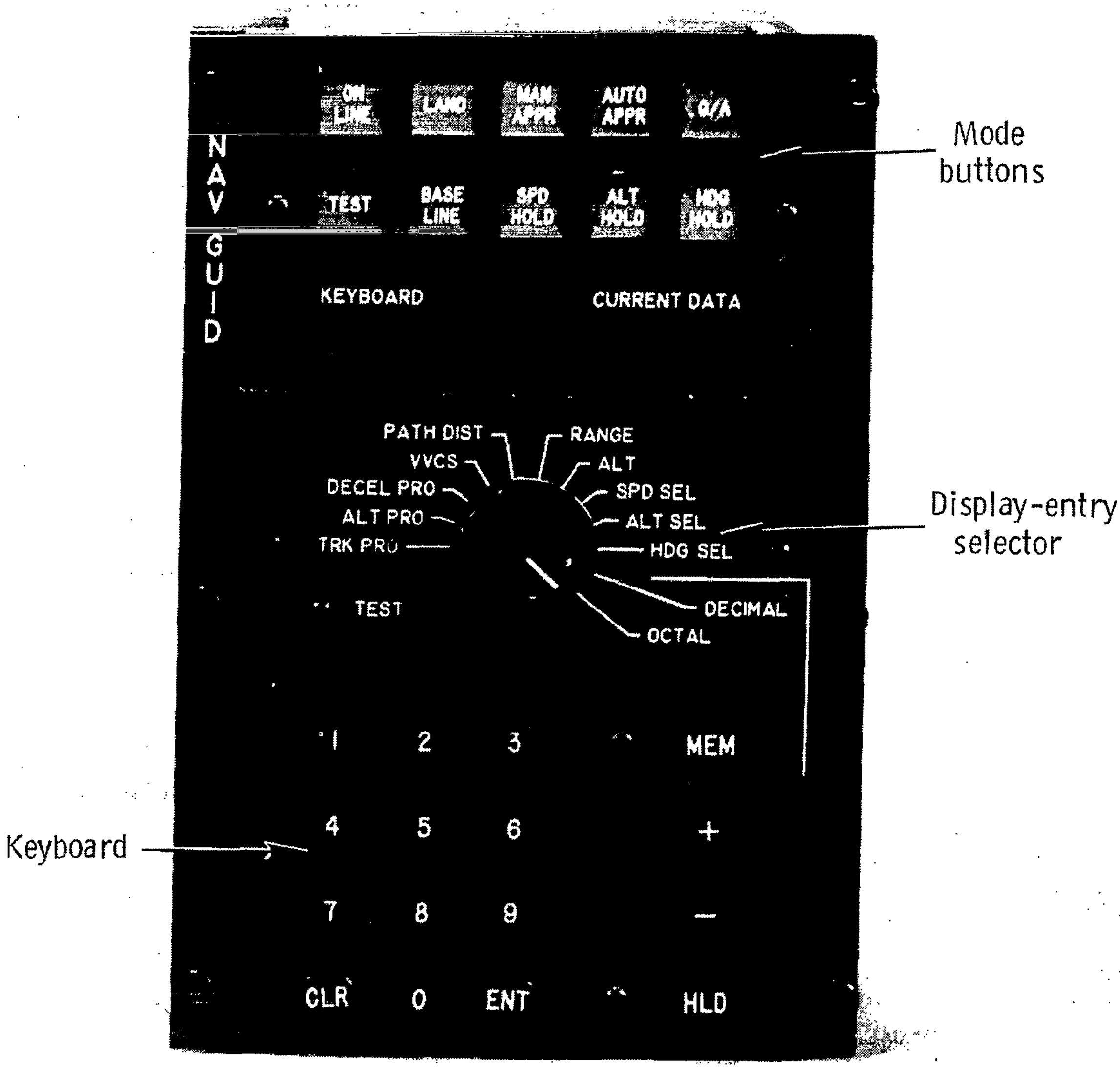


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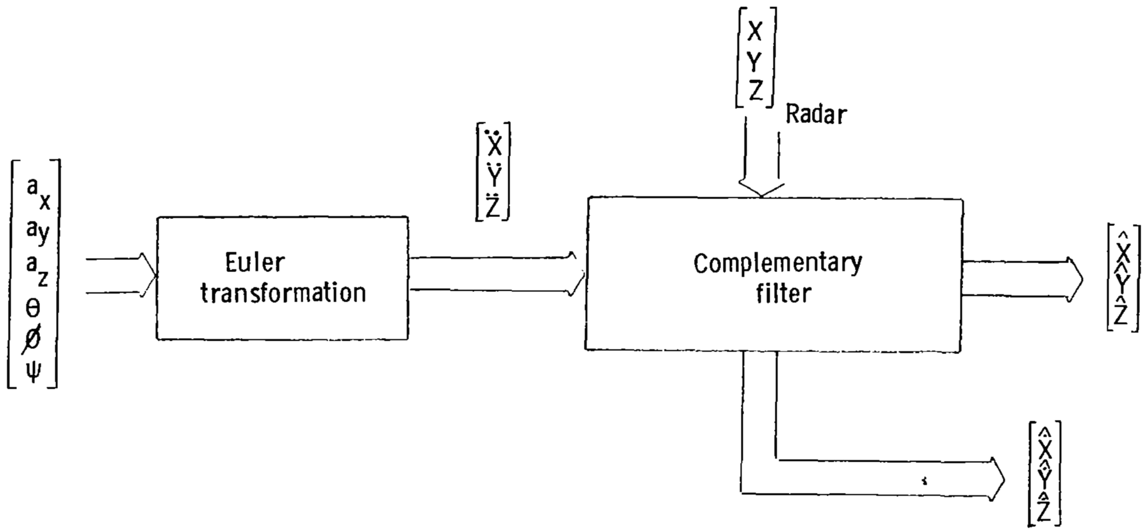
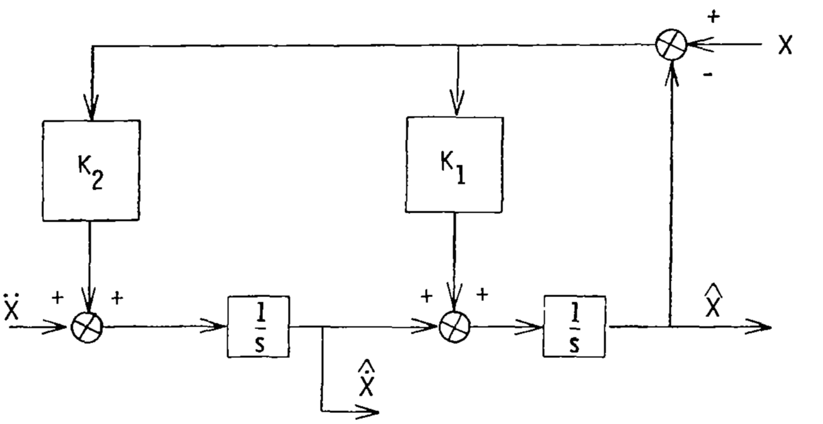
Figure 25.- CDU configuration for approach tests.



(a) General arrangement of filter.



(b) Complementary filter in the X degree of freedom.

Figure 26.- Terminal-area navigation filter technique.

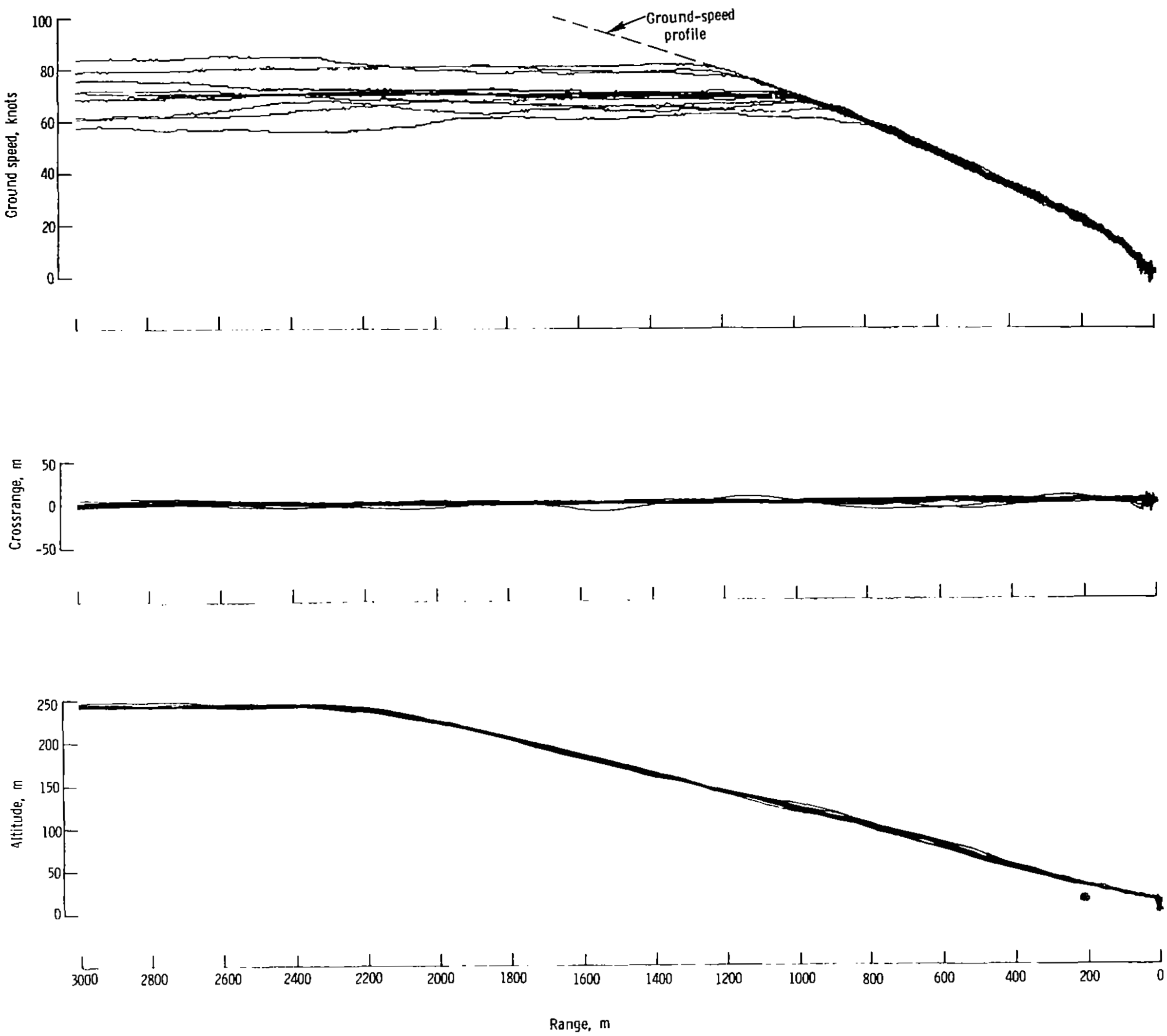


Figure 27.- Automatic decelerating approaches at 6° glide slope.

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16. Abstract

The Langley Research Center has modified a CH-47B helicopter to provide a general-purpose variable-stability capability for the VTOL Approach and Landing Technology (VALT) Program. This report describes the functional aspects and capabilities of the overall system. Automatic decelerating approach data are presented to illustrate the performance of the overall system.

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