NASA TECHNICAL MEMORANDUM

NASA TM X-62,183

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October 1972

13

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Summary

STOLAND has been developed to perform navigation, guidance, control, and flight management experiments in advanced V/STOL aircraft. The experiments have broad requirements and have dictated that STOLAND be capable of providing performance that would be realistic and equivalent to a wide range of current and future avionics systems. An integrated digital concept using modern avionics components was selected as the simplest approach to maximizing versatility and growth potential. Unique flexibility has been obtained by use of a single, general-purpose digital computer for all navigation, guidance, control, and displays computation. Modularity of the software insures easy change of experiments. The general-purpose computer is integrated with flexible pilot controls and with both electromechanical and cathode-ray-tube (CRT) displays for maximum cockpit versatility. One of the CRT displays includes a versatile moving map. A complex hierarchy of control modes with safety monitors and interlocks has been provided. Development of STOLAND has required special approaches to hardware and software design in order to provide all of the desired advanced capabilities.

Nomenclature and Acronyms

A/D	analog-to-digital conversion
AHS	airborne hardware simulator
C-8A	DeHavilland "Buffalo" STOL aircraft
CRT	cathode ray tube
D/A	digital-to-analog conversion
DME	distance-measuring equipment; ultra-high frequency navigation aid which provides range information
DOT	U. S. Government, Department of Transportation
EADI	electronic attitude director indicator
HSI	horizontal situation indicator
MODILS	modular instrument landing system; an advanced C-Band scanning-beam landing guidance system
MFD	multifunction display
STOL	short takeoff and landing aircraft
STOLAND	research STOL avionics system
TACAN	tactical area navigation; an ultra-high frequency navaid providing bearing and range information
VOR or NAV	very high frequency omnidirectional range; a navaid providing bearing information
VTOL	vertical takeoff and landing aircraft
V/STOL	vertical or short takeoff and landing
Ax, Ay, Az	aircraft-referenced accelerations
$x, \dot{x}, \ddot{x}$; $y, \dot{y}, \ddot{y}$; $z, \dot{z}, \ddot{z}$	Earth-referenced coordinates, velocities, accelerations
θ, ϕ, ψ	Euler angles
ω_1, ω_2, ω_3, ω_4	Filter parameters

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Introduction

STOLAND has been developed to respond to requirements for an avionics system that can be used in both flight and ground simulation to perform V/STOL terminal area navigation, guidance, and control research as defined by the joint DOT/NASA Operating Experiments Program. The experiment requirements are broad, and have dictated a system that is flexible enough to operate realistically at several levels of sophistication. System design selection has also been heavily influenced by the

5359 3

necessity that it answer future research needs with minimum change and that it be readily applicable to radically different STOL and VTOL aircraft. The versatile research tool which resulted is an integrated digital system and has intrinsic and potential capability for expansion and for interfacing with additional equipment.

Several unique features of the system contribute to its research utility, and each of these features has posed an interesting development challenge. The primary feature of STOLAND is the use of a single general-purpose digital computer for all computation. This facilitates research by allowing changes to the experiments to be made by changing software only, but methods for handling the resulting high level of data transfer have had to be devised. Inclusion of modern software-programmable displays, such as moving maps, has required special techniques to avoid using excessive computer time. Inclusion of a wide range of selectable flight modes has required careful design of the pilot controls and a comprehensive mode interlock design. Handling of navigation data to provide good flight guidance accuracy has required development of sophisticated techniques which do not use too much computer time. The software package required to accommodate all of these requirements is extensive, yet it has to be modular to allow easy change of experiments and application to different aircraft. To allow this complex software to be fully exercised on the ground prior to flight testing, a special validation facility has had to be developed.

Present plans call for first installation of STOLAND on an unmodified DeHavilland C-8A "Buffalo" STOL aircraft.

STOLAND Development Requirements

The requirements to which STOLAND has been developed are summarized in Table 1. The greatest emphasis has been placed on achieving a broad research capability, as represented by the requirements listed under "Versatile Research Capability" and "Built-In Growth Capability."

The major research tasks that have been defined to date for STOLAND require flight and simulator investigation of the levels of V/STOL terminal area guidance performance that can be achieved using various degrees of avionics equipment sophistication. STOLAND has therefore been required to be able to provide levels of performance which are realistically equivalent to several different combinations of standard avionics components, displays and subsystems. Figure 1 illustrates this requirement as a set of building blocks, and also indicates increasing complexity and cost as more sophisticated capabilities are added. In response to this primary requirement, STOLAND has been designed as an advanced, integrated digital system with most functions (or "building blocks") implemented by separate software modules. Any reasonable combination of equivalent capabilities shown in Fig. 1 can therefore be assembled without changing hardware or software, and the characteristics of any block can be changed by changing one or two software modules.

STOLAND has been designed to include a total capability that is potentially greater than that of commercial systems to provide a performance and system expansion margin in case additional or more stringent requirements for operational V/STOL guidance are identified during the research program.

STOLAND System Description

The elements of STOLAND are grouped and mounted to facilitate use in research V/STOL aircraft. The distribution of the system throughout a typical STOL aircraft is shown schematically in Fig. 2. The bulk of the equipment is installed in an airborne rack, as shown in Fig. 2, which has integral forced air cooling. Interfaces between this rack and other aircraft systems (e.g., navaid antennas, power) are designed for easy installation and removal. Prior to installation in the research aircraft, the rack with all its harnesses and components is operated in the simulation facility, which will be described subsequently, to perform a complete checkout of the system. After initial aircraft installation checks have been completed, a preflight test of the system can be performed automatically by a program in the flight computer or flight tape recorder whenever it is desired to verify operational readiness.

Inertial sensors are mounted on a single platform for easy alignment. Parallel electromechanical servos are used for control functions (elevator, aileron, rudder, flap, and throttle) in the aircraft because this approach yielded a minimum complexity interface with the existing cable control systems. This gives some stability augmentation feedback to the control column and wheel in the C-8A aircraft, but the configurations considered for later aircraft will eliminate control column feedback which might be objectionable to the research pilot during handling qualities evaluation. In other advanced vehicles now under consideration for use with STOLAND, the control interface will most probably be with an integrated electrohydraulic servo package.

A most interesting area is of course the cockpit. An artist's concept of STOLAND equipment in the C-8A cockpit is shown in Fig. 3. STOLAND provides flight management information to the research (left hand) pilot using both standard and advanced techniques on electronic and electromechanical displays. At the top, directly in front of the pilot, is a cathode-ray-tube electronic attitude director indicator (EADI). The EADI always presents attitude, indicated airspeed, vertical speed and radar altitude, and it is also programmed to add the appropriate symbols and indicia as additional STOLAND functions, such as flight director, are called up.

The EADI, in addition to its dedicated symbology, has the capability of vector writing under control of the flight computer. This allows the development of some interesting flight experiments, such as generation of a perspective runway symbol during final approach. A TV camera interface is also present in the EADI system, and this may later be exploited in the flight research program.

Beneath the EADI is an electromechanical horizontal situation indicator (HSI) which always presents heading but is otherwise controlled by the system programming. The dual bearing pointers and distance displays may be referenced to any of the navaids onboard, or to computer-generated waypoints on stored flight paths.

To the right of the EADI and HSI is the cathode ray tube multifunction display (MFD) and its special control panel. It was convenient to show barometric altitude and clock reference on the MFD to preserve a basic scan pattern, but its major purpose is to provide a very flexible research display. The presently defined experiments require a complex moving-map display for some configurations and this is included in the present programming. At the right of the MFD is the mode select panel, which is the primary operational pilot control over the system, and will be described in more detail subsequently. Surrounding the STOLAND instruments on the main panel are navigation and aircraft status instruments which are independent of STOLAND.

In the pull-out tray between the pilots, surrounded by navaid controllers, are a keyboard and status panel that provide a flexible interactive pilot interface to the system. Using this interface the research pilot can rapidly select and evaluate different system gains and filter characteristics, thereby conserving airplane operating time. Pilot access to the computer program is limited for safety to those portions of interest on any particular flight. The keyboard and status panel can also be used to enter flight path waypoints and to access the system check and test routines when appropriate. The keyboard is designed to be easily replaced by other kinds of experimental pilot interfaces, such as a magnetic card input, for some investigations.

One other piece of STOLAND cockpit equipment is important—the control wheel, which houses in its hub a two-axis force sensor for the control wheel steering input. An emergency STOLAND disconnect switch rests under the pilot's left thumb; the right-hand pilot has a similar switch.

STOLAND Development

Figure 4 shows a block diagram for STOLAND. Rather than discuss the genesis of the entire system, this section will concentrate on some of the unique features which have presented interesting development challenges. These include: the system concept, which uses a single general-purpose digital computer for all computation; the displays, which are programmable and flexible; the mode control, which is flexible and operational; the navigation technique, which is accurate and simple; and the software package, which includes all research functions in a modular fashion and which requires use of a dedicated facility for validation.

System Concept

Overall, the most emphasis during development has been placed on versatility and flexibility. Selection of an all-digital system allows all of the important research parameters, which are the basic operational functions, to be varied or changed under software control, and allows additional sensors or input data to be handled without changing the hardware. A general-purpose digital computer is easiest for the experimenter to program. Also, use of a single computer simplifies communication between programs and minimizes hardware for data transfer. The main problem with the concept has been to prevent the software from completely filling the medium-speed computer so that no cycle time is left for additional experiment software. The problem has been compounded by the necessity to maintain modularity of the STOLAND software. The key to solution of this problem is the design of the data adapter.

As can be seen from Fig. 4, the data adapter plays a central role in the system. It provides the interfaces between elements of the system and the interfaces between the system and the aircraft and external devices. Communication with the computer is by means of high-speed parallel data transfer in 18 or 36-bit modes. A party-line input-output interface between the computer and data adapter allows full control over data transfer to reside in the program while reducing timing constraints. The data adapter itself has modular circuit construction and built-in spare capacity to facilitate substitution or addition of interfaced devices.

Extensive use of serial data communication (as indicated in Fig. 4) minimizes the wiring interface difficulties, which can be severe in a system of this complexity. System partitioning is arranged so that installation in a new aircraft should require changes only to the servo interlock unit, which provides interfaces to the vehicle control servos.

Another basic function of the servo interlock unit is to provide closure of servo velocity and position loops. This avoids the large load on computation time that would result from software solution rates of 50 or 100 per second. Elimination of the servo loop functions from the software also minimizes the number of solution rates that have to be used, thereby simplifying programming. The servo interlock unit, like the data adapter, employs modular circuit construction and has some built-in spare capacity for easy application to other aircraft. This unit also contains all of the hardware safety monitors.

Displays

As mentioned previously, one use for the cathode-ray-tube multifunction display is to present a complex moving map with selectable flight paths, predictor elements, and other features which consume computation time. The potentially great load on the computer has been minimized by including a considerable amount of the data processing within the MFD symbol generator. For example, map data derived from the computer's navigation computation and storage of landmark and airways symbols is updated only once every second. To provide smooth map translation and rotation, incremental position data computed from determination of the velocity vector is fed to the symbol generator at a higher rate; the symbol generator moves the map based on these data 20 times per second and refreshes the entire display at 50 times per second.

The electronic attitude director indicator (EADI) also uses a symbol generator to reduce the computation load on the central computer. Because the EADI is a primary flight reference, attitude and radio altitude input data are received by the symbol generator without computer processing. Control of movement of most of the raster and stroke-written symbology takes place within the symbol generator, based on the gyro inputs, without accessing the computer program.

Control of the electromechanical HSI from the central computer is a feature that has been added during development to provide greater research flexibility. In order to maintain spare interface and growth capability of the data adapter, the HSI signal conditioning unit shown in Fig. 4 was designed to perform the digital-to-synchro data conversions.

Mode Control

Development in the cockpit area was focused on utilizing the restricted panel space and volume in an operationally valid and effective manner. Component size had to be minimized without limiting research flexibility. The numerous STOLAND configurations and modes had to be manageable by the pilot using mode selection controls in a manner commensurate with present autopilot and flight director controls. Also, the small available space required combination of control functions which had to be carefully designed to avoid confusing inconsistency. The mode select panel layout that was finally selected and accepted by the project pilot is shown in Fig. 5. This panel is designed for push-button simplicity of operation, and contains no synchros, gear trains, or mechanical displays.

The mode select panel functions entirely under software control, and all system interlocks are embodied in the computer program; this implementation makes it extremely easy to evaluate different mode priority combinations in a short time. Of course, the numerous interlocks required for the very complicated hierarchy of manual, flight director, autopilot, autothrottle, and automatic guidance modes has resulted in a more complicated and computation time-consuming set of software modules than had originally been contemplated. This problem was made more complex during development by several additions to the panel functions, for example, slew switch selection of mode reference values. Pilot input interfaces to the system through the mode select panel, status panel and keyboard are serviced every compute cycle rather than on an interrupt basis. Essentially no computer input/output time is required for this service because the discretes which represent pilot inputs are loaded into spare bit locations of the A/D converter output words. The A/D converter digitizes 12-bit words, leaving 6 bits of each 18-bit word for discrete data. Continuous servicing has been chosen instead of interrupts to simplify programming and to insure that a stuck switch failure will be isolated to that switch and will not affect an interrupt line. In the STOLAND system pilot inputs are always serviced within one-tenth second.

Navigation

One of the interesting analytical challenges for STOLAND has been development of a navigation scheme that provides wide bandwidth position and velocity information for use in the guidance equations and for the map display, but which does not require complex, computer-time-consuming filtering. The technique that has been developed for STOLAND employs complementary filtering of single rho-theta navaid data with the velocity and acceleration data obtained from the strapdown inertial sensors (standard vertical and directional gyros, accelerometers) that are also used for the autopilot reference. The four-parameter filter is diagrammed in Fig. 6. The complementary filter may be viewed either as a means of filtering the noisy radio navigation data without loss of bandwidth or as a means of updating the inertial computation of velocity and position by slaving that computation to the steady-state values computed from the radio navigation data source. This technique can also be used with only minor changes when STOLAND is flown with various inertial reference units; an accuracy improvement over the unfiltered inertial reference system is expected. Accuracy using the standard sensors is quite good as is illustrated in Fig. 7. This figure shows simulation results of navigation errors as the system attempted to follow a test case trajectory (flight path). Figure 7(a) shows the entire trajectory. The solid line is the prescribed flight path which has a 360° descending turn in the upwind leg (detailed in Fig. 7(b)). The irregular line is the instantaneous position as computed using the raw navaid data only. Note that the large bias error associated with the VOR-DME error model reduces abruptly as the navigation reference is switched to the precision DME of the MODILS when the aircraft enters the region where the MODILS is valid. The dashed line is the smoothed position reference computed by the complementary filter, which included attitude and heading reference and accelerometer error models. This smoothed reference path is the one which the aircraft is constrained to follow by the guidance laws.

Software

As implied by the preceding development discussions, if the hardware had not been organized to minimize computation time, the extensive software programs could have exceeded the computer capability. Highest priority during software development has been placed on maintaining software modularity to make change of individual control modes, or even the complete navigation scheme, a matter of changing only one or two modules without disturbing other modules or the executive. Software techniques for reducing computation, such as optimizing the difference equations that represent analytical functions, or deriving difference equations from Z transforms, were not used in order to keep the programming as much like analog programming as possible.

At the start of STOLAND development it was planned to reserve unused at least one-half of the core storage and 50% of the computation cycle for additional experiment software and for growth. However, preservation of modularity has been given higher priority than reservation of computer time; therefore, as development has progressed and as requirements have been added the computer time margin has been reduced in lieu of interleaving computations. After programming all of the functions necessary to meet the "nongrowth" requirements listed in Table 1, more than half of the storage and about 43 percent of the total time available have been saved. Table 2 shows the results of the software development for each major module grouping. Table 2 also compares the time requirement for each module group to the estimate that had been made at the beginning of system development. In general, the results compare well to the estimates. The largest increase has been in the input/output program time. This is partly a result of additional requirements, particularly addition of computer control over the electromechanical HSI, but the amount of data transfer has also been found to be greater than was originally anticipated. Also, some functions that were to be included in the executive have been incorporated in the input/output for convenience. Except for air data and navigation, the other instances where computer time has increased over the estimates are generally a result of additions such as programmable vectors to the EADI and addition of programmable slew rates for the mode select panel slew switches.

Software Validation

A major problem that arises from dependence on software to perform most flight functions is the necessity for validating that the software will operate the system properly and safely before undertaking flight research. Also, the experiments will require frequent change of software, so that validation must be carried on almost continuously. This problem has been solved by providing a dedicated piloted validation/simulation capability within the NASA-Ames simulation complex using a set of STOLAND equipment which duplicates the flight equipment. The validation/simulation facility is shown schematically in Fig. 8. Peripheral equipment is connected to the STOLAND computer to allow rapid program assembly, modification, and validation. Using the simulator, a program can be assembled, debugged, and tested against the simulated aircraft and flight environment to verify that it will perform the research objectives. The facility can then be used to make an object program which can be immediately reloaded and validated through a realistic regimen of simulated flight conditions, including off-nominal cases. The object program thus validated can be loaded in flight STOLAND, and the preflight test used to verify that the program and equipment, including hardware and software monitors, are functioning properly and are ready for flight.

A key element of the validation/simulation facility diagrammed in Fig. 8 is the airborne hardware simulator (AHS). This equipment provides an exact electrical interface for all airborne sensors and subsystems that interface with the data adapter. An illustration of the AHS function and its importance in the system validation concept can be given using the MODILS DME as an example. The error model including quantization effects is computed in the simulation equations and the numerical value measured by the simulated DME receiver is transmitted to the AHS. Within the AHS, the DME data are encoded into the six-wire, serial digital format that would be output from the actual airborne DME hardware, and the data are transmitted to the data adapter at the same data rate and with the same electrical characteristics as the MODILS DME receiver output. The data adapter then decodes, stores, and transmits data to the airborne digital computer just as it would in flight. In this manner, the AHS allows an exact duplication of all airborne data traffic that must enter and leave the STOLAND computer complex. Not only are the hardware interfaces of the data adapter thoroughly exercised by this procedure but all of the computer's software for input-output, data acquisition, packing and unpacking digital data, and A/D and D/A conversion can be validated. To the extent that the entire real time data flow is exactly duplicated, a validation flight in the simulator becomes truly representative of a real flight as far as the avionics computer complex is concerned.

Concluding Remarks

The features of STOLAND that make it a uniquely flexible research avionics system have required that a number of development challenges be met. Some of the more interesting system features have been described, and the techniques used to solve the problems that they presented have been discussed. These features include the use of a single, general-purpose digital computer and modular software to perform all computations, integration of CRT displays including a moving map, provision of a complex hierachy of control modes to the pilot in an operationally sound manner, development of a sophisticated navigation technique, and use of a dedicated facility for validation of software.

The most difficult problems that have required solution during development were proper utilization of limited cockpit space for controls and displays, design of operational pilot controls for STOLAND control modes, and providing for all of STOLAND'S advanced capabilities in modular software within the single computer. Of these, the last presented the greatest challenge and has required development of special hardware designs, analytical techniques, and software provisions to minimize computation time and thereby keep it safely within the computer's capability.

Table 1 STOLAND Requirements Summary

Versatile research capability

- realistic configurations offering various levels of automation
- time-constrained guidance to curved, steep descending, decelerating flight paths
- modular software for easy change
- flight path generation from inserted waypoints
- selectable control wheel steering
- advanced flight director
- automatic guidance and control to touchdown
- flexible display formats
- choice of various navaids including MODILS
- system self-test and monitor controlled by flight computer
- in-flight gain, flight path, other changes by research pilot

Experimentally operational

- safe (fail-passive)
- realistic flight performance
- valid pilot interface
- simple, reliable, maintainable
- applicable to existing research aircraft

Built-in growth capability

- computer time and storage reserved for experimental software
- integrated inertial reference systems interfaces
- new navaids interfaces
- redundant configurations
- fly by wire
- DOT avionics system interface
- data link interface
- applicable to future V/STOL aircraft
- automatic takeoff and departure software

Table 2 STOLAND Computer Usage

Function or module group	Storage, 18-bit words	Time per solution, msec	Solution rate, per sec	Time, msec/sec	Time estimated at start of development, msec/sec	Increase + or decrease -
Master executive and timing	306	0.45	20	9	24	-15
Input/output	502	5.7	20	114	39	+75
Air data	720	2.0	20	40	15	+25
Navigation	640	6.0	10	60	36	+24
Guidance (Autopilot and Flight Director)	4700	4.0	10-20	60	103	-43
Guidance (Speed control and time constraint)	800	10.0	0.1-10	20	30	-10
EADI	333	2.9	20	58	22	+36
MFD map	1800	1.0	1	1		
Stored flight paths	1000	4.0	20	80	60	+21
HSI	161	2.2	10	22	-	+22
Keyboard and status panel	1000	0.05	20	1	48	-47
Mode select panel	1710	1.2	20	24	12	+12
Stability augmentation and control wheel steering	1500	2.2	20	44	24	+20
Monitor and diagnostic	300	0.5	10	5	19	-14
Magnetic tape recorder	70	0.7	10	7	17	-10
Data acquisition	200	1.2	20	24	-	+24
Preflight test (nonresident)	3500	-	-	-	-	-
Total resident	15,742	-	-	569	449	+120
Margin	17,026	-	-	431	551	-120

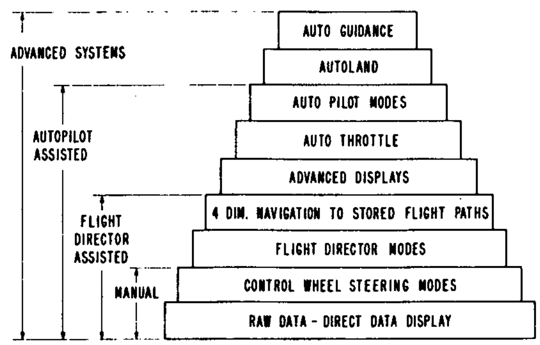


Fig. 1. STOLAND operating configurations.

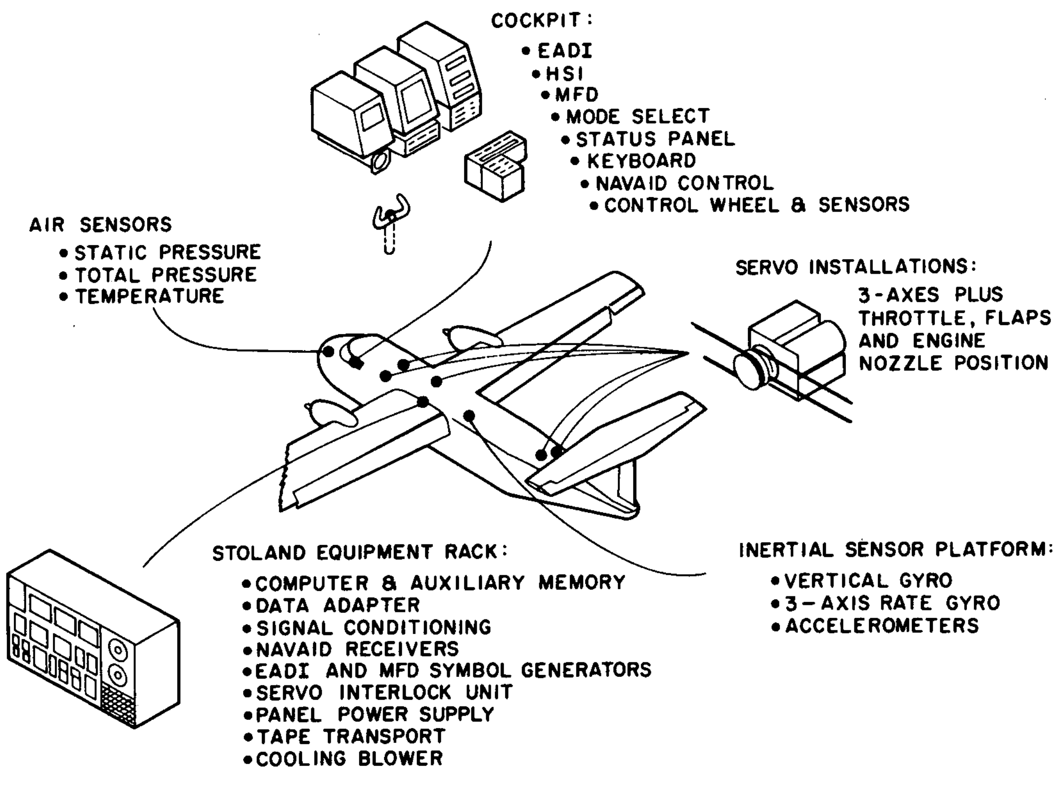


Fig. 2. STOLAND installation in STOL aircraft.

5359 10

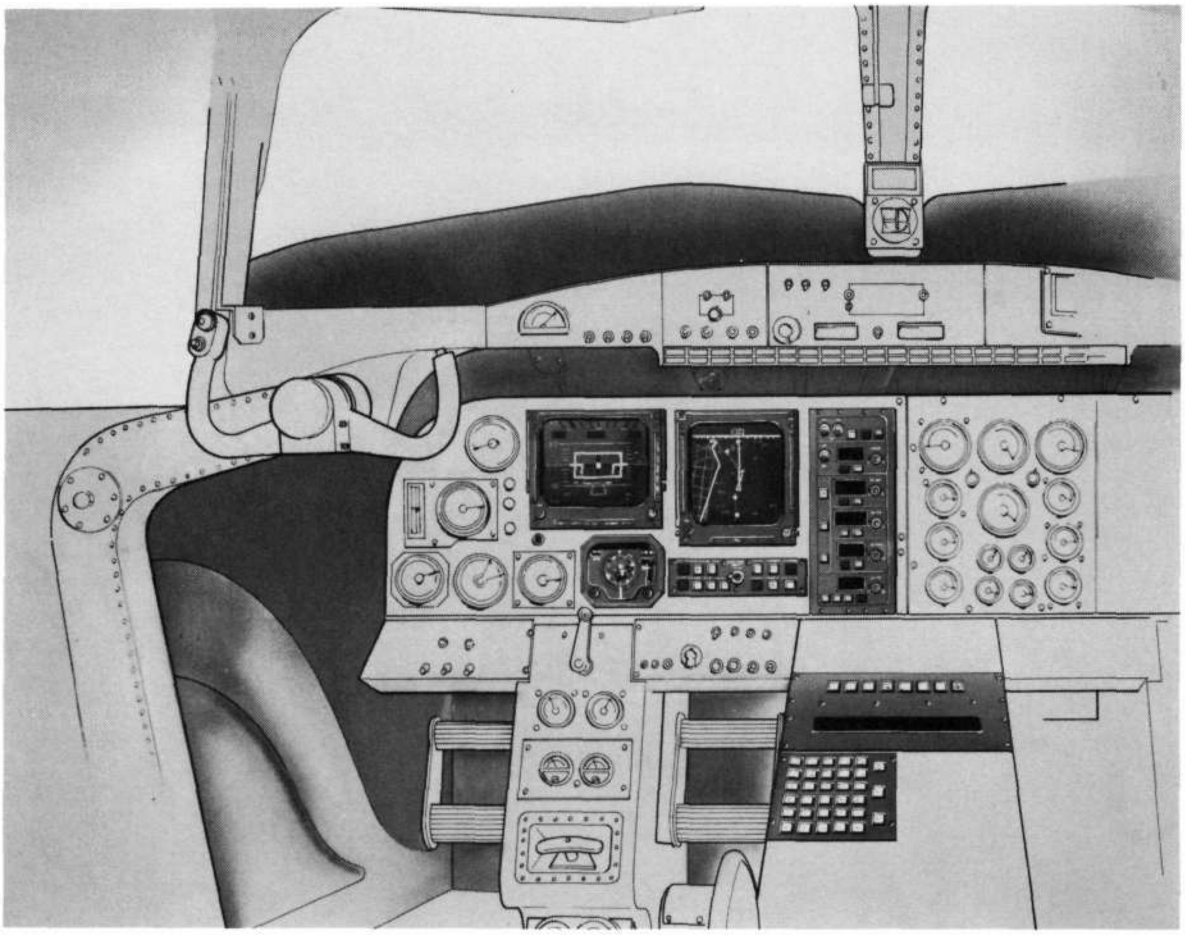


Fig. 3. STOLAND cockpit arrangement.

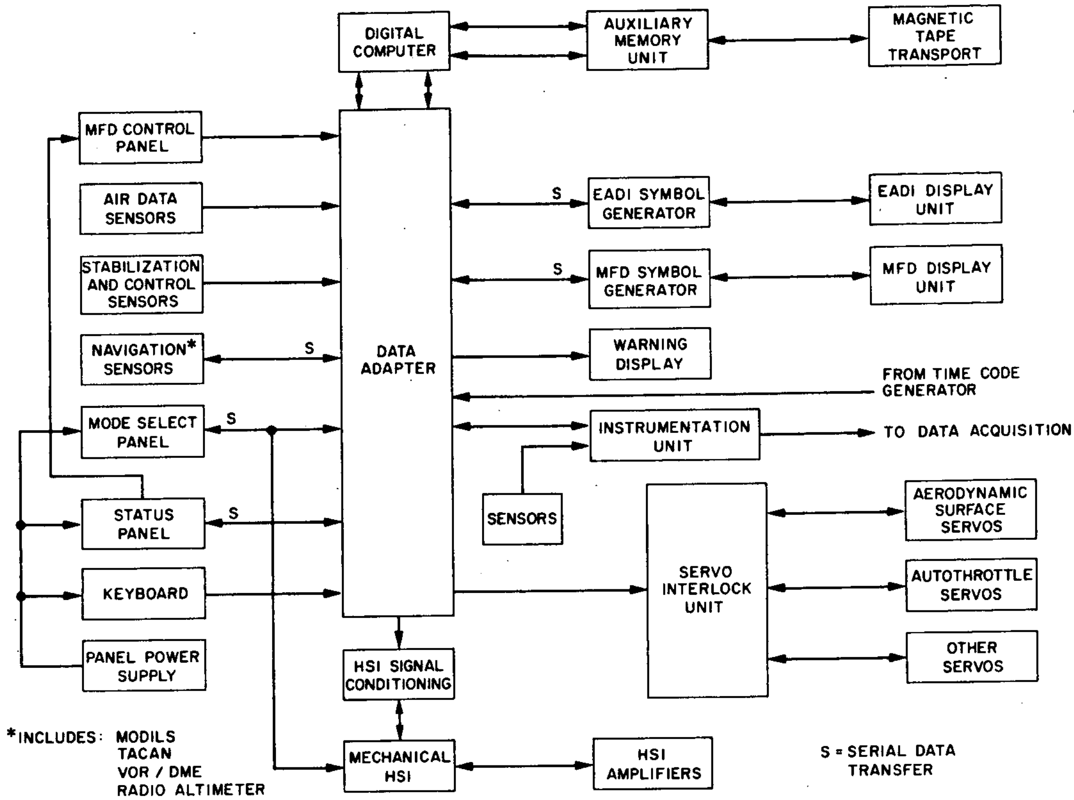


Fig. 4. STOLAND block diagram.

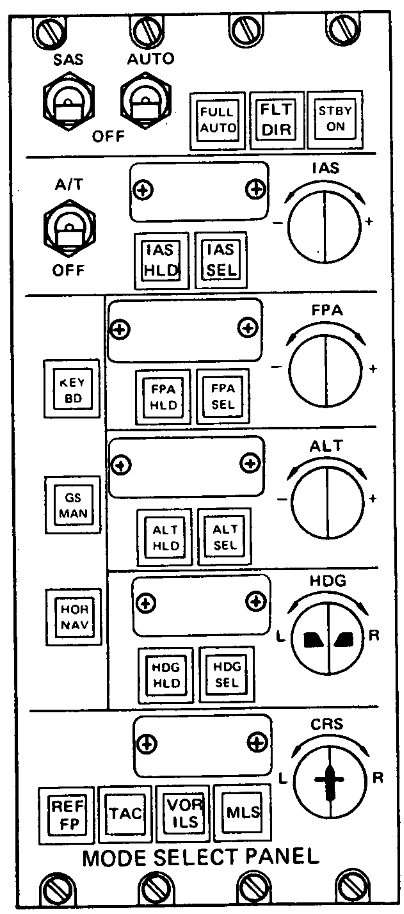


Fig. 5. STOLAND mode select panel layout.

5359 12

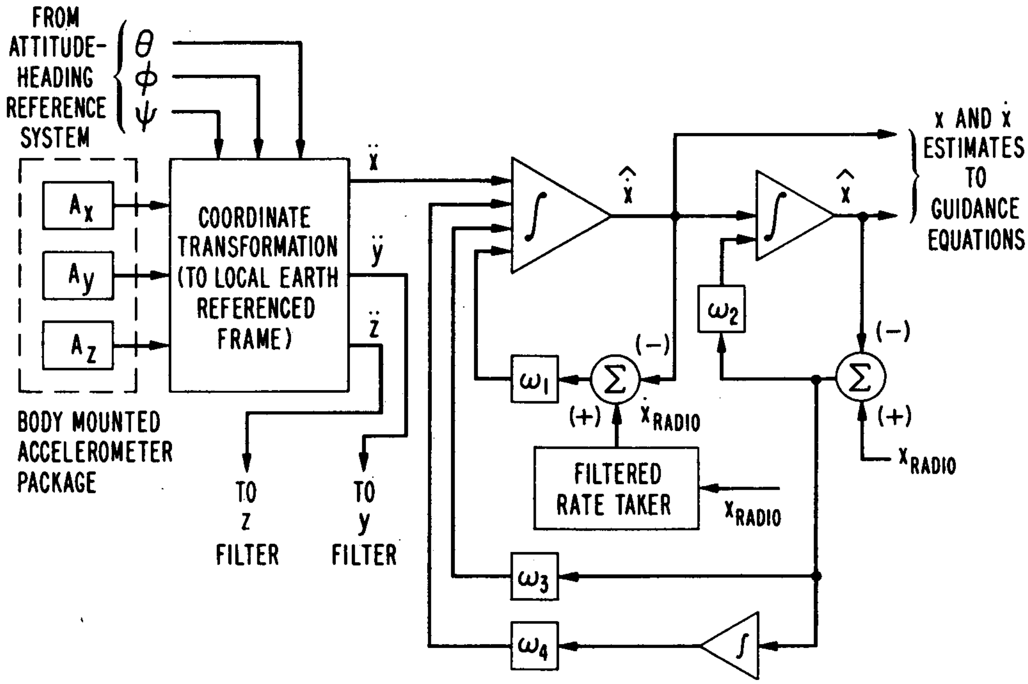
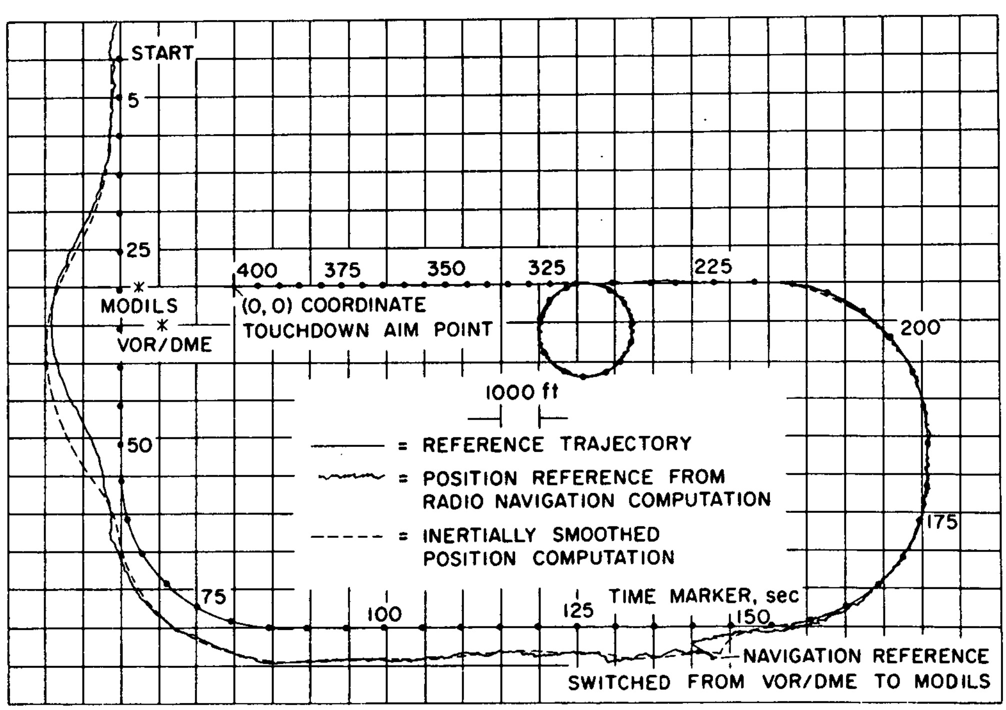


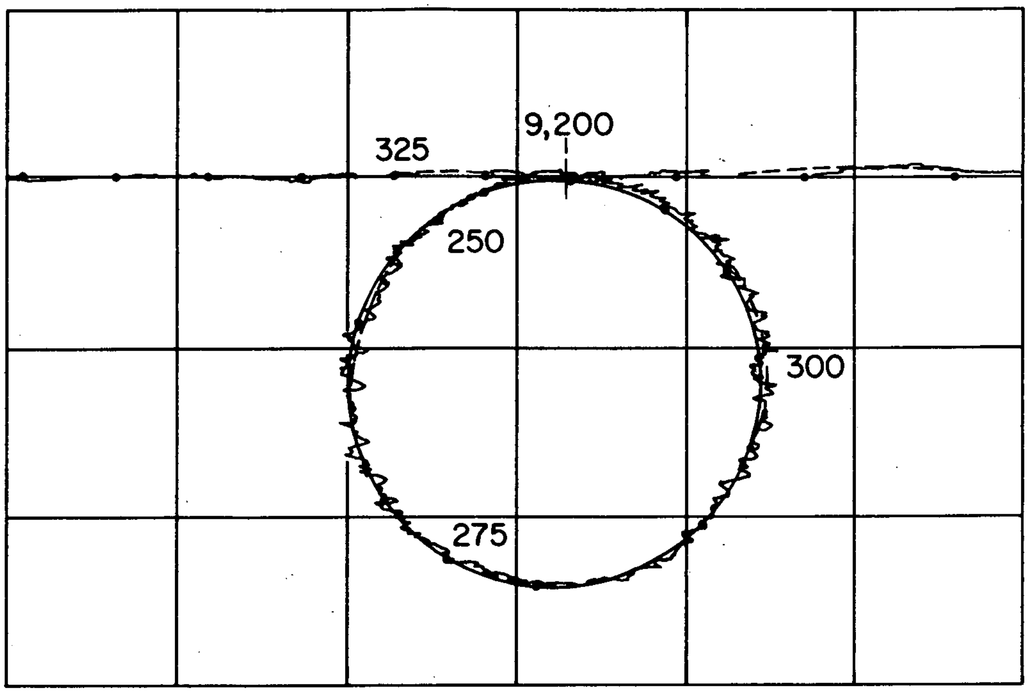
Fig. 6. STOLAND navigation complementary filter.



(a) Complete test trajectory.

Fig. 7. Results of simulation of navigation complementary filter.

5359 13



(b) Detail of test trajectory.

Fig. 7. Concluded.

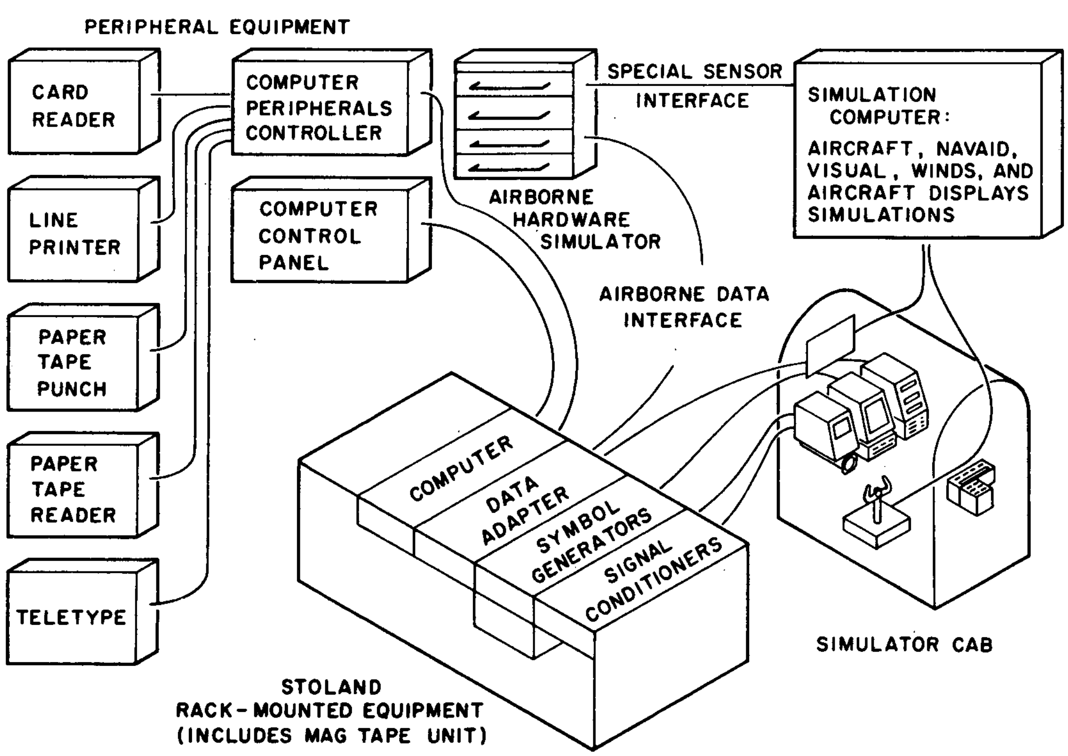


Fig. 8. Schematic of simulator STOLAND validation facility.

5359 24