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Summary

This report (published as a NASA Technical Memorandum and a DRA Working Paper) summarizes activities that have taken place from 1979 to the present in a collaborative program between NASA Ames Research Center and the Royal Aerospace Establishment (now Defence Research Agency), Bedford on flight control system and cockpit display tradeoffs for low-speed and hover operations of future V/STOL aircraft. This program was created as Task 8A of the Joint Aeronautical Program between NASA in the United States and the Ministry of Defence (Procurement Executive) in the United Kingdom. The program was initiated based on a recognition by both parties of the strengths of the efforts of their counterparts and a desire to participate jointly in future simulation and flight experiments. In the ensuing years, teams of NASA and RAE engineers and pilots have participated in each other's simulation experiments to evaluate control and display concepts and define design requirements for research aircraft. Both organizations possess Harrier airframes that have undergone extensive modification to provide in-flight research capabilities in the subject areas. Both NASA and RAE have profited by exchanges of control/display concepts, design criteria, fabrication techniques, software development and validation, installation details, and ground and flight clearance techniques for their respective aircraft. This collaboration has permitted the two organizations to achieve jointly substantially more during the period than if they had worked independently. The two organizations are now entering the phase of flight research for the collaborative program as currently defined.

Nomenclature

AFS	Advanced Flight Simulator (RAE)
AMSU	air motor servo unit
ASTOVL	Advanced Short Takeoff Vertical Landing
BAe	British Aerospace
DRA	Defence Research Agency (UK)
FCC	flight control computer
FCS	flight control system
FSAA	Flight Simulator for Advanced Aircraft (NASA)
HUD	head-up display
IFPCS	integrated flight and propulsion control system
IMC	instrument meteorological condition
MOD	Ministry of Defence (UK)
MOU	memorandum of understanding
RAE	Royal Aerospace Establishment
SAS	stability augmentation system
SI	Smiths Industries
STOVL	short takeoff vertical landing
VAAC	vectored thrust aircraft advanced flight control
VIFF	vectoring in forward flight
VMS	Vertical Motion Simulator (NASA)
VSRA	V/STOL research aircraft
V/STOL	vertical/short takeoff and landing

Background

For the past twelve years, the authors have been the technical representatives for the United States and United Kingdom on a collaborative research program on control system and cockpit display tradeoffs for V/STOL aircraft. Over this period, a great deal of interaction has taken place between their two laboratories at NASA Ames Research Center and the Royal Aerospace Establishment, Bedford (In April 1991, this became DRA, Bedford but, for ease of reading, the present document uses the original RAE title throughout). This report has been prepared for the sake of summarizing this work and providing an understanding of the interaction between the two organizations in the field of V/STOL control and display research. To begin, it is worthwhile to assess where each laboratory stood at the beginning of the joint endeavor.

In the mid-1970s, NASA, in support of the US Navy, began a research program to investigate the potential of advanced control technology to improve the operational capability of V/STOL aircraft aboard small, aviation-capable ships in adverse weather. The objectives were to develop pilot control mode and cockpit display concepts, define their design criteria, and evaluate their acceptability in ground-based simulation and research aircraft. A range of control and display concepts was envisioned, based on earlier NASA and industry research centered on civil V/STOL transport applications, as well as investigations carried out for the Navy at the Cornell Aeronautical Laboratory. This earlier research had explored rate, attitude and velocity command controls, head-up and head-down displays consisting of raw data situation information and flight director commands. Prior to that time, NASA Ames had a history of V/STOL flight investigation centered on the X-14A and B models and the XV-5B at Ames, along with evaluations carried out on the XV-5A, P1127 and Kestrel, X-22A, CL-84, and DO-31 as participants in those programs. This flight work, along with data obtained from other V/STOL flight programs, culminated in AGARD Report R-577-70, drafted at Ames, that defined design criteria for control power and control response characteristics for V/STOL aircraft during hover and transition flight, as well as several other reports detailing design and operating criteria. The later civil V/STOL transport control display concept development and simulation investigations were described in detail in NASA TP-1040 by V. K. Merrick.

Throughout the 1960s and '70s, the research staff at NASA had been aware of V/STOL research and development activities in the UK, and in the earlier days had collaborated with counterparts in the UK aiding in the development of the prototype for the Harrier, the Hawker-Siddeley P1127. In particular, personnel from Hawker-Siddeley visited Ames to review the status of V/STOL technology and to participate in simulations and flight evaluations of the X-14 in preparation for the first flight of the P1127. In the mid-1970s, engineers and pilots from NASA Langley joined with the RAE in exploring the use of in-flight thrust vectoring (VIFF) to enhance the maneuvering capability of the Harrier. When apprised of RAE's work for the Royal Navy on control and display enhancements for night and low-visibility semi-jet-borne transitions to hover and vertical landing aboard ship for the Sea Harrier, interest was rekindled for collaboration in control and display research, and led to the establishment of the task statement which is the subject of this report.

In the UK, RAE Bedford had been active in the jet V/STOL field since the mid-1950s. Analytical studies and piloted simulator trials supported flight research with Jet Deflection Meteor, Rolls-Royce Flying Bedstead, Short SC1, P1127, Kestrel, and Harrier aircraft. Kestrels of the Tripartite Evaluation Squadron operated from the "Hole in the Woods" at Bedford.

This work contributed to development of the Harrier/AV-8A stability augmentation system (SAS). RAE Bedford provided the launch performance charts used by US Marines and Royal Air Force for ship operations through the 1970s. Following this, the first experimental ski-jump was built at Bedford and joint British Aerospace/RAE flight trials led to its adoption by the Royal Navy. Bedford also led the 1975-76 combat, ground-attack, and documentation flight trials of the US/UK Phase II Harrier VIFF program.

Over the 1975-78 period, RAE Bedford developed the system for the Sea Harrier night and low-visibility recovery to Hermes and Invincible class ships. This work built on piloted simulator trials through airfield flight trials to full demonstrations aboard Hermes and centered on the two-seat research Harrier, XW175, with its programmable HUD and other experimental systems. It defined flight procedures, HUD format, the MADGE microwave guidance system requirements, audio angle-of-attack, "speed-trim" nozzle series actuation, ship lighting and deck marking, and Landing Signal Officer's HUD and data-link, to make the most effective use of the Sea Harrier aircraft with its existing flight control system (FCS) for the specific recovery task. This work was reported by the Bedford staff in AGARD CP-258.

This work was followed by simulator and flight trials with Harrier XW175 to develop and demonstrate (1) the RAE Fast-jet HUD format (now being introduced into all Royal Air Force aircraft), (2) the Harrier hover-margin indicator (incorporated into the Sea Harrier HUD), (3) pitch and roll-rate command with attitude-hold using a digital computer to drive the existing SAS and trim actuators, (4) automatic speed control in deceleration to the hover, by coupling the Sea Harrier's "speed-trim" nozzle series actuator to its MADGE microwave guidance system. Items 3 and 4 were proposed for the Sea Harrier mid-life update, but were not incorporated.

Against this long background of development of the operational use of existing Harrier aircraft for specific tasks, it was clear to RAE Bedford that fundamental control and display questions were raised for the effective use of future STOVL aircraft, particularly the layouts and propulsion concepts being considered for advanced STOVL (ASTOVL) designs. An internal RAE paper was issued in August 1978 proposing what later became the VAAC research program into this topic. RAE could also see that NASA Ames' background of control and display simulator studies for future STOVL aircraft represented an important area which could complement RAE Bedford's experience in the operation of existing Harrier aircraft.

The final review meeting of the US/UK Phase II Harrier VIFF program was held at NASA Langley in October 1978. At this meeting RAE and NASA management agreed that they should seek to build on this highly successful joint program by collaborating on V/STOL control and display research aimed at future generation V/STOL aircraft. The authors met at NASA Ames in February 1979 to make initial contact at a working level. This visit showed that NASA and RAE had major common interests in simulator and flight-based control and display research for future V/STOL aircraft. It also highlighted the fact that the two establishments' V/STOL experience at that time covered substantially different aspects which were largely complementary, so that collaborative research could build on a broad base to mutual benefit.

Formal Terms of Reference

In April 1980, the authors along with J. W. Britton of RAE Bedford met at NASA Ames and drafted terms of reference for formal collaboration under the NASA/MOD Joint Aeronautical Program. These terms of reference (listed in Appendix A) were formally approved in June 1980 as Task 8A of the Joint Aeronautical Program.

When details of the US/UK Memorandum of Understanding (MOU) on ASTOVL technology were being settled in 1986 the Joint Aeronautical Program management agreed that revised terms of reference were required for Task 8A, to clarify areas of collaboration and distinguish these from related ASTOVL MOU topics. The authors drafted revised terms of reference in September 1986 and these were formally approved in June 1988 (Appendix A).

Task 8A covers the exchange of information on V/STOL research aircraft (VSRA and Harrier XW175) equipment, modifications, clearance, and operations. It also covers the exchange of pilot/engineer teams to participate in collaborative simulator and flight trials for the investigation of controls and displays generally applicable to V/STOL aircraft. These topics are outside those covered by the ASTOVL MOU.

Program Description

Overview of the NASA and RAE Programs

NASA's research in V/STOL flight dynamics was supported as part of the Agency's Research and Technology Base Program and included investigations of control augmentation systems and displays for operation in the terminal area and aboard ship in adverse weather. A timeline of the program is shown in figure 1 to provide an overview of this work. From the late 1970s through the mid-1980s, analytical studies were performed to define control and display concepts, and moving-base simulation experiments were carried out to permit pilots to evaluate the new concepts as applied to V/STOL aircraft configurations of interest. To substantiate these ground-based results, it was considered essential to develop the capability to carry these concepts into flight using a modern V/STOL aircraft. Accordingly, in the early '80s, approval was sought to acquire one of the YAV-8B Harrier prototypes and modify it to achieve an appropriate research capability. With this approval secured and the aircraft loaned to NASA by the US Navy and Marines, attention turned to the design and modification of the aircraft, which would be known as the V/STOL Research Aircraft (VSRA). The program has progressed to the point of installation of the final control system features that will enable high levels of control augmentation and displays to be evaluated in flight.

When the original objectives of Task 8A were agreed, it was clear that in general future STOVL aircraft, particularly advanced STOVL designs, might not have the Harrier's benign longitudinal characteristics in the V/STOL regime. They might have discontinuities in thrust magnitude and direction which limit the combinations which are available. They might have potentially large thrust pitching moments which impose control power limitations on the performance envelope. They might also have the benefit of thrust center control. Hence they must rely on an integrated flight and propulsion control system (IFPCS) for safe and effective operation.

The VAAC program at RAE had been launched against this background, to study at RAE and in the UK industry the integration of control laws, displays, and inceptors to provide maximum operational effectiveness with particular emphasis on the V/STOL regime. This is being achieved through off-line studies, ground-based piloted simulator trials focussing on the RAE Bedford Advanced Flight Simulator (AFS), and flight trials in the RAE two-seat research Harrier, XW175. Flight trials are an essential component of this program; they serve to validate the simulation and ensure that all aspects have been considered. They are also crucial in demonstrations to the customer, since a new aircraft must be able to fly safely through its IFPCS on day one.

The VAAC program includes study of a broad spectrum of control concepts in the pitch plane. These range from the "traditional" Harrier concept of three inceptors (pitch, thrust magnitude, and thrust direction) at one extreme, to a two-inceptor unified control concept at the other, in which the inceptors control flightpath and longitudinal acceleration respectively throughout the flight envelope with no discontinuous mode changes. Initial piloted simulator studies concentrated on control of a Harrier model, and flight trials of the control concepts have now started in Harrier XW175.

Important milestones of the NASA and RAE program are noted on figures 1 and 2, including the events where interaction took place between them. The following narrative provides a description of each of these events and notes their significance to the overall program at both establishments.

Synopsis of Program Activities

Generalized V/STOL control and display research– At the first contact on the subject between the authors in February 1979, it was decided to capitalize on the relative strengths of the two organizations by engaging a NASA research pilot in simulation and flights on the RAE Harrier XW175, and an RAE engineer and pilot in a NASA simulation to explore control system design issues. In the first case, NASA would gain valuable experience in the operational utilization of the Harrier and a view of RAE's work on control systems and displays for the Sea Harrier; in the second instance, RAE would obtain data from NASA's motion simulator that would aid in the design of a research control system to be employed in their aircraft. Over a two week period in May 1979, a NASA pilot was involved in the simulation experiment and flight test at RAE Bedford evaluating rate and attitude control augmentation systems in the simulator and the use of RAE's HUD format for low visibility approaches to hover. The device used for these experiments was the Bedford No. 1 Simulator, which was a limited motion device with a single-window visual system employing a terrain model belt. According to the pilot's trip report, valuable experience was gained in the understanding of operational problems associated with shipboard recovery. Then, in August 1979, an RAE engineer and pilot joined the NASA team for a simulation conducted on Ames' six-degree-of-freedom simulator, shown in figure 3. This simulator features a translational motion envelope circumscribed by an 18-ft cube and is an open cockpit device. Thus, for hover flight, the pilot's motion and visual cues, when operating within the confines of the "cube," were as close to real world representation as could be achieved in a simulator. NASA performed this simulation to permit RAE to examine the effects of failures in control system servo drives that would be installed in the RAE research aircraft (Harrier XW175) and to explore the design of safety monitors for the control system. Various combinations of failure conditions were examined and failure monitors tested, with the result that RAE and NASA were assured that a satisfactory design could be achieved for a full authority, high response rate control system that would provide a generous research flight envelope without compromising flight safety. NASA took this information to complete a research system design package for a two-seat research aircraft and later used it to advantage in designing the control system that would eventually be installed in the NASA single-seat VSRA. RAE reported results to NASA in reference 1.

The next phase of activities concerned the development of transition and hover control concepts as applied to fighter aircraft and centered on simulations at Ames on the Flight Simulator for Advanced Aircraft (FSAA) in November 1979 and November 1980. This facility is also shown in figure 3 and is a large motion simulator with a closed cockpit that employed a single-window visual scene of a terrain model board presented on a television monitor. Representation of full mission operations could be achieved, in contrast to the "cube," which excelled in the hover. This simulation was Ames' opportunity to define and examine competing control modes for use in performing decelerating transitions to hover in instrument conditions, and of executing precision vertical landings on the airfield and aboard ship. Attitude and translational velocity command systems were developed through analytical studies on the computer and prepared for initial examination on the FSAA in 1979. RAE sent their engineer/pilot team to Ames, to gain familiarization with the NASA control designs and to join in the experiment. The simulation was generally considered a success; however, deficiencies were identified with the attitude control mode and the flight director displays. Data were exchanged between NASA and RAE in references 2 through 4.

This visit provided RAE with a valuable introduction to the capabilities of advanced control laws in the V/STOL regime. At that time, the NASA thrust management control system was engaged at a point where thrust was substantially deflected from the horizontal. The advanced law was then flown in a different way from conventional flight and required inceptors in addition to those of the stick, throttle, and thrust deflection. A further discontinuous mode change, and change in inceptors, was required to reach the final stage of maneuvering in the hover. This simulation stimulated RAE to consider an alternative "Unified Control" concept in which the same single right- and left-hand inceptors are used throughout the flight envelope without any discrete mode changes. This leads to hover control in which right hand controls height and the left hand controls fore and aft motion, i.e., a different arrangement from Harriers or helicopters. RAE placed a contract with Smiths Industries (SI) to develop this concept from initial block diagrams to what has become VAAC Law 001.

NASA worked over the next year making improvements in the control system and mounted a second effort on the FSAA the following autumn. The same RAE team, accompanied by a control law specialist, took part in this experiment. This time, objectives were to evaluate the improved control and flight director laws, and, in addition, to determine the influence of these system designs on control usage, thrust margins, and control inceptor arrangements. An indication of the inceptor configurations that were examined is provided in figure 4. Fully satisfactory flying qualities were achieved with the control modes and flight directors, though the pilots expressed interest in having a head-up display (HUD) that provided a better integration of command and situation information. The latter concern led to the next phase of experimentation. Data were exchanged in references 5 and 6.

The participation in the November 1980 simulator study at Ames permitted the RAE pilot to assess, among other things, various inceptor aspects of the Unified Control concept, well before its first piloted simulation in the UK. From the array of inceptors evaluated, new approaches to cockpit control arrangements were identified and led to experimental configurations that were to be adopted by RAE for investigation in their simulator and flight programs.

These simulations were followed by a visit of a NASA pilot to RAE in June of 1982 for the purpose of demonstrating to NASA the RAE work on HUD and controls for Sea Harrier. Flights were conducted in Harrier XW175 to examine the Sea Harrier system during decelerating approaches to hover. The experience in the actual aircraft was important to NASA in assessing similar systems in the NASA simulators.

The next series of experiments were planned and carried out at Ames through 1982 to 1984, and focussed on HUD formats and drive laws as suggested by the pilots' evaluations from the 1980 FSAA experiment. Based on experience with flightpath-centered, pursuit-tracking displays that had been investigated for application to conventional and STOL aircraft, displays were designed and evaluated initially by the Ames researchers in an experiment on the then new Vertical Motion Simulator (VMS) in 1982. This device, shown in figure 3, has the largest translational motion envelope of any known simulator in existence (usable vertical and longitudinal travel are 60 and 40 ft respectively). This is combined with a wide-angle computer-generated visual scene that provides an array of environments from airfields to decks of small and large aviation ships. In October 1983 RAE sent a new team of engineers and a pilot, experienced in display assessment, to work with their NASA counterparts on the VMS.

Following that experiment, the NASA project pilot and an engineer returned to RAE in October 1983 to perform more extensive evaluations of the RAE HUD and an attitude hold control mode, and to compare the RAE and NASA decelerating approach guidance. The pilot was able to evaluate attitude controls and displays in-flight that were comparable to those assessed on Ames' simulators, thus obtaining an early comparison between simulation and flight of one control/display combination for decelerating approach. He was also able to contrast the two decelerating approach guidance schemes and found they produced similar performance and pilot ratings.

In figure 5, a comparison of the latest NASA HUD format is shown in contrast to the earlier version that included flight director commands. Different displays are used for transition and hover that emphasized the specific requirements of those tasks. Results of the evaluation were particularly encouraging and NASA chose to pursue this approach in HUD designs applied to VSRA. Data were exchanged with RAE in reference 7. The HUD concept was documented and transmitted to RAE in reference 8.

Final developments of the NASA HUD were completed for the research aircraft application in the late 1980s, and a final VMS simulation was performed in May 1990. An RAE engineer came to Ames for this experiment. Data were also provided to RAE on applications of this HUD to civil V/STOL operations in the form of an informal report authored by Richard S. Bray and in a video tape explaining its use in IMC terminal area operations.

Meanwhile, in the UK under the VAAC program, a broad range of V/STOL control concepts had been developed by RAE, and UK industry and universities. The more promising were assessed on the Bedford Advanced Flight Simulator (AFS). For consistency, similar HUD formats, closely following the RAE design incorporated in the Sea Harrier, have so far been adopted for all piloted assessments. The wing-borne HUD format has the pitch ladder referenced to the climb/dive angle symbol, changing to an attitude symbol reference for V/STOL flight (fig. 6), both with fixed peripheral scales. In the V/STOL regime, climb/dive angle is displayed, becoming height rate at low groundspeed.

The AFS complex (fig. 7) offers two motion platforms, including the 5-axis Large Motion System which can generate large displacements, velocities, and accelerations to provide the high fidelity motion cues necessary for handling qualities assessments, and the choice of a wide-field-of-view computer-generated visual scene or a model-based scene. This simulator has been used for VAAC flight control studies and also for failure studies to guide the pre-flight selection of certain monitor characteristics for the VAAC Harrier.

In August 1990, a NASA engineer and pilot went to RAE for the first NASA evaluation on the simulator of two VAAC control laws, inceptors, and HUD (ref. 9). The first of these control laws is now being assessed in flight on the VAAC Harrier, and two other laws are being prepared for flight in 1992.

Additional information on the NASA and UK control and display concepts being prepared for flight evaluation is provided in references 10 through 12. To summarize, the concepts which have been investigated successfully by NASA and under the VAAC program over the duration of the present collaboration may be categorized as follows:

Longitudinal Control

- Three inceptors commanding pitch attitude, thrust magnitude, and thrust direction in all flight regimes, in a manner similar to the current generation Harrier (a baseline configuration against which to judge the merits of the other candidates)—NASA and RAE/BAe.
- Three inceptors in the transition regime, commanding pitch attitude, flightpath or vertical velocity, and longitudinal acceleration or velocity, and pitch attitude changes if these are required to achieve the necessary performance—NASA and BAe.

  The UK and US approaches to this control concept are substantially different, but complementary. For the UK scheme, as the decelerating transition is entered, the control mode is blended to right-hand stick control of flightpath and left-hand lever control of longitudinal acceleration, supplemented by thumb control on the stick for any pitch changes. This mode leads to an "unconventional" hover with right hand controlling height and left hand controlling longitudinal velocity. The US approach uses a mode blend to left-hand lever control of flightpath and left-hand thumbwheel control of longitudinal acceleration with right-hand stick control of pitch attitude. On reaching hover, the control mode is switched to left-hand lever control of height and right-hand stick control of longitudinal velocity, which is a more "conventional" hover control. Both the UK and US approaches require a special mode for ski jump launch.

- Two inceptors in all flight regimes. A single mode is used for wing-borne, transition, and hover flight. Right-hand stick controls normal acceleration or vertical velocity and left-hand lever controls longitudinal acceleration or velocity throughout. Pitch attitude responds as necessary to achieve commands. This concept leads to "unconventional" control in the hover—RAE/SI.

  Control with these three concepts changes in significantly different ways when it is necessary to impose limitations to prevent pitch departures which can occur with some V/STOL layouts. Both NASA and RAE are addressing this question.

Lateral-Directional Control

- Both NASA and RAE are using conventional stick and pedal inceptors to provide roll rate command with bank angle hold during transition and hover, and sideslip command in transition, blending to yaw rate command in hover.
- NASA is, in addition, providing the option of bank angle command or lateral velocity command in the hover.

Displays

- NASA is concentrating on flightpath pursuit display HUD formats for transition, with guidance information centered on the flightpath symbol, switching to a mixed vertical and plan view velocity vector centered display in the hover.
- RAE is currently utilizing a Sea Harrier based, attitude-referenced HUD format with decelerating transition guidance on the peripheral scales. At this time no hover guidance is provided.

V/STOL research aircraft development–

VAAC aircraft: The VAAC aircraft program is illustrated in figure 2. In March 1979, immediately after their first discussions with Ames, RAE placed a contract with British Aerospace (BAe) Kingston Division for a preliminary design study into potential Harrier XW175 modifications. The contract also covered control law design studies and RAE launched their own control law studies at Bedford and Farnborough at the same time. The creation of a wide-envelope model (the Bedford Harrier WEM) to represent XW175 throughout its flight envelope was also launched, to replace various piecemeal models which existed at that time. By July 1979, the VAAC program objectives had been agreed by MOD and BAe. In April 1981, cost estimates from the first stage of the BAe preliminary design study led RAE to reduce its roll/yaw actuator requirement from full authority to use of the limited authority SAS series servos. This change reflected the judgment at that time that the prime new problems in control of future generation V/STOL aircraft would be predominantly in the pitch plane.

The BAe preliminary design study was completed in April 1982. It showed that the VAAC requirement for a rear-cockpit FCS incorporating full-authority, high-rate pitch, throttle, and nozzle actuators, plus flap control, could be incorporated within space, weight, and funding constraints. Supported by BAe, RAE sought formal approval for expenditure on the full VAAC program. Approval was granted in December 1982. In January 1983, a contract was placed with the College of Aeronautics, Cranfield (with BAe participation) to incorporate the VAAC installation in XW175, update it to broadly reflect the Harrier model T4 standard and undertake a weight-saving exercise. Shortly afterward, contracts were placed with Smiths Industries to supply the VAAC FCC based on their Flight Management System computer in the A310 Airbus, and a new HUD system for XW175 and the RAE Bedford Advanced Flight Simulator (AFS). Further control law studies were also launched in industry.

Harrier XW175 was flown to Cranfield at Christmas 1983 for the start of its VAAC conversion. In September 1986, the aircraft, shown in figure 8, returned to Bedford at the end of the Cranfield modification program. The full VAAC system had been fitted and ground tested, and the aircraft cleared for flight from the front (safety pilot) cockpit. RAE started flight tests to set up the new high data rate telemetry, plus ground and flight tests to set up and clear the VAAC system in flight with the FCS disengaged. The VAAC aircraft made its first flight with the FCS engaged in May 1990. The "Digital Harrier" control law (software representing the control system of a production Harrier with SAS off) was used. This was the start of a flight test program with the following objectives: (1) to exercise the full VAAC FCS, (2) to determine sensor noise characteristics in flight, (3) to set up and exercise monitors, (4) to train and establish safety pilot capability, (5) to take structural mode measurements, and (6) to measure nozzle drive characteristics under flight load conditions at hover and 120 knots (the latter two objectives with additional FCC software). This work has been completed and led, among other things, to the completion by Stirling Dynamics, Ltd, Bristol of a mathematical model representing the aircraft's nozzle control system. By June 1991, the VAAC FCS and monitors had been exercised and cleared in flight from 250 knots to hover at 75 ft. This clearance was immediately followed by the successful first flights of the baseline control law (VAAC Law 002). Flight trials with this control law are continuing. They will be followed by experiments with the advanced three and two inceptor laws.

There is now a changing emphasis towards next-generation STOVL aircraft which are less advanced than the full ASTOVL designs previously considered. Such an aircraft may well be a Harrier development, with similar lateral/directional stability and control constraints in the V/STOL regime. Studies have therefore been launched into providing Harrier XW175 with full authority VAAC FCC roll and yaw control. In the UK, the Royal Navy is also moving away from its previous requirement for recovery in zero/zero weather conditions. In October 1991, Cranfield provided the first draft of a preliminary design study of a full-authority, high-rate VAAC roll/yaw actuation system for the aircraft.

VSRA: At Ames in the mid 1980s, attention turned from development of control and display concepts through analytical studies and simulation experiments, to implementation of these concepts for flight evaluation on the NASA research aircraft VSRA. In the late 1970s, NASA had inquired about availability of operational V/STOL aircraft on which to pursue the validation of its ground-based technology. At that time, as at the present, the only aircraft for consideration was the Harrier. In the US, two seat trainers (TAV-8As or TAV-8Bs) were not available at that time; however, the prototypes for the AV-8B (YAV-8B) were candidates for further technology exploration beyond their use for development by the Navy. Discussions were held between NASA and the Naval Air Systems Command (NAVAIR) that culminated in a commitment by the Harrier program office in NAVAIR in January 1980 to loan a YAV-8B to NASA at the completion of AV-8B development on that aircraft in 1984. The aircraft was delivered to NASA in April 1984 (fig. 9). While awaiting resources to develop the aircraft for control and display research, experiments were performed to measure pressure distributions at different spanwise stations on the wing at transonic speeds, to document the use of compressor bleed air for reaction control during transition and hover, to document the aircraft's aerodynamic characteristics in semi-jet-borne flight, and to compare its hot gas flow characteristics with predictions made using computational methods.

In 1986, funding became available from NASA and through the government's international program fund source (administered by the Defense Advanced Research Projects Agency) that permitted NASA to embark on the aircraft's modification. Preliminary design of the research system had been accomplished by that time by NASA, and detailed design and procurement of component parts of the system, shown in figure 10, were initiated. NASA Ames functioned as the system integrator and performed overall system fabrication and installation as well. System and application software design got underway at the same time. Critical simulations on the VMS took place in 1986 to establish safety monitor designs and a safe operational envelope. Data on these exercises were transmitted to RAE in reference 13.

The first phase of the system installation was completed in mid-1990 and the aircraft was flown initially without control servo actuators in November 1990. Checkout of flight computers, system sensors, HUD, and display and guidance software was completed in December 1991. An instrument approach guidance experiment was performed during the summer and autumn of 1991 to establish performance for that part of the system and to demonstrate near-term applications of approach guidance for the AV-8B. The aircraft entered the final phase of system installation in December 1991, to add the throttle and nozzle servo actuators and qualify them for flight. Flight experiments are anticipated to resume in late 1992, with the full research control and display system operational.

Areas of common concern: Over the course of development of the VSRA and VAAC aircraft research systems, several meetings were held between NASA and RAE staff to exchange information on system design and qualification. The authors met annually, or more frequently, from 1984 through 1990 to discuss and review data on servo performance and installation, software development and validation, structural mode interactions, safety monitoring schemes, clearance methods, and control and display law details. In April 1986, an RAE team came to Ames Moffett and Dryden facilities to carry on detailed discussions on software design and validation and system safety monitoring. In August 1988, a team of Ames designers went to RAE to review servo installation and software design with the Bedford staff and the VAAC modification at Cranfield. Details of NASA's software structure were provided to RAE and VAAC servo design drawings were made available to NASA. Finally, the RAE author of this report came to Ames to convey data on nozzle servo system performance as well as to participate in drafting this document. Nozzle drive performance had been a subject of particular interest over the course of the development, due to hysteresis in the nozzle drive mechanisms and sensitivity of aircraft response to irregular nozzle control. Both NASA and RAE exchanged analyses, including results of work contracted by RAE and reported in references 14 through 18. Satisfactory modeling of the nozzle drive system has now been achieved.

The NASA and RAE research systems in the two aircraft, as well as the aircraft themselves, have major differences; however, there have been many areas of common concern, e.g.:

- Weight growth must be minimized to achieve desired performance for a V/STOL research aircraft.
- Access and space for research equipment are severely limited in a Harrier.
- Precise control of thrust direction is crucial for closed-loop control in the hover—both aircraft have the same standard nozzle air motor servo unit (AMSU) which has relatively poor dynamics for this purpose.
- Harrier structural vibration is high with deflected jets, thus presenting problems in siting and using inertial sensors.
- The programs rely on effective but flexible software management.
- The experimental FCS and its monitoring must be easy to clear and flexible in use.

These and related areas of concern have provided the basis for fruitful collaboration. Highlights have been:

- Engineering design of experimental throttle and nozzle servo installations
- Measurement and modeling of nozzle drive characteristics plus studies of a possible AMSU replacement
- Structural modes and their potential effect on closed-loop control laws
- Structural noise and its effect on inertial sensors for guidance and control laws
- Guidance systems
- Software structure and management
- FCS architecture and monitor philosophies
- Clearance procedures

In the following section, the two research aircraft systems are described in sufficient detail to give the reader an appreciation of their respective capabilities.

Research Aircraft

VAAC

RAE Bedford operated two-seat Harrier XW175 over the 1976-83 period as a near-RAF-T2 standard aircraft, fitted with an inertial navigation system with a moving-map display and with the following research equipment:

- Programmable HUD in both cockpits
- Rear-cockpit blind, for IF trials
- MADGE microwave guidance system
- Radio altimeter
- Audio angle of attack
- "Speed-trim" series servo in nozzle control system
- Front pitch reaction control series actuator
- "Digital autopilot" driving SAS and trim actuators, also driving speed-trim actuator
- Forward looking infra-red and night-vision goggles
- Low data-rate telemetry
- Pilot heart-rate recording

When conversion for the VAAC program had been completed by Cranfield in 1986, XW175 was a near-RAF-T4 standard aircraft, without the inertial navigation system or moving-map. An overall layout of the longitudinal control system is shown in figure 11. The complete system includes the following research equipment:

Rear cockpit (Research Pilot)

- Stick disconnected in pitch—damping,variable feel, and electrical pickoffs added
- Throttle, nozzle, flap levers disconnected, electrical pickoffs added
- Stick (roll) and pedals retain production linkage to control runs
- Dual-combiner version of Sea Harrier HUD
- Blind for IF trials
- Controls and head-down displays for VAAC system management
- VAAC FCS disengagement by switch

Sensors—some 120 including

- Radio altimeter
- MADGE
- Duplicated airspeed
- Duplicated strapdown accelerometers
- Duplicated rate gyros
- Duplicated angle of attack and sideslip vanes

Flight control computer

- 4 processor-pairs for control-laws
- 2 processor-pairs for Independent Monitor
- Servo-model processor
- I/O interfaces
- 2-way communication with Display Computer
- Drives to VAAC FCS servos

VAAC FCS servos

- Full-authority high-rate (approx. 1 sec stop-to-stop) VAAC pitch, throttle, nozzle servos
- Front-pitch reaction control limited-authority series actuator
- Production flap actuator
- Production limited-authority SAS roll servo
- Production limited-authority SAS yaw servo
- Rear-cockpit pitch stick variable-feel unit

Front cockpit (Safety Pilot)

- Stick, throttle, nozzle back-driven by VAAC servos
- Stick (roll) and pedals driven by rear cockpit controls
- HUD driven by VAAC Display Computer
- Displays for VAAC system monitoring
- VAAC FCS disengagement by switches or force on stick, throttle or nozzle levers

Display computer

- Separate display formats in front and rear cockpits
- I/O interfaces
- 2-way communication with FCC

Telemetry system

- High date-rate, 250 k bits/sec
- All aspects coverage of aircraft
- On-board analog recording for structural-mode measurements
- Inputs from sensors, FCC and Display Computer

VAAC FCS monitor

- Pitch servo has dual valves/servo amps
- Other servos monitored by math models
- Prime sensors are duplex, cross monitored
- Other sensors have reasonableness checks
- Front and rear cockpit HUDs virtually independent with separate sensors
- Maximum benefit from Safety Pilot flying with back-driven inceptors
- Safety pilot assisted by Independent Monitor (envelope monitor independent of control laws for maximum research flexibility)

Ground-based simulator

The RAE Bedford AFS cockpit used for VAAC trials has:

- Representation of XW175 rear cockpit control and display equipment
- HUD driven by hardware and software effectively identical to XW175

- Left-hand inceptors can be back-driven by servos identical to XW175

The aircraft is currently being flown through the VAAC FCS over an envelope from hover at 75 ft to 250 knots airspeed. The system and its monitoring philosophy have been designed for clearance up to higher speeds, should this be necessary later.

Future plans for XW175 include:

- MADGE removed
- Proposal to fit GPS and Inertial Reference System
- Studying possible full-authority high-rate VAAC roll and yaw servos
- Studying possible right-side-mounted mini-stick
- Studying means of clearing VAAC FCS to higher speeds

VSRA

Objectives of the VSRA flight research program are to demonstrate an integrated flight/propulsion control system concept, to substantiate generalized control and display design criteria derived from experiments conducted previously on flight simulators, and to perform key aerodynamic and reaction controls experiments to provide flight data to validate predictions of reaction control bleed requirements, computational fluids codes for jet-induced aerodynamics and hot gas ingestion, and provide measures of hot gas flow fields around the airframe in vertical flight.

The integrated flight/propulsion control and display system has capability to represent a variety of control and display modes for evaluation by the pilot in the transition and vertical flight phase. Rate, attitude, flightpath, and translational velocity command systems with their associated HUD guidance formats can be implemented. Drive laws for the controls and HUD are adjustable over a range sufficient to permit assessment of control and display law design criteria. An overall description of the system is provided in reference 11. An overall layout of the longitudinal system is shown in figure 12. The single-seat airframe dictated a fail-safe system design for control hardware and software. Manual backup controls were essential for the pilot as was dual, in-line monitored flight computers, critical sensors, and servo-actuators. For the throttle and nozzle controls, combined low-rate, full-authority parallel and high-rate, low-authority series actuators were selected.

The VSRA is derived from the YAV-8B Harrier prototype. It is composed of an AV-8A fuselage and empennage, and AV-8B composite wing, modified engine inlets, and a Rolls-Royce Pegasus F402-RR404 engine. Its research configuration consists of the following equipment:

<u>Cockpit</u>

- Modified center stick and throttle inceptors
- Conventional pedals and nozzle handle
- Thumbwheels on stick and throttle
- Thumb button on stick
- Dual combiner HUD
- Head-down display for system management
- System disengage switch on stick

<u>Sensors</u>

- Dual radio altitude
- Dual linear and angular accelerometers
- Dual ring-laser gyros
- Air data
- Microwave landing guidance
- Laser and radar tracker uplink

<u>Flight control computer</u>

- Dual processor pairs for control laws
- Dual model response processor
- I/O interfaces
- Communication to symbol generator
- Drives series/parallel servos

<u>Flight control servos</u>

- Production pitch, roll, yaw SAS series servos
- Pitch, roll trim servos
- Front reaction control actuator
- Throttle, nozzle high-rate, limited-authority series servos
- Throttle, nozzle low-rate, full-authority parallel servos

<u>Display computer</u>

- Programmable symbol generator
- Communication to flight control computer
- I/O interfaces

Telemetry system

- High data-rate
- Inputs from airframe/engine sensors, FCC and Display computer, HUD camera
- All aspect coverage

Flight control monitors

- Dual, in-line response monitors
- Comparison between dual computers
- Independent servo loop monitors
- Critical sensors and inceptors duplex cross-monitored

Development facility

- AV-8A cockpit
- HUD, HDD, inceptor hardware
- Aircraft simulation computer
- Flight control and display computers
- Airborne hardware simulator

Conclusions

A collaborative program between NASA Ames and RAE Bedford was initiated in 1979 and extended in 1988 for research on flight control system and cockpit display tradeoffs for V/STOL aircraft. This program has built on substantially different background experience of these two organizations. While NASA and RAE have employed somewhat different approaches, their aims have been broadly in common.

NASA, with its background in early V/STOL aircraft and detailed simulator studies, set out to develop the control and display concepts necessary to achieve the most demanding of V/STOL tasks, that of operation aboard small, aviation-capable ships. In particular, this effort focussed on flying an instrument approach, followed by vertical landing on a small platform in severe sea state and very low visibility. NASA's approach has been to optimize controls and displays for discrete phases of this operation, then draw them together to create a total integrated system.

RAE, with its background including simulator and flight trials to develop and demonstrate the Sea Harrier night and low-visibility recovery system, has sought to develop control concepts which regard the V/STOL regime as an extension of conventional flight. The concern has been with future aircraft having less benign V/STOL characteristics than the Harrier; the most demanding task has been operation to a larger ship than studied by NASA in rather less demanding visibility conditions.

These different but complementary approaches have provided the basis for a very active and productive collaboration. Throughout the program, a number of exchanges have taken place between engineers and pilots of the two laboratories to explore, through flight tests of the RAE Harrier research aircraft and simulator experiments, control and display concepts and their design criteria. Further, in the process of developing their Harrier aircraft for future flight research on controls and displays, NASA and RAE have exchanged information on fabrication techniques, software development and validation, installation details, and ground and flight clearance techniques for their respective aircraft. This collaboration has permitted the two organizations to achieve jointly substantially more during the period than if they had worked independently. Both are now entering the phase of flight research for the collaborative program as currently defined.

Changing emphasis is expected to lead to a new Task definition under the NASA/MOD Joint Aeronautical Program, to replace Task 8A which currently covers NASA/RAE collaboration on V/STOL control and display research.

This collaboration between RAE and NASA, over more than ten years, has had a symbiosis from which both have gained; it should therefore be maintained to provide a firm basis for the future.

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Appendix A:

Official Terms of Reference

V/STOL Control System/Cockpit Display Trade-Offs

An informal cooperative NASA/RAE program will be undertaken in the area of "V/STOL Control System/Cockpit Display Trade-Offs" requiring the use of in-flight and ground-based simulators. In this activity, RAE staff will participate in relevant Ames Research Center programs, such as ground-based simulations of Harrier and lift fan aircraft, and also the proposed flight program on the YAV-8B, if this is undertaken.

An Ames pilot/engineer team will participate in the continuing RAE V/STOL control and display research programs utilizing ground-based simulation and flight trials with Harrier XW-175.

Exchange of data will be limited to that directly associated with these pilot/engineer interchanges.

Technical representatives for this program will be Dr. J. A. Franklin of the NASA Ames Research Center and Mr. J. W. Britton of RAE Bedford.

Concurrence:

Walter B. Olstad (signature) Date: 6/9/80

Walter B. Olstad
Acting Associate Administrator for
Aeronautics and Space Technology
National Aeronautics and Space Administration

R J E Glenny (signature) Date: 12th May 1980

R. J. E. Glenny
Group Head/A
Royal Aircraft Establishment

TECHNICAL STATEMENT OF TASK

Task 8

V/STOL Control System / Cockpit Display Trade-offs

DESCRIPTION

The original Statement of Task is modified to incorporate specific objectives to be carried out during the next phase of the research program.

The informal cooperative NASA/RAE program to study the effective integration of control laws, displays, and inceptors for V/STOL aircraft will be continued. This program requires the use of the research aircraft and ground-based simulators of the participating organizations.

OBJECTIVES

Data exchange and participation in research programs concerning the following:

> Design and flight clearance of research systems for the Harrier XW-175 and the Vertical and Short Take Off and Landing Research Aircraft (VSRA).
>
> Ground based simulation and flight experiments with the Harrier XW-175 and VSRA aircraft concerning evaluations of attitude, flightpath, and velocity control modes, cockpit display modes, and control inceptors for V/STOL aircraft.

The collaboration is expected to continue through 1991. It will complement research contained within the framework of the US/UK Memorandum of Understanding on "ASTOVL Technology Program"

RESPONSIBILITIES

Specifically, NASA will use its best efforts, consistent with program priorities and funding, to:

1. Conduct research on the objectives using its ground-based simulators and the VSRA aircraft.
2. Provide opportunities for RAE to participate in this research.
3. Provide results of its research to the RAE.
4. Provide RAE with information on the design and flight clearance of research systems in the VSRA aircraft.

Specifically, RAE will use its best efforts, consistent with program priorities and funding, to:

1. Conduct research on the objectives using its ground-based simulators and the Harrier XW-175 aircraft.
2. Provide opportunities for NASA to participate in this research.
3. Provide results of its research to the NASA.
4. Provide NASA with information on the design and flight clearance of research systems in the Harrier XW-175.

Technical representatives for the collaborative program will be Dr. J.A. Franklin of the NASA Ames Research Center, and Mr. O. P. Nicholas of the Royal Aircraft Establishment, Bedford.

C.C. ROSEN III
Director of Aeronautics
Office of Aeronautics
and Space Technology
National Aeronautics and
Space Administration

Date: ________________

D.L.I. KIRKPATRICK
Head of Aerodynamics Department
Procurement Executive
Ministry of Defence
Royal Aircraft Establishment
Farnborough

Date: ________________

Appendix B: Chronology

Date	Activity
February 1979	O. P. Nicholas visit to NASA Ames. Original contact on collaboration
May 1979	R. Gerdes to RAE Bedford for simulation and flights in XW175
August 1979	J. Hall and P. Bennett to NASA Ames for simulation on failure recovery, monitors, and safety pilot issues for TAV-8A
November 1979	P. Nicholas, J. Hall, P. Bennett and R. Searle to NASA Ames for advanced control mode simulation
April 1980	J. W. Britton and O. P. Nicholas to NASA Ames to draft formal terms of reference for Task 8A
June 1980	Terms of reference approved and signed
November 1980	P. Nicholas, J. Hall, S. Winter and P. Bennett to NASA Ames for velocity command control and inceptor simulation
June 1982	R. Gerdes to RAE Bedford for simulation and flight evaluation on XW175 of Sea Harrier HUD
June 1983	J. Franklin to RAE Bedford for program briefing and future simulation experiment planning
September 1983	J. Hall, C. Wills, and S. Wood to NASA Ames for simulation evaluation of velocity command controls and flightpath HUD
October 1983	R. Gerdes and G. Hill to RAE Bedford for flight evaluation of Sea Harrier HUD and nozzle speed trim control on XW175
October 1984	J. Franklin to RAE Bedford to present NASA plans for VSRA and to Cranfield to review VAAC design
November 1985	J. Franklin to RAE Bedford to discuss safety monitors and review servo installation design
April 1986	P. Nicholas and M. Haigh to NASA Ames to review software validation, failure monitoring, and VAAC systems design
September 1986	P. Nicholas and J. Franklin to NASA Headquarters to draft revised terms of reference
June 1987	J. Franklin to RAE Bedford to discuss flight clearance procedures, nozzle control design, and present VSRA system description
December 1987	P. Nicholas to NASA Ames to review nozzle control characteristics
June 1988	Revised terms of reference approved and signed
July 1988	J. Franklin to RAE Bedford for program planning
August 1988	D. Watson, V. Holland, K. C. Shih, N. Rediess and J. Schroeder to RAE Bedford and Cranfield to present detailed VSRA design and discuss servo installation, software design, and ground resonance testing for VAAC aircraft
August 1988	P. Smith to NASA Ames to discuss structured software design
November 1988	V. Lebacqz to RAE Bedford for VAAC program briefing and VSRA summary
June 1989	J. Franklin to RAE Bedford for review of safety monitors and servo dynamics and to plan 1990 NASA and RAE simulation exchanges
May 1990	P. Nicholas to NASA Ames for velocity command control and HUD simulations and to review HUD design
August 1990	E. Moralez, M. Stortz and J. Franklin to RAE Bedford for VAAC simulation and to review status of VAAC and VSRA system design and flight clearance
November 1991	P. Nicholas to NASA Ames to convey nozzle performance data and to draft Task 8A status report

Appendix C: Participants

NASA Ames Research Center

J. Franklin—Technical Leader and Powered Lift Group Leader

R. Bray—Display Concepts*

T. Carson—Control/Display Research*

G. Farris—Control/Display Research*

J. Foster—VSRA Project Manager

R. Gerdes—VSRA Project Pilot*

R. Greif—Control/Display Research*

G. Hill—VSRA System Engineer*

V. Holland—Asst. Chief, Flight Systems

C. Hynes—VSRA System Software

V. Lebacqz—Branch Chief, Flight Dynamics*

V. Merrick—Control/Display Research

E. Moralez—Control/Display Research

N. Rediess—VSRA Servo Design

J. Schroeder—Control/Display Research

K. Shih—VSRA Servo Design

M. Stortz—VSRA Project Pilot

D. Watson—Branch Chief, Flight Systems

RAE Bedford

P. Nicholas—Technical Leader and VAAC Project Manager*

Sqn Ldr P. Bennett—VAAC Project Pilot*

W. Britton—Head, Flight Systems (Bedford)*

S. Gale—VAAC Deputy Manager*

M. Haigh—VAAC FCC Manager*

J. Hall—Flight Simulation

T. Hartwell—Harrier XW175 Manager

G. d'Mello—VAAC Control Laws

R. Searle—RAE Test Pilot*

G. Shanks—VAAC Project Manager
Head, Flight Control Section*

B. Singer—VAAC Project Pilot

P. Smith—Head, Flight Control Section

J. Webb—VAAC Project Manager (Cranfield)*

C. Wills—VAAC Displays*

S. Winter—Head, Flight Control Section*

Flt Lt S. Wood—VAAC Project Pilot*

P. Woodruffe—VAAC Displays

*No longer in this position.

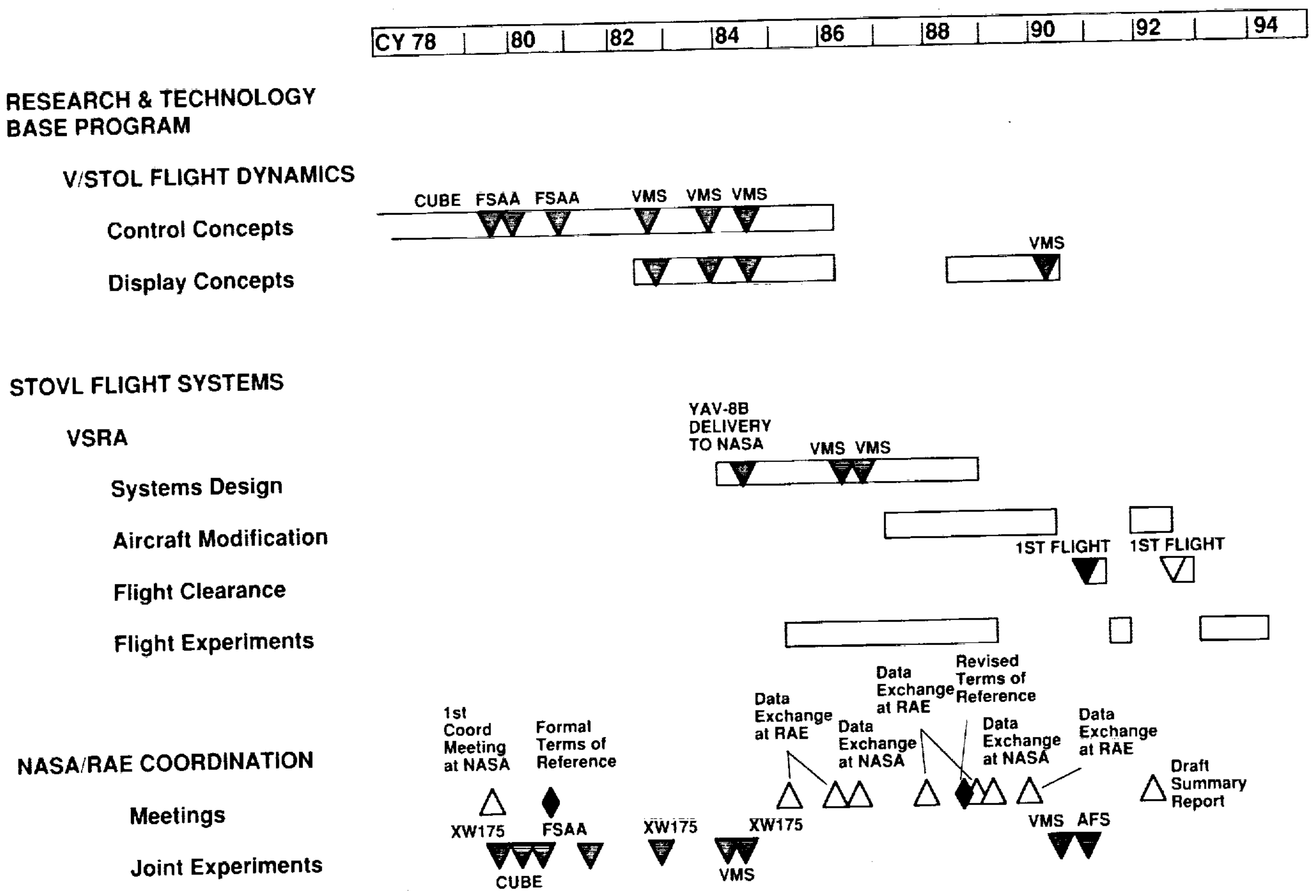

Figure 1. NASA V/STOL flight dynamics program.

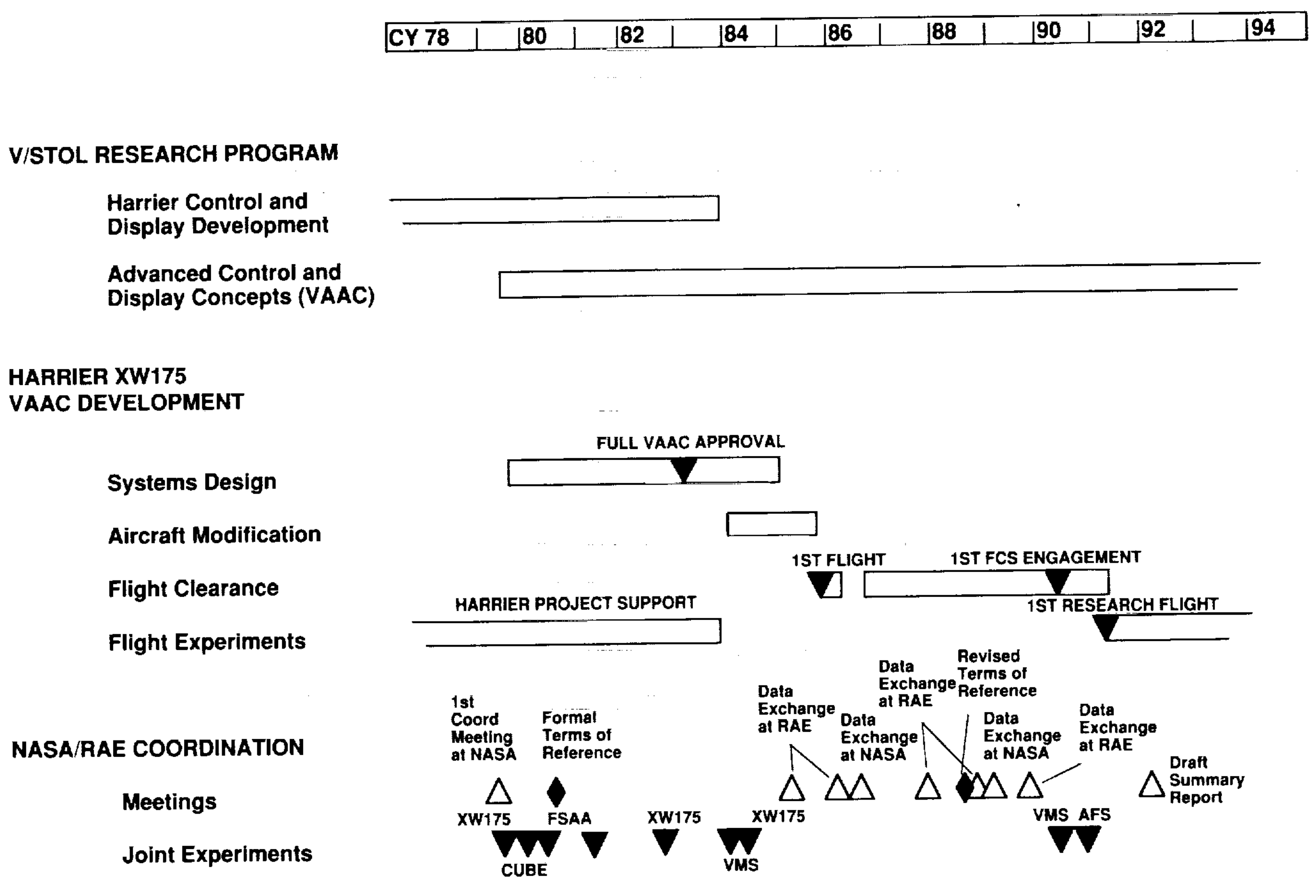

Figure 2. RAE V/STOL research program.

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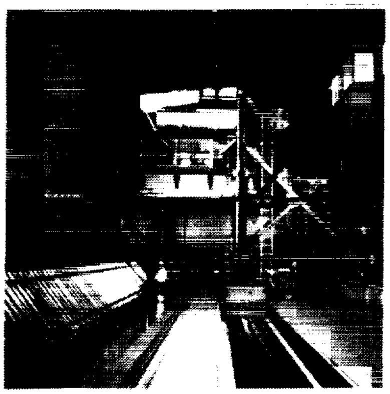
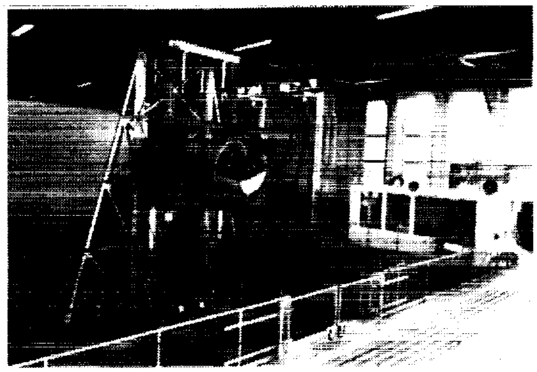
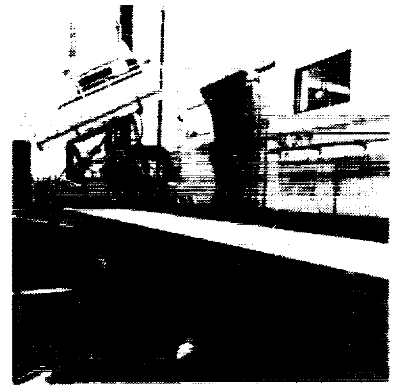

Flight Simulator for Advanced Aircraft


Six Degree of Freedom Simulator


Vertical Motion Simulator

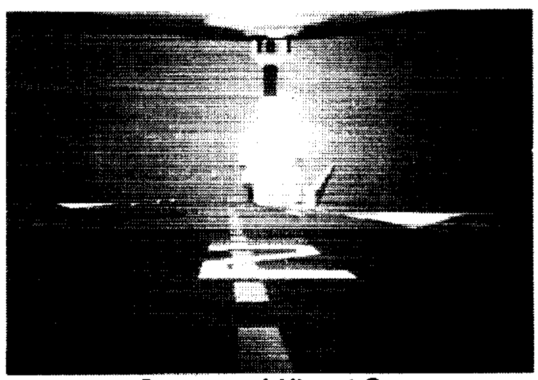

Computer Generated Visual Scene

Figure 3. NASA Ames simulation facilities.

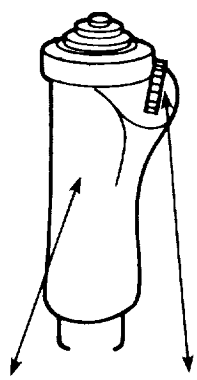
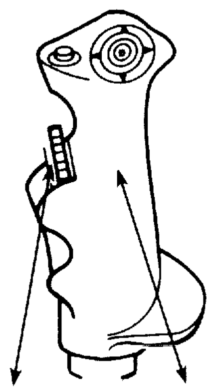
TEST CASE					PILOT RATING			SYSTEM
					TRANSITION (T)	HOVER (H)	DESCENT (D)	
1	LONG.	VERT.			3¼	4	4½	
2	LONG.		VERT.		3	2¼	4½	
3	LONG.			VERT.	3	3¼	4½	
4		LONG.		VERT.	3	3¾	4½	
5		LONG.	VERT.		3	2¼	4½	
6			LONG.	VERT.	3	3¼–6	4½	
7	VERT.	LONG.			5	3¾	4½	
8	VERT.		LONG.		3	3¼–6	4½	
9	VERT.			LONG.	3	1½	4½	TYPE 1A (H&D)
10		VERT.		LONG.	3¾	1½	4½	
11		VERT.	LONG.		3¾	3¼–6	4½	TYPE 1A (T)
12			VERT.	LONG.	3	1½	4½	

Figure 4. Cockpit control inceptor configurations.

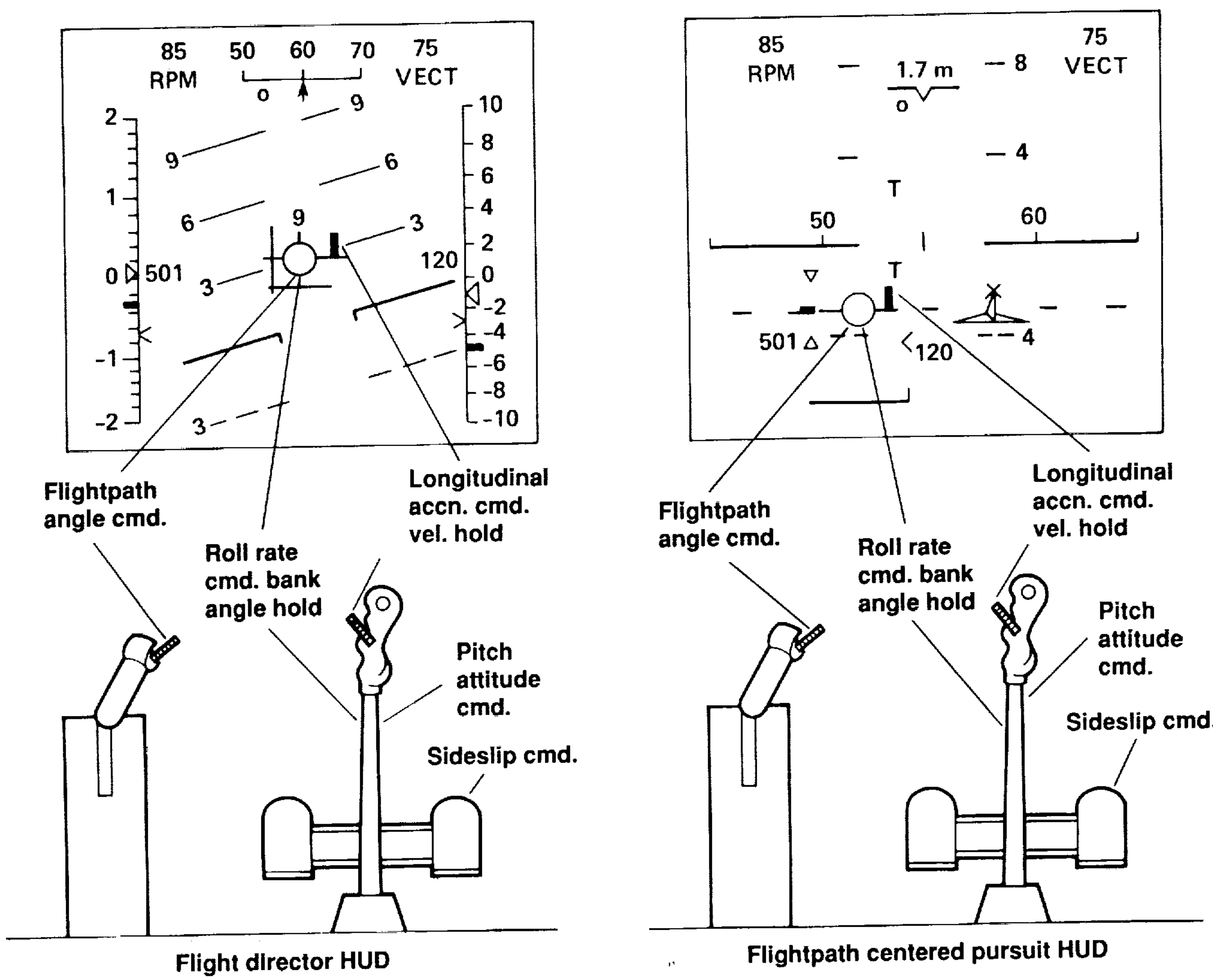


Figure 5. NASA HUD formats.

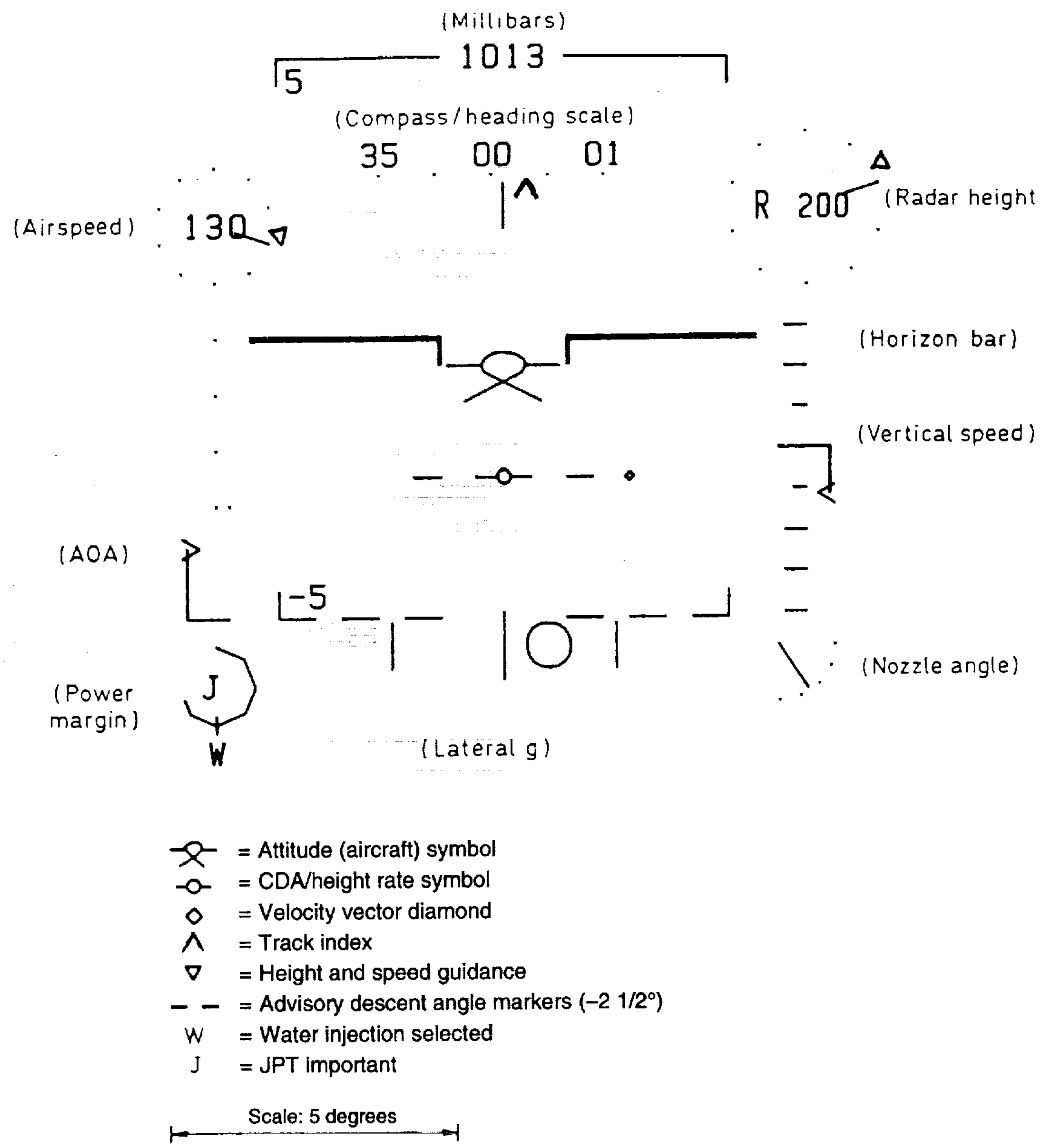


Figure 6. RAE HUD V/STOL format.

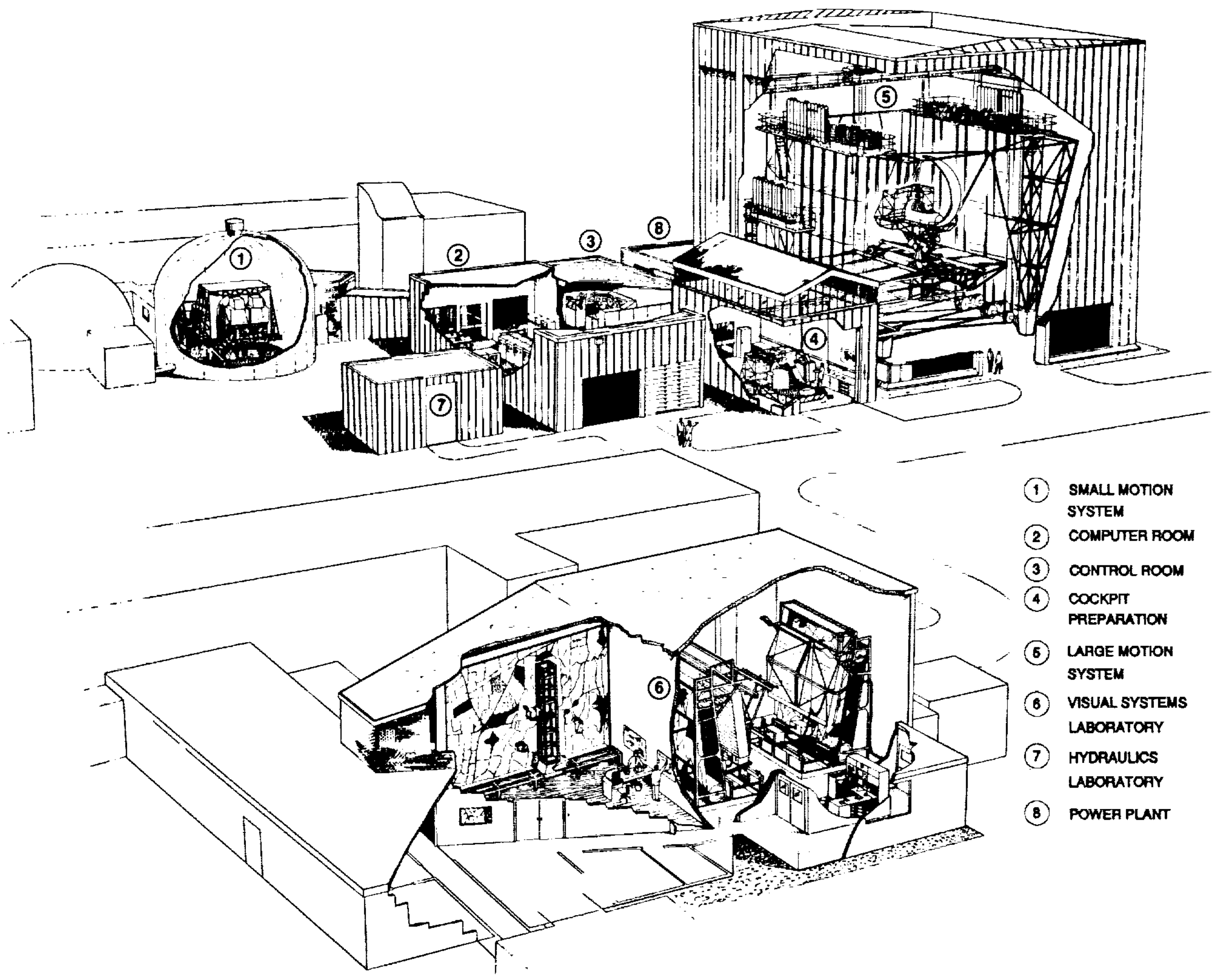


Figure 7. Bedford simulation facilities.

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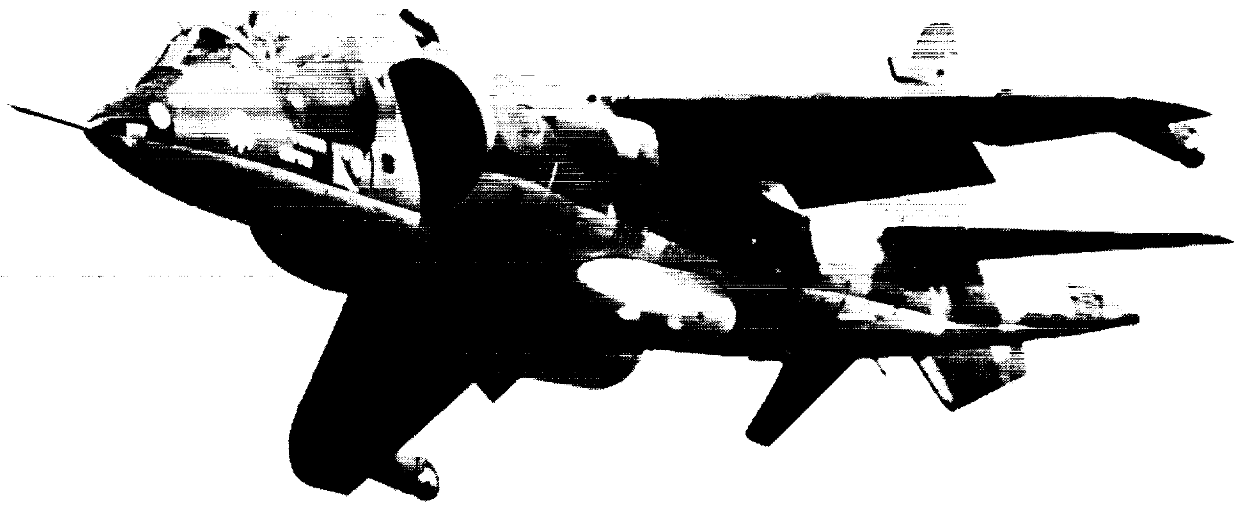

Figure 8. RAE Bedford Harrier research aircraft XW175.

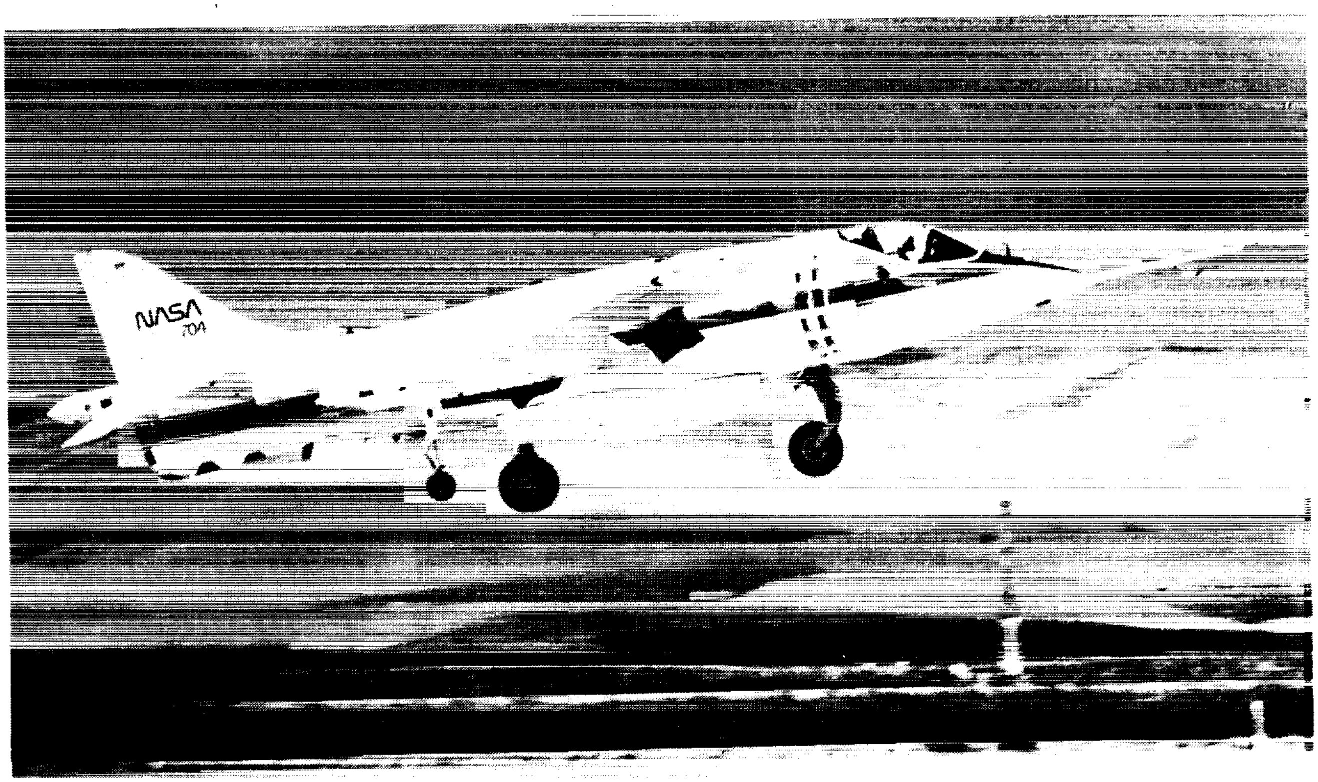

Figure 9. NASA VSRA.

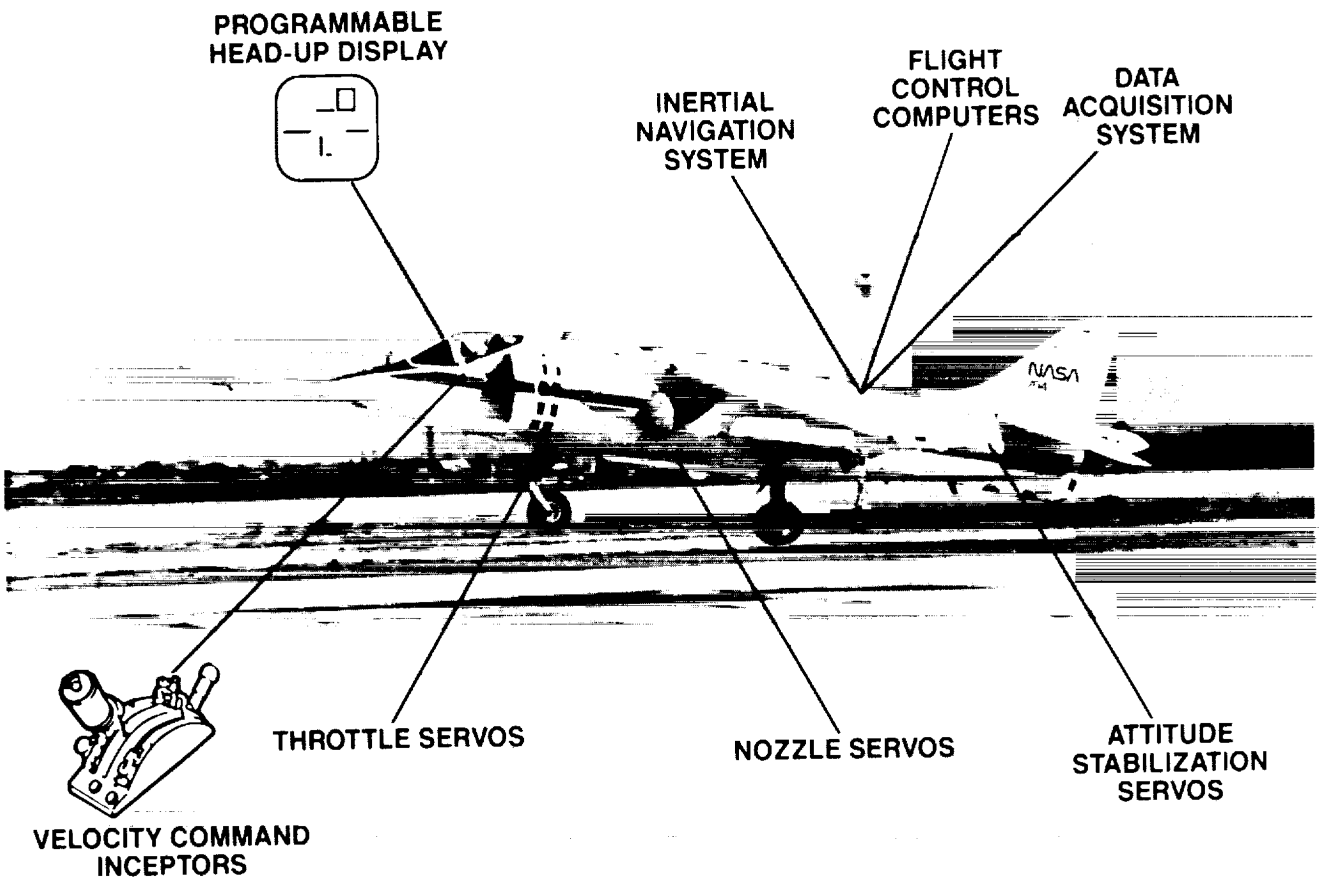

Figure 10. VSRA research system elements.

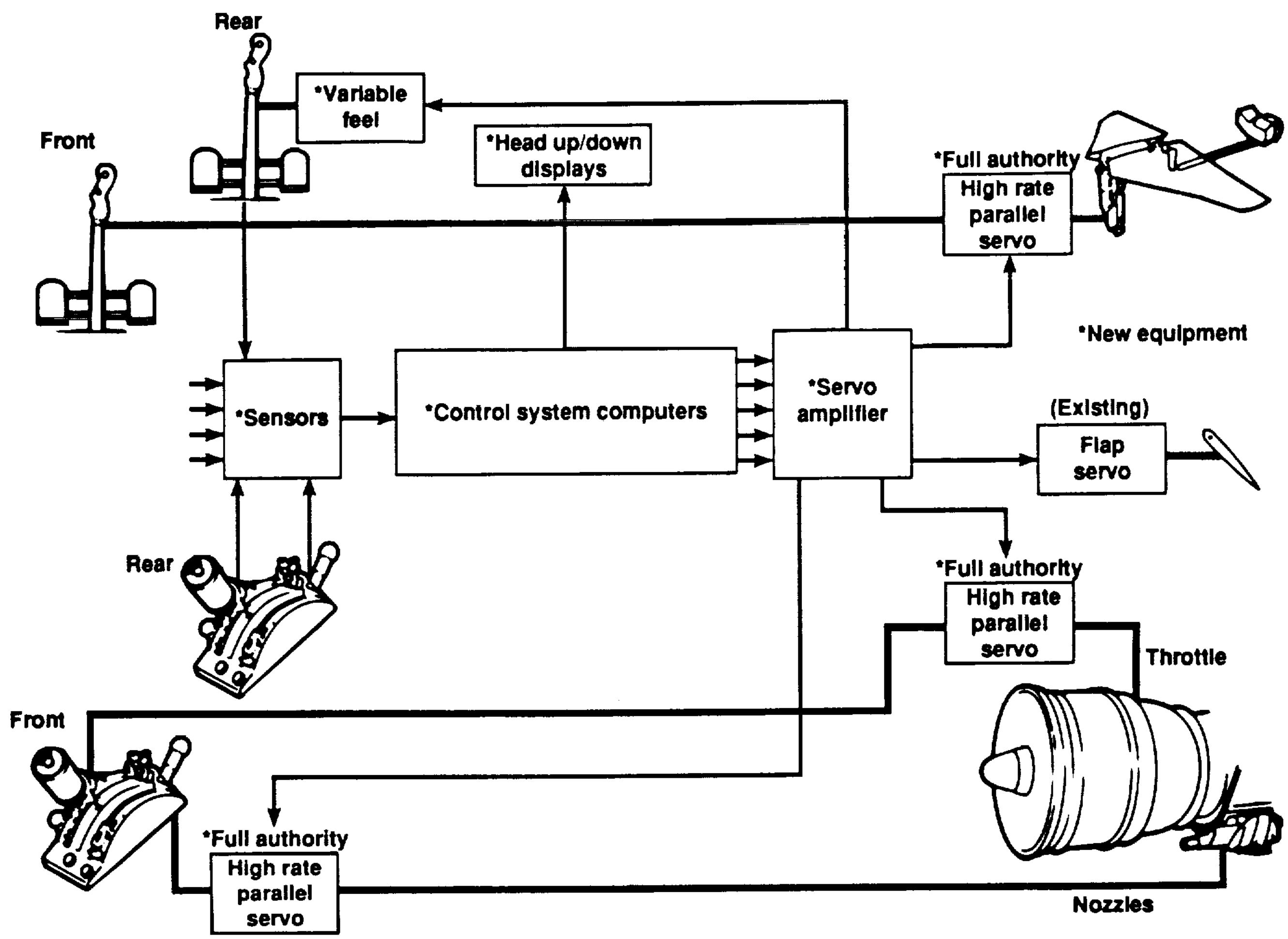

Figure 11. Harrier XW175 VAAC longitudinal control system.

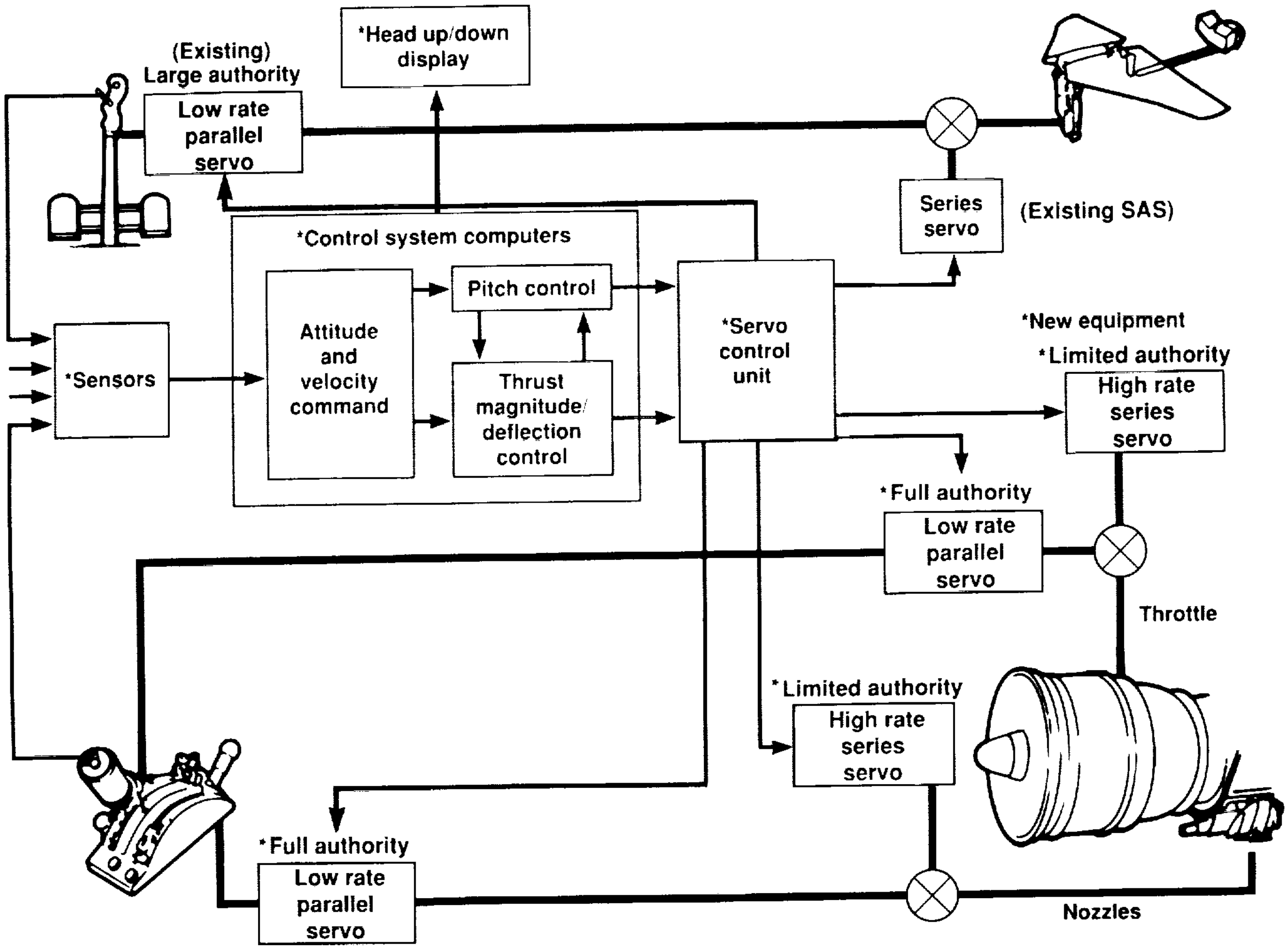

Figure 12. VSRA longitudinal control system.

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11. SUPPLEMENTARY NOTES

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13. ABSTRACT *(Maximum 200 words)*

This report (published as a NASA Technical Memorandum and a DRA Working Paper) summarizes activities that have taken place from 1979 to the present in a collaborative program between NASA Ames Research Center and the Royal Aerospace Establishment (now Defence Research Agency), Bedford on flight control system and cockpit display tradeoffs for low-speed and hover operations of future V/STOL aircraft. This program was created as Task 8A of the Joint Aeronautical Program between NASA in the United States and the Ministry of Defence (Procurement Executive) in the United Kingdom. The program was initiated based on a recognition by both parties of the strengths of the efforts of their counterparts and a desire to participate jointly in future simulation and flight experiments. In the ensuing years, teams of NASA and RAE engineers and pilots have participated in each other's simulation experiments to evaluate control and display concepts and define design requirements for research aircraft. Both organizations possess Harrier airframes that have undergone extensive modification to provide in-flight research capabilities in the subject areas. Both NASA and RAE have profited by exchanges of control/display concepts, design criteria, fabrication techniques, software development and validation, installation details, and ground and flight clearance techniques for their respective aircraft. This collaboration has permitted the two organizations to achieve jointly substantially more during the period than if they had worked independently. The two organizations are now entering the phase of flight research for the collaborative program as currently defined.

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