THE ROLE OF FLIGHT SIMULATION IN THE DESIGN AND DEVELOPMENT OF THE SEA HARRIER NAV-ATTACK SYSTEM

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ABSTRACT

The introduction of more complex avionic systems into the single seat Harrier aircraft posed several problems, not the least of which was the question of whether the pilot workload would be acceptable. To determine this, and to obtain more detailed information on system integration and performance, well in advance of flight testing, a maths model was developed on the existing BAe Hatfield flight simulator. The paper includes a brief description of the facility and of the Sea Harrier model in particular. Numerous investigations were carried out and a pragmatic system of testing and reporting was used to ensure the results were incorporated at an early stage. The areas of study are mentioned and, to illustrate the central theme of the paper, the development of the air-to-air interception display is described fully.

The simulation, used at an early stage, has been an extremely cost effective tool in eliminating faults in design conception and developing new ideas. It has a continuing support role during flight testing and future planning, and is being used as a training aid for the first squadron pilots.

INTRODUCTION

The Sea Harrier is a direct development of the Royal Air Force ground attack aircraft, to be operated by the Royal Navy from "Hermes" class and through-deck carriers providing Fighter Support, Reconnaisance and Attack capabilities for the Fleet. It has been equipped with a new suite of avionics equipment, including an AI RADAR, digital Head Up Display/Weapon Aiming Computer (HUDWAC) and digital Doppler-Inertial Navigation Heading and Attitude Reference System (NAVHARS).

The small size of the aircraft (6500 kg Basic Wt.), resulting from the lift capacity of the single Pegasus engine, dictates a single-seat configuration, and with the multiple roles assigned to the aircraft, and the inherent difficulties involved in recovering VSTOL aircraft at sea, there were many problems to be overcome in keeping the pilot workload factor within acceptable limits. The design of a suitable nav-attack system involved several concepts which were novel to BAe Kingston.

SIMULATION REQUIREMENTS

It was decided in mid 1975, when the go-ahead for the Sea Harrier Aircraft was finally given, that the system simulation effort should be shared between two distinct sites - BAe Hatfield, and the BAe flight test aerodrome at Dunsfold, where the following facilities would be provided.

1) BAe Hatfield - a manned cockpit simulator with representative (but not aircraft) cockpit hardware, with the aircraft and avionic systems entirely represented by mathematical model programs run on a mainframe computer, having the following objectives:-

a) To provide a facility with which the soundness of the proposed system design could be evaluated, with particular reference to its ergonomic and pilot workload aspects.

b) To highlight any performance or pilot interface deficiencies in the system, and to develop improvements to overcome them.

c) To produce operational performance statistics for the aircraft/weapons system, particularly for those areas of the operational envelope that would be difficult or hazardous to cover during flight trials of the aircraft.

d) To develop any new capabilities for the system that may arise as a result of revised staff requirements for the aircraft.

2) BAe Dunsfold - a much simpler cockpit, and mathematical model of the aircraft interfaced to either mathematical models, or the actual hardware versions of the avionics system components. This facility was envisaged as being the main means of rectifying any faults in the design or operation of the hardware and manufacturers software which may cause it to malfunction with respect to its specification. This task is progressing as planned.

At Hatfield work on sections a) and b) was to proceed well ahead of the actual equipment production programme and subsequent flight trials, so that the corrective modifications could be embodied in the relevant equipments in time for them to be properly evaluated during flight trials. Operational performance statistics would not be required from the simulation until flight trials results had validated it over those parts of the envelope that could conveniently be covered.

A significant anticipated benefit was the ability the simulation would give for a number of experienced pilots to try out every aspect of the system under controlled, repeatable conditions - a difficult if not impossible goal to achieve during actual flight trials.

THE HATFIELD SIMULATION FACILITY

Historical

The simulation department at Hatfield was formed in 1957 to study flight flutter and aircraft dynamic stability problems using a Saunders Roe type "D" analogue computer. Piloted work in support of the TRIDENT aircraft project followed shortly afterwards using a rudimentary fixed base rig. This stimulated the development of a visual display system leading to a C.G.I. runway lighting pattern displayed cursively on a C.R.T. monitor and collimated by a large lens.

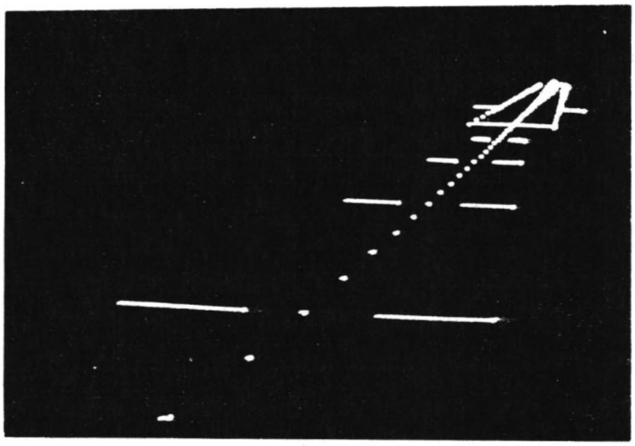

FIGURE 1 - Runway display in use in 1963

Simultaneously the main computing capacity was enlarged by the addition of two EMIAC II computers and a remote land line link established to the TRIDENT hydraulic and electrical controls rig. This was used initially to assess handling qualities and later, in conjunction with autopilot hardware, to support the autoland project. By 1964 autoland work had reached such proportions that a separate facility using 4 E.A.L. TR 48 computers was set up (This was destined to be used for the next decade).

Meanwhile, research into future projects at Hatfield was directed towards civil VSTOL transport aircraft, and from 1965 into the early 70's most of the work on the main computer was concerned with these projects.

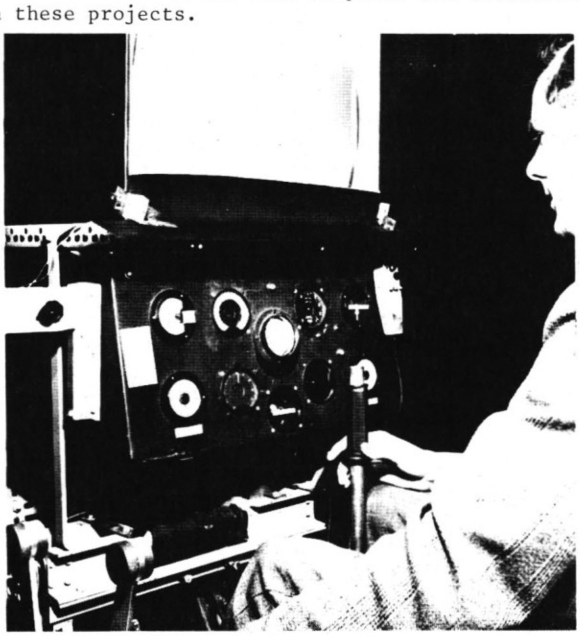

FIGURE 2 - 1962 simulation of the P1127

The facility was considerably enlarged during this period with the addition of more in-house special purpose developments and amplifiers. An electrohydraulic controls feel system was also developed and incorporated into a new fixed base cockpit. This was followed by the development of a programmable Head Up Display. By 1970 however, it was felt that for any further useful work in the VSTOL field, a wider angle visual display system and cockpit motion would be required. At the same time, with the advent of fast, reliable, mini-computers, it was decided to convert to the increased versatility and flexibility of a digital computer system. (1).

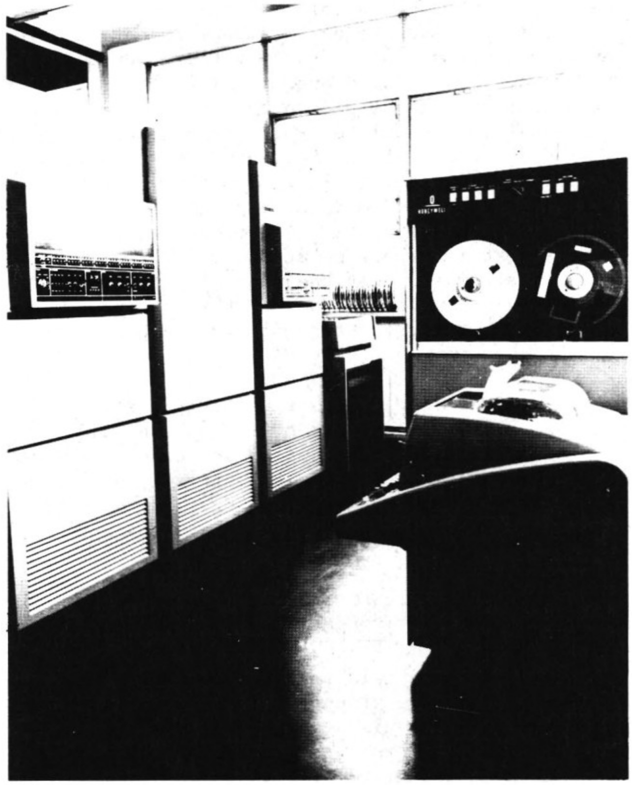

FIGURE 3 - The Honeywell H632 computer system installation

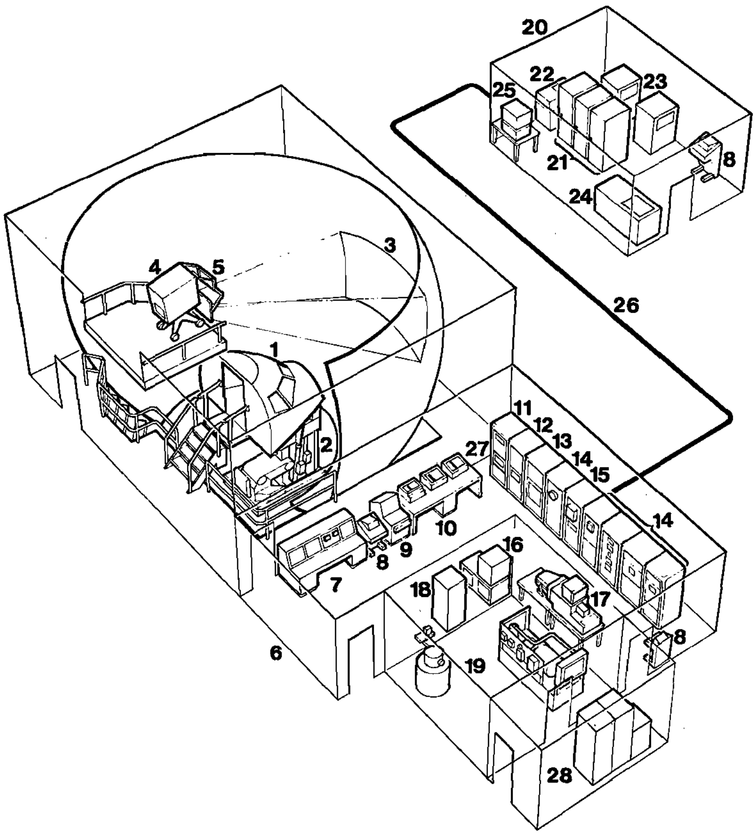

FIGURE 4 - The Hatfield simulation facility from 1970 onwards

Naturally, one of the first aircraft to be simulated on the new system was the Harrier. A low-speed model developed at Hatfield was successfully used to validate the system. Unfortunately, by this time, the Rolls Royce difficulties and fuel crisis had removed the "V" from VSTOL studies and the accent on departmental work had changed considerably.

The development of support software quickly enabled the new facility to be used with the same ease of operation as the analogue system. Furthermore the total simulation being within the digital computer, enabled rapid recall and store of diverse projects. Thus, by 1973, the departmental work was scheduled on a 3 session per day basis and, using side-by-side civil and military cockpits mounted on a moving base, encompassed projects from all divisions of the Hawker Siddeley Group. One such project for the Kingston division was the development of a high speed version of the Harrier model, again as validation of the simulator for the Hawk (P1182) aircraft simulation. This model was later used to test the Kingston Avionic Section's embryonic version of an air-to-air interception guidance display.

In 1975 when the decision was made to model the full aircraft and avionic systems for the Sea Harrier, Hatfield, if not geographically, was otherwise ideally situated to take on the work.

THE SEA HARRIER MATHS MODEL

1) The aircraft

The programming of the H632 computer is done on a modular basis and a considerable library of standard modules is now available. The dynamics of motion of a six-degree-of-freedom rigid body are handled in a fairly text book manner as depicted in Figure 5.

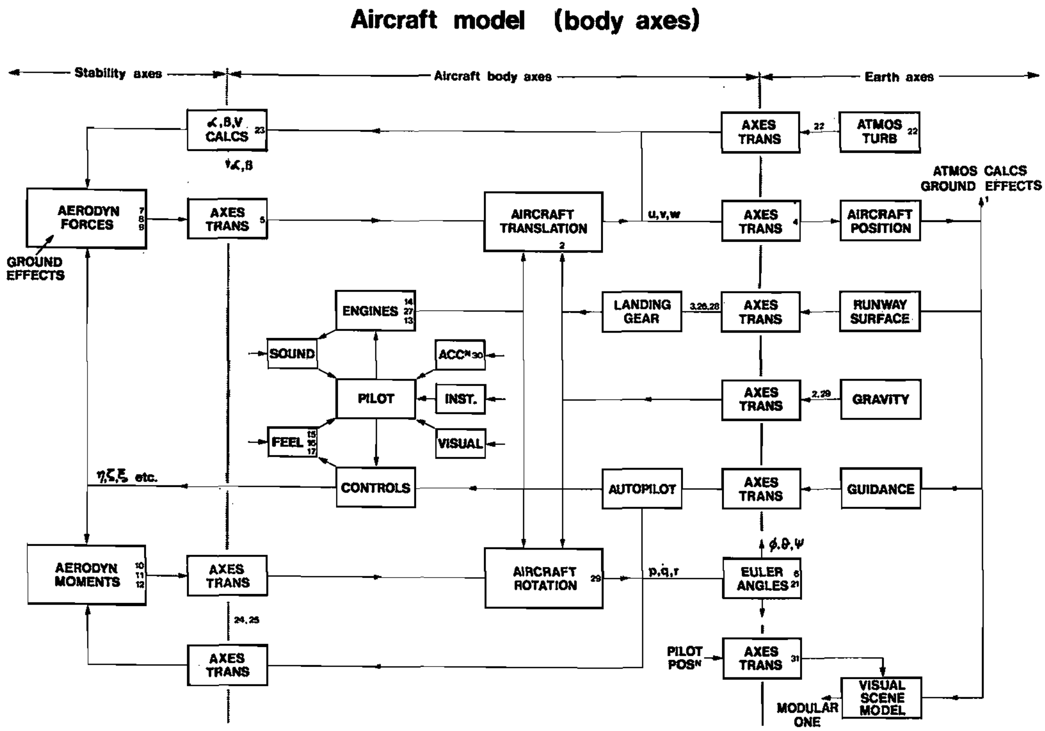

FIGURE 5 - 6 degree of freedom equations

Most of the modules used therein are standard. The non-standard modules used in the Harrier model are listed in Figure 6 and, as can be seen, are fairly comprehensive.

Particular attention is given to the engine, reaction controls, hover dynamics, and interference effects. The aerodynamic derivatives are "tail-plane off" because of the nature of the original low-speed wind-tunnel data, with tailplane lift, drag and pitching moment computed separately. The effects of engine, nozzle and flaps on the tail-plane dynamic pressure and downwash are treated separately. The available high speed data, in a completely different format, has been modified to fit into this model to give a "total sortie" capability.

It was recognised from the outset that the complexity of the model and its high update rate of 50 Hz, may have meant abandoning the luxury of total sortie capability when used as a vehicle for the additional avionic systems. Fortunately however, by judicious use of memory/disc switching

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ENGINE RESPONSE AND OUTPUTS
REACTION CONTROLS
AERODYNAMIC DERIVATIVES
TAILPLANE EFFECTS
WING-ROCK AND BUFFET
HOVER DYNAMICS
INTERFERENCE FORCES, MOMENTUM DRAG, ETC.
SUMMATION OF FORCES AND MOMENTS

FIGURE 6 - List of non-standard modules

and split commutation rates, this has not so far proved necessary.

2) The avionic system

2.1 Navigation and attitude reference system (NAVHARS)

The mathematical model of the inertial platform was not available initially and a considerable simplification was used to enable an ergonomic assessment of the system to be made. The barometric-inertial height loop was not simulated, nor was the doppler system. This work has now been considered elsewhere and it has not been thought worthwhile including it in the Hatfield model. The dynamics of motion are not therefore modified to take into account the motion and shape of the earth nor its non-uniform gravitational field. However, by suitable modification of the rate terms, the aircraft flies around a sphere of radius approx. 3960 miles with its positional information computed in latitude/longitude angles. Using double length floating point calculations the worst positional resolution accuracy (at high latitudes) is within .000001 feet!

The navigational system model performs a parallel integration to achieve its positional data, allowing controlled errors to be included. This has been successful for ergonomic studies and the simulator seems to give a similar degree of positional uncertainty as is now experienced in the aircraft.

The control and display of navigation data is achieved by a single unit, mounted on the right hand cockpit panel. This was simulated in its entirety from the specification sheet, as, once again, neither hardware nor logic flow diagrams and details of the algorithms used in the actual unit were available at the time. The program, which is fairly large, resides in the H632 computer and provides the basic display and switching logic along with the navigation facilities. These include, input and output of aircraft position and up to ten moving waypoints in Lat/Long., or Naval Grid notation, or range and bearing. Steering information is computed along with groundspeed, track, and drift. A built-in variation map allows heading information to be magnetic or true. TACAN data, including offsets, is displayed and there is a fuel and time-remaining-on-station monitor. Means are provided for positional fixing and grid and waypoint updating. The unit can also take control of the RADAR for use in waypoint tracking, inserting, and position fixing.

2.2 Weapon Aiming Computer and Head Up Display (HUDWAC)

A special purpose drawing computer has been developed for the display of head up information. This provides the control of the C.R.T. via a number of coded instructions and also contains a library of symbols available as subroutines programmed on EPROM store. The unit has a direct memory access to its controlling program, held within a TI 990/10 computer. The "drawing list" as it is called, giving control of symbol size, position, orientation, brightness, and content, is in turn controlled by the "990" itself. The mode switching logic, ballistic algorithms, guidance computing, etc., required for the individual modes are, once again, computed in the main H632 computer. These programs are fairly large and are switched from the storage disc into the core memory as the pilot switches from mode to mode. The data required for this area of simulation was fortunately well documented by the sub-contractors, Smiths Aviation, and was therefore very accurately represented. (The degree of co-operation with Smiths was very high, particularly as some of the late revisions involved interference with their production schedules. Even earlier participation in the design cycle would have been beneficial in this area).

2.3 RADAR

With the exception of the hand controller, which is a production item, the RADAR was totally simulated. The software provides the full lock, point, and search capability. Lock and point modes are fairly accurately represented and contain the effects of noise, glint and radome aberrations, along with the full loop equations. In the search mode there is only provision for a single target. Jamming is simulated and the ability to switch the horizontal stabilisation in and out has recently been added. Mapping, ground returns and clutter, etc., are not represented. However, as more operational data is acquired, and a larger computing facility is added, it is hoped to improve the model in this area.

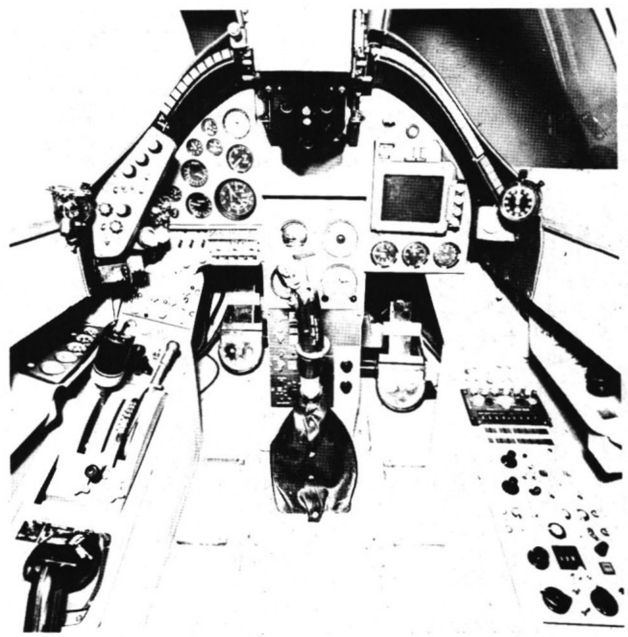

FIGURE 7 - The Sea Harrier simulator cockpit

PROGRAMME OF STUDIES

The first task, covering a period of some 3 months and involving 10 pilots, was the assessment of the head-down instrument panel lay-out. (2) Preparation of the report took a further two months and it became obvious that, to cover the programme with the limited number of staff available, a more streamlined approach was required. Therefore, subsequent tasks were carried out in the following manner:- A team of three pilots, chosen from, and reporting to, the larger inter-service/company/ministry Pilot Working Group, carried out the assessment. Individual pilots varied from task to task and the assessment was broadened where a concensus agreement could not be reached. The programme was formulated and supervised by a steering group composed of representatives from the Royal Navy, the Ministry of Defence, BAe, and the various sub-contracting companies. Reporting was by inter-office memoranda and, at the end of each phase, an ad. hoc. committee was convened from all concerned to decide and provide any necessary action.

Whilst not providing the ideally dispassionate scientific detail required in ergonomic system design, it has been estimated that this method initiated some £0.2M worth of mandatory or highly desirable design changes in the first two phases alone. The cost of these changes would have been between 5 and 10 times greater had they not been initiated until flight trials or squadron assessment had taken place.

In the first phase the general flying modes of the HUD were tidied-up and an initial assessment of the air-to-air mode made without the RADAR model. The major effort in this phase however, centred around the NAVHARS. This unit was a derivative of a system designed for a two man crew and contained many features which were found to be confusing and undesirable for single crew operation.

The development of the RADAR model for the second phase allowed a more detailed look at the air-to-air mode. The interception equations were refined and developed and the need for a "Visident" mode was recognised. (The mode was further changed in a later phase which is the subject of the illustrative example given later in the paper.) The equations and symbology for a toss bombing mode were also defined in this phase, and the proposed air-to-air gun sight was programmed and investigated. (Further work on the gun sight was left to be completed during flight trials as the simulator visual display and environment was deemed unsuitable for a proper assessment to be made.)

A similar programme of work, under a separate contract, was being conducted at the Royal Aircraft Establishment at Bedford on the generation of a Pilot Interpreted Approach (PIA) display, using data from the aircraft RADAR (3). The resultant display was well liked by the pilots but, because of the independent nature of the studies, it required some modification to harmonise with the rest of the display modes on the HUD. This work was done at Hatfield with the later extension of the mode to provide all angle azimuth guidance and to include the use of MADGE or NAVHARS data. Initial flight trials at sea have shown this to be a useful and easily interpreted display.

The current programme continues in support of A&AEE clearance of the air-to-air interception display mode, investigation of an improved RADAR tracking system, and the rest of the air-to-ground modes. Future work will investigate the requirements of different weapon systems which may be carried by the Sea Harrier, and continue to provide support for flight trials.

Separate studies include the initial pilot assessment of the 'SKI-JUMP' launch responses prior to the Bedford flight trials, (4) and the investigation of the guidance requirements, display, and response for a possible use of the aircraft as a torpedo carrier. (5) Until the training simulator for the Royal Navy is completed, the Hatfield Simulator is being used for the training of the initial squadron pilots.
(This work will probably cover a period of two years.)

For the purpose of this paper, it would be impractical to cover all aspects of the programme in any more detail, therefore, as an example, the following description of the development of one of the main modes is included.

THE DEVELOPMENT OF A HEAD-UP INTERCEPTION DISPLAY

The original system specification called for a computed interception display providing a manoeuvre that would bring the fighter round from a position in the target's ahead sector to an astern sector approach from which a Sidewinder AIM 9G missile (which has a small detection range on a target flying towards the missile) could be launched successfully.(6)

The manoeuvre was required to :-

a) Bring the intercepter to a position well inside the missile's seeker and aerodynamic range boundaries, while keeping it outside the likely range of a target's radar-controlled rear-firing guns.

b) Keep the RADAR sightline to the target within the azimuth and elevation gimbal limits of the RADAR antenna.

c) Only demand a rate of turn from the interceptor that it could comfortably achieve without excessive buffet or speed loss.

d) Provide the pilot with an informative, interpretable display of the situation.

e) Not be too sensitive to errors in the computed target heading and turn rate.

f) Enable a manoeuvring (turning) target to be successfully intercepted.

g) Be continuously computable from current data on target's range, speed, heading and relative position.

As the HUD provides the primary flight instrument display for Sea Harrier, the Interception display was required head up, with a back-up version on the head down radar display. (PPI or B Scan).

The display thought to be most informative was a synthetic PPI-type picture (Figure 8).

The "frying pan" represented the target's relative plan position, with its handle pointing in the direction of the target's relative heading, and its radial distance from the datum dot (d) being an approximately logarithic function of its range. The so called "I" bars were positioned on the required azimuth look-angle direction and the pilot's task was to turn his aircraft until the I bars lay over the target symbol. (A turn to Stbd as illustrated) The cross-bars on the I bars acted as a range scale.

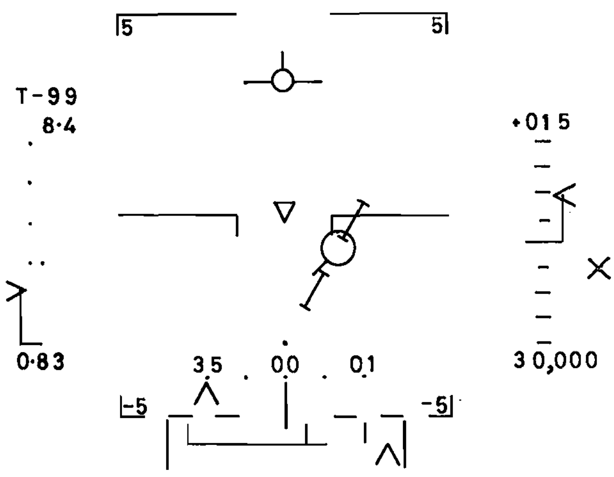

FIGURE 8 - An early arrangement of the AI display

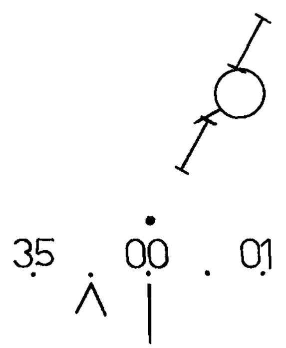

FIGURE 8a - Interception elements of the display

This display was found to be quite interpretable, once the pilot had got used to the idea that the I bars "stayed with the aircraft", and the target moved on the display as he turned them towards it. It suffered from two serious disadvantages, however:-

a) The target's relative height was not apparent (since the display was a plan position indicator) except by the pilot watching a digial display of target relative height. In the heat of manoeuvring towards the climax of an interception, this parameter could easily get neglected, leading to the elevation getting too large for the radar gimbal limits.

b) At shorter ranges the "angular compression" effect gave the pilot no clear indication of the accuracy with which he was flying the interception and it was particularly easy to develop too much lag, with its resultant loss of radar and missile head illumination.

To overcome the elevation gimbal limit problem the relative height digits were flashed when the elevation was within 5 degrees of the limit. This alerted the pilot, but he still was not instinctively able to adjust his aircraft pitch in the right sense to counteract the excessive elevation.

The angular compression effect at short range was tackled as follows. A "B Scan" display, in which the I bars were moved laterally, parallel to the HUD axis, to give demanded angle was tried.

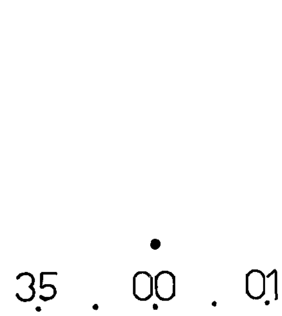

FIGURE 9 - "B scope" display

This overcame the angle sensitivity problem, but the relative direction of the target's heading was now a problem, since the pilot tended to interpret the "frying-pan" handle direction relative to the radial from the datum dot.

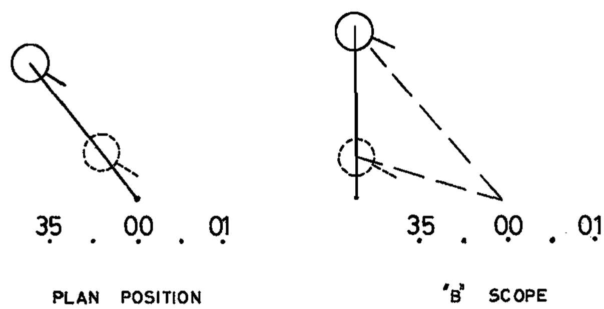

FIGURE 10 - Showing ambiguous interpretation of heading information on "B scope" display

A different version of the PPI display was tried in order to avoid this difficulty with the B Scan display. Target range was kept at full radius from the datum dot until the range reduced to 1 mile, after which it was brought in linearly as the range continued to close. Digital target range was also displayed above the ADD thermometer on the LHS of the display, in whole miles down to 10 miles and tenths of a mile down to zero.

This display proved the most successful so far, and it showed that the pilots were quite happy with only a digital display of range, but it still did not overcome the serious deficiency in elevation control and interpretation. A further problem then encountered was the requirement for the simultaneous display of an Ahead Sector Approach steering demand, arising from the change-over to the Sidewinder AIM 9L missile, with its much better IR detection range against targets approaching head-on.

The initial solution chosen was to display this option on the waypoint steering bug under the heading tape - a useable, but not very much liked option, since it gave no real indication of the relative pointing direction until the aircraft had been turned to satisfy the demand. (The displayed heading scale being limited to only relatively small angles) Thus, when it was realised that the B Scan problem could be solved by displaying the target aspect angle instead of relative heading, as shown below.......

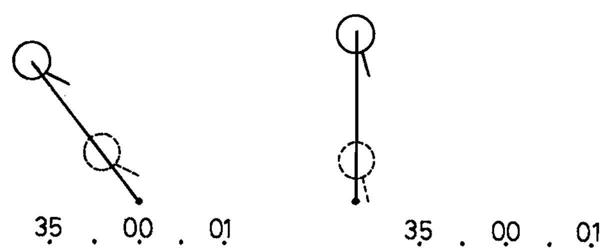

FIGURE 11 - Showing a better method of displaying heading on a "B scope" display

.......it was decided that a "C Scope" display would give improved elevation information and allow the two steering commands to be simultaneously displayed. This was finally chosen as the best version and is shown in Figure 12 and described below.

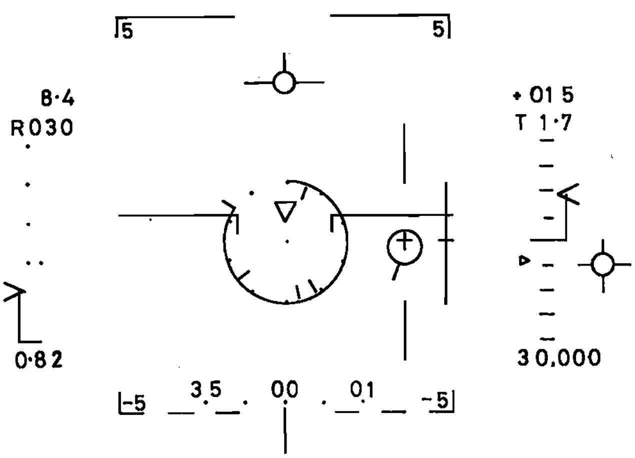

FIGURE 12 - The present display

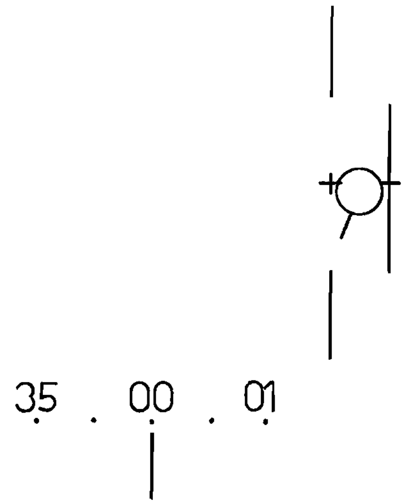

FIGURE 12a - Interception elements of the display

The circle of dots is centred on the HUD display area, and subtends 3 degrees actual diameter, representing a 15 degree radius circle about the aircraft's air velocity vector direction. A range thermometer runs around the circle from 12 o'clock to show range from 10 miles down. The "frying pan" is positioned to show the target's direction in azimuth and elevation relative to velocity vector, on a 1/10 th scale (i.e. 5 degrees of HUD deflection represents 50 degrees true deflection). The pan handle represents the target heading relative to sight line - the so-called aspect angle. This is the most difficult factor to interpret on the display but it provides invaluable information when the pilot has learned the task. The overall advantages of the "C Scope" display are:-

1) The target's azimuth and elevation are easily interpreted, and the 15 degree radius range circle also acts as a simple indication of ASE (allowable steering error) for the AIM 9L missile direction at launch. (The latter particularly for an ahead sector engagement).

2) Both the ahead sector approach (smaller line) and the astern sector steering demand lines can be displayed simultaneously and the target's elevation read off against them. Having both approach path directors together allows the pilot to quickly judge whether there is any advantage in opting for an ahead sector attack under conditions where the rear sector approach would be difficult to accomplish.

3) It remains possible to use the display of target position alone to decide on a good interception (i.e. the I bars remain advisory rather than mandatory information). Thus, in this sense, with the extra elevation information, the pilot may devise interceptions in all three dimensions.

The ahead sector and astern sector steering laws tend to be complimentary to one another, particularly at short range, i.e. if one can only be achieved with difficulty, then the other will be relatively easily done. The relative merits and disadvantages of the two approach paths are:-

Astern sector

advantages

1) Slows down the relative range rate between the fighter and the target, increasing the missile firing opportunity time.

2) Puts the fighter into a region where the IR emissions from the target are maximised.

3) Allows a fair amount of latitude in pointing accuracy since the missile has an easier collision course task than from a head on position.

disadvantages

1) It requires a very tight turn radius to be flow if the interception is started from a short range, head on position.

2) Gives only a fleeting firing opportunity against a very fast target, due to reduced missile firing bracket range, and rapidly opening range rate.

3) Places the fighter in an area defended by radar-controlled rearward firing guns.

Ahead sector

advantages

1) Can be made from a short range head on position.

2) Effective against very fast targets.

3) Keeps the fighter clear of the rearward firing guns.

4) The missile is not limited by aerodynamic range considerations, owing to the high closing speed.

5) Places the fighter in a good position to fire with guns.

disadvantages

1) Low IR emissions ahead of the target give much reduced IR detection range (particularly subsonic targets).

2) Large minimum firing range due to the effect of the missile's safety arming time and high lateral manoeuvre demands give a very short firing opportunity.

3) Things happen very fast, requiring high concentration and rapid decision making by the pilot.

4) Requires very accurate flying by the pilot, since the missile minimum range boundary is very sensitive to excessive lead/lag.

5) Cannot be performed if the fighter is displaced too far from the targets ahead position.

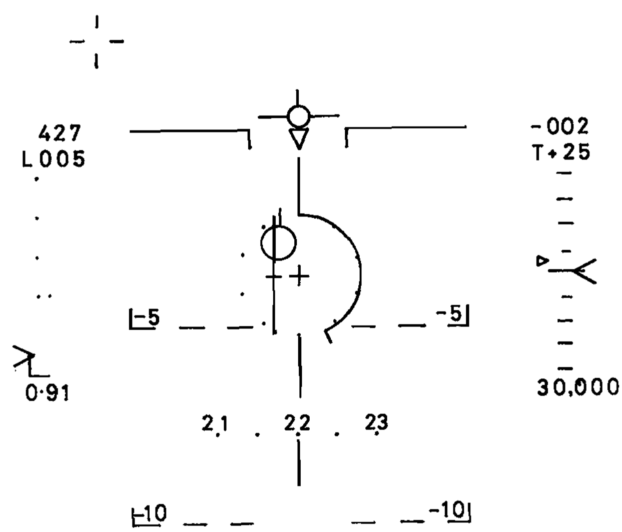

FIGURE 13 - The VISIDENT display

A varient of the display is used for VISIDENT (visual identification) a cold war role in which the fighter is required to close to visual range on a target, which may well have extinguished its navigation lights, and is likely to manoeuvre in such a way as to place the fighter in its turbulent slip stream. For this mode the "pan handle" reverts to relative heading (paradoxically a much easier parameter to interpret when the target's aspect angle nears 180 degrees) and the I Bars display a collision course demand. The range scale on the central circle is made 1000 yds maximum, giving a further indication of closing speed, with the range digits changing to yards also at 1000 yds range.

These displays have been extensively evaluated in the simulator by some ten pilots and are both well liked and give a high success rate in simulated missile engagements and VISIDENT encounters.

CONCLUSIONS

The design aims of a separate mathematically modelled simulator containing little actual hardware have been fully achieved. Its total cost has been recouped many times over in the early elimination of design faults and inadequacies, whilst further saving is achieved in flying time. Its value in improved system design by allowing designers and pilots to work closely as a team has been demonstrated and its worth proved in the early flight trials of revised HUD symbology and NAVHARS logic.

The usefulness of the simulator as a training aid for the pilots designated for the first Sea Harrier Squadrons has been an unplanned bonus.

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D.K. Mandela and R.E. Sawtell
(Royal Aeronautical Soc. 2nd. Flight Symposium Proceedings)
(MAY 1973)

Ref 2 Sea Harrier Head Down Instrument Layout Assessment on the HSA (Hatfield) Simulator.
J.H. Miles
(HSL-T-GEN-001907 MOD contract K/A9a/45/CBA9a)
(JUNE 1976)

Ref 3 Recovery of Sea Harrier in Poor Visibility.
(RAE Bedford Tech. Memo. (unpublished))

Ref 4 Programme for Simulator Assessment at HSA (Hatfield) in Connection with Ski-jump Demonstration Programme.
T.S.R. Jordan
(HSA-KAD-N-HAR-2375 and HSA-KAD-N-HAR-2432)
(FEB 1977)

Ref 5 Simulation Activities Carried Out in Support of the HARRIK ASW Investigations.
L. Trerise, J. Allen, R. Sawtell
(HSL-R-HAR-001942 MOD Contract A9a/165)
(MAR 1980)

Ref 6 The Computation of a Suitable Interception Trajectory for the Delivery of Infra-red Homing Missiles.
P.R. Walwyn
(HSA Kingston ASN 556) (MAR 1974)
