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THE DEVELOPMENT OF NIGHT VISION PILOTING SYSTEMS
FOR LOW LEVEL HELICOPTER OPERATIONS

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ABSTRACT

This paper describes a research programme at the Royal Aircraft Establishment, Farnborough, to develop night vision piloting systems for low level helicopter operations. Two forms of system were investigated using a Sea King helicopter, the first comprised a fixed forward looking low light television camera, whose output was displayed on an instrument panel mounted monitor. The second system was helmet mounted image intensifier night goggles, where special optical concepts had to be evolved to enable the pilot to read the instruments. The third concept was a visually coupled system, which was investigated during a fixed based simulator trial. In the airborne system, which is due to be assessed in the Sea King in 1980, a night vision sensor is mounted on a slewable platform in the nose of the helicopter, the sensor output being presented on a helmet mounted display. The sensor line of sight is locked to the pilot's head position using an angular head position detector. The paper describes the development of the equipment, and the piloting techniques which were evolved to use them. The paper also discusses the human factor problems encountered with each of the systems and the solutions developed to overcome them.

1 INTRODUCTION

The helicopter in its military role has the ability to undertake many types of operational mission. This inherent flexibility of operation, which is far greater than conventional fixed wing aircraft, depends to a large degree on the pilot's ability to maintain good ground contact in order to recognise and identify features. When this ground contact is prevented by low scene illumination or poor visibility, the mission capability is lost particularly for missions involving low level flight at or below the local obstacle clearance level. So to make helicopter poor weather or night operations possible it is not solely a question of providing suitably processed flight information, as is the case for some types of fixed wing aircraft. Rather means must be devised to give the pilot some direct or indirect view of the outside world to re-establish ground contact and regain the mission capability. The subject of the present paper is the exploration and development of electro-optical imaging systems to aid helicopter operations when pilot vision is limited by low scene illumination.

The research programme was run by the Helicopter Display Section in the Display Division of Flight Systems Department, mainly using the Royal Aircraft Establishment Sea King helicopter which was fitted out as a flying laboratory equipped with a number of electro-optical imaging systems and other avionics system. Supporting research was also done using a fixed base flight simulation of a Lynx helicopter.

Three types of night vision system were investigated during the trials. The first comprised a fixed forward looking externally mounted sensor driving a head down display mounted in the cockpit. The bulk of the research was done with this system to highlight the fundamental problems of using a television image of the terrain to pilot the vehicle, and to establish the essential requirements of the system in terms of camera field of view and resolution, image magnification presented on the monitor, and supporting avionics system required to minimise the pilot workload for night operations. Details of the systems used for this work are given in section 3.

The second night vision system investigated was image intensifier passive night goggles. The attraction of these devices is that they are completely self contained, and therefore little or no helicopter modifications are required to use them. In normal use, they are mounted on the pilot's helmet, ambient light from the terrain is focussed by the goggles' objective lenses onto the channel plate intensifiers which provide amplification in the order of 10^5 times. The resulting image is viewed by the pilot on the phosphor screen at the back of the intensifiers via adjustable eye piece lenses. Because of volume and weight restrictions, the real aperture of the intensifier is limited in size, and this limits their low light performance.

Since the present design of night goggles precludes any direct view of the cockpit, instrument reading has to be performed via the goggle intensifiers, necessitating very low instrument lighting, and some form of bifocal optical system on the goggles. Viewing of hand held maps in this manner is also very difficult. The flight trials conducted concentrated therefore on the impact of the night goggles on the normal night cockpit lighting systems and how these could be improved or modified to reduce pilot workload. Another area of particular interest was the design of a helmet mounting and quick release system for the goggles.

The final night vision system investigated was a visually coupled system comprising a helmet mounted display fed from an external platform mounted sensor, the angular orientation of the platform being determined by a helmet sighting system. This concept has to date only been evaluated on the fixed base simulator, flight trials of an airborne system are due to commence in early 1980. The visually coupled system combines the advantages of the large aperture externally mounted fixed sensor, with the look-around capability of passive night goggles, the main penalty being a large escalation in cost and complexity. The most significant human factors problem of the visually coupled system is caused by the present design monocular viewing systems. This was the area where most research was carried out during the trials to assess the effects of binocular rivalry and disorientation. Other system characteristics investigated were platform slew performance and overlay flight information requirements.

2 OBJECTIVES

The overall objectives of the flight and simulator programmes were to investigate the problems, define the limitations and establish operating procedures for using an indirect view of the terrain ahead as provided by each of the systems investigated to pilot and navigate at low level. In particular the research programme had the following specific objectives.

(a) To investigate sensor fields of view and image resolution requirements for the piloting task when flying at very low level.
(b) To assess the additional navigation aids required when undertaking the low level piloting task over unknown terrain.
(c) To establish the division of crew responsibilities.
(d) To determine the form and nature of any flight information required to be superimposed on the TV image in order to reduce the pilot task level. This particular investigation only really applied to the fixed sensor and visually coupled night vision systems.

(e) To devise a cockpit lighting system, and helmet mounting arrangement, which would increase night goggle effectiveness.

3 SEA KING NIGHT VISION SYSTEMS

For the purposes of the fixed sensor trials the Sea King was fitted out as a flying laboratory as described in the Introduction. Two camera systems were available, a daylight Vidicon and a low light Isocon described below. To assist in the piloting and navigation tasks, a symbol generator could provide overlay flight information on the forward view, and a Doppler navigation computer coupled to a moving map display could provide a continuous readout of present position.

3.1 Low light television camera

The LLTV camera was mounted rigidly to the external starboard side of the airframe of the Sea King below the cockpit. The camera was aligned in azimuth and depressed by 8^o in elevation relative to the aircraft longitudinal flight datum. At a cruising speed of 90 kn the aircraft normally held a nose down attitude of 2^o depressing the camera sightline 10^o from the horizontal. The camera itself was a 55mm intensifier image Isocon produced by Marconi Avionics Systems Ltd. The intensifier was a single stage electrostatically focussed inverter tube having unity magnification and a gain of 100. For the majority of the night flights, particularly during the later stages of the trial, the camera was fitted with a 50mm focal length lens with a relative aperture of $f1.4$. This gave an outside world field of view of 32^o by 24^o.

3.2 Daylight TV camera

The daylight TV camera was a Marconi-Elliott 25mm Vidicon. This was rigidly mounted to the port side of the airframe aligned in azimuth and depressed by 10^o in elevation relative to the longitudinal flight datum. The camera was fitted with a zoom lens unit providing a range of outside world field of view from 4^o to 40^o in azimuth.

3.3 Symbol generator

The flight information format investigated during the trial is shown in Fig 1. Pitch and roll attitude were presented by an artificial horizon referenced to an aircraft symbol with pitch and roll scales. Digital readouts were provided for airspeed and height. Aircraft heading was presented as a linear tape and vertical speed as a thermometer read against a vertical scale.

The other symbol used during the trials was a 'heading to steer' director positioned above the heading tape and referenced to the lubber line. The linear displacement of this symbol from the lubber line represented the angular difference between the helicopter heading and that required to intercept the next waypoint computed from the navigation system.

3.4 Cockpit layout

The cockpit layout of the aircraft is shown in Fig 2. A 0.18m × 0.13m head down television monitor was mounted in the port instrument panel. This monitor could display the output from either the daylight or low light television camera, the selection being made from a control unit at the observer station. The pilot's eye to monitor distance in the cockpit was approximately 0.75 m. At this distance the monitor subtended an angle of $14^o \times 10^o$. The LLTV camera could be fitted with lenses of different focal lengths to provide different outside world fields of view. Changing the field of view altered the magnification of the outside scene as compared with the view through the windscreen and hence the ground feature resolution of the system.

The three different lenses used on the LLTV during the flight trials are listed below with the field of view presented on the monitor and the corresponding magnification obtained.

Table 1
LLTV camera lenses

Lens focal length	Lens relative aperture	Field of view	Magnification
50 mm	$f1.4$	$32^{\circ} \times 24^{\circ}$	0.42
85 mm	$f1.8$	$19^{\circ} \times 14^{\circ}$	0.72
135 mm	$f1.8$	$12^{\circ} \times 9^{\circ}$	1.14

With the zoom lens unit on the daylight camera providing fields of view on the monitor between $41^{\circ} \times 33^{\circ}$ and $4.2^{\circ} \times 3.4^{\circ}$, the magnification factors were 0.32 and 3.1 respectively.

Mounted immediately above the monitor and below the cockpit coaming were the switches and LED meters for the control and position readout of the zoom lens on the daylight camera and the panning head on the LLTV camera. To the right of the TV monitor the symbol generator control panel was mounted. This allowed the pilot to change the digital height readout on the picture from radio to barometric. Similarly a groundspeed readout could be called up in place of airspeed.

3.5 Navigation system

The Sea King was fitted with a Decca Doppler 71, a Sperry GM7 gyro-magnetic compass and a Decca TANS (Tactical Air Navigation System) digital navigation computer. This had the capability of way point storage and in addition providing the waypoint with a velocity vector if for example recovery to a moving ship was undertaken.

Bearing and distance or heading to steer and time to go from the aircraft to the selected waypoint could be displayed as an alpha-numeric on the TANS display. For the bulk of the flying, the TANS was coupled to a moving map display mounted above the centre coaming as shown in Fig 2. Although the map unit could accommodate various map scalings, standard 1:50000 maps were used throughout the trial. By means of the rotating drum and sliding cursor, present position could be read very easily throughout a sortie.

3.6 Passive night goggles

The night goggles used for the majority of the flight trials were twin intensifier units manufactured by ITT. These are shown in Fig 3, and had a 40° circular field of view. The goggles were fitted with 18mm format channel-plate intensifier tubes with $f1.4$ objective lenses, which could be focussed from infinity down to 0.25 m. The goggle eye piece lens could also be individually adjusted to suit particular observers, over a range of ± 5 dioptres.

To assist in instrument viewing, the goggles had a bifocal optical system so that the lower 40% of the total field of view was focussed at

0.7 m, the average instrument viewing distance, when the remaining upper 60% was focussed at infinity. The weight of the basic goggles evaluated was 0.825 kg, which posed some problems with helmet mounting, not only due to their basic weight, but also because of the forward moment they produced.

4 VISUALLY COUPLED NIGHT VISION SYSTEM

In the normal airborne installation, the visually coupled system comprises a head sighting system coupled to a slewable platform in the nose of the aircraft. Within the platform, a suitable night vision sensor is mounted, either low light television (LLTV) or forward looking infrared (FLIR). The sighting system measures pilot head angular orientation in elevation and azimuth, and these signals are fed to the platform so that the night vision sensor is locked to the pilot's line of sight. The sensor output is fed to a helmet mounted display which presents to the pilot a collimated scene image at unity magnification. As the pilot moves his head, the platform follows (up to the gimbal limits) giving a continuous view of the outside world as if the pilot were looking through the windscreen. Typically the system provides an instantaneous field of view of 40° with an area of coverage from the platform of $\pm 180^{\circ}$ in azimuth and $+ 20^{\circ}$ to $- 110^{\circ}$ in elevation. Because of the elevation coverage, the pilot can actually 'look through the floor' of the helicopter vertically downwards. Provided potential disorientation effects can be overcome the visual coverage at night is much greater than with passive night goggles. This can be very advantageous during search and rescue missions or when landing in a restricted site.

4.1 Helicopter simulation

The assessment of the helmet mounted display system was carried out using a fixed base digital simulation of the Lynx helicopter (WG 13). The mathematical model was programmed on a Redifon 2000A computer and was based on the full flight equations of a Lynx helicopter. This gave a full six degrees of freedom simulation from the hover up to 160 kn. The digital computer was coupled to an analogue to digital input and digital to analogue output system which handled stick and collective inputs etc, and provided output drives to a visual outside world presentation and the flight instrument displays. The simulator cockpit was a representative wooden mock-up of the front of the Lynx helicopter.

The simulated outside world was provided by closed circuit television system which comprised a camera viewing a contoured modelled belt scaled at 3000:1. This scaling was just adequate to provide realistic contouring and reasonable simulation of airfields, towns, woods etc. Helicopter forward velocity was represented by a combination of belt speed and camera lateral tracking. Height was represented by camera displacement above the terrain. The camera viewed the modelled terrain via an optical probe which reproduced aircraft pitch, roll and heading changes. The inputs to the various angular and linear servo systems was provided by ground axis transformation algorithms in the computer programme, via the digital to analogue converter interfaces.

The only instrumentation in the cockpit was an 0.28m diagonal television monitor which presented the terrain image, together with superimposed flight information provided by a programmable symbol generator. The initial display format used was identical to that shown in Fig 1. As the camera field of view of the modelled terrain was $40^{\circ} \times 30^{\circ}$ and the monitor only subtended $17.5^{\circ} \times 13^{\circ}$ at the normal viewing distance of 0.7 m, the outside world image was seen at less than half scale.

4.2 Helmet mounted display

The only parts of the normal airborne system which were used in the simulation were the head sighting unit and helmet mounted display and associated drives. The action of the platform mounted sensor was simulated by driving the camera and optical probe of the simulated outside world in a suitable manner as described below.

The head sighting system and helmet display were manufactured by Honeywell and are illustrated in Fig 4 in position in the cockpit. The head sighting system basically consisted of two sensor surveying units (SSU) mounted each side of the pilot's head which produced horizontal fan shaped infra beams, which swept in an arc downwards through the cockpit. These beams were detected by a pair of phototransistors mounted horizontally with a separation of 150 mm on one side of the helmet, together with a corresponding pair on the other side. Each SSU produced two synchronised infrared fans separated vertically by about 100 mm. The intersection of these beams with the phototransistors generated pulses whose timing relative to the start of the scan was used to calculate the helmet attitude relative to the SSU. Axis transformation calculations were then performed to convert the SSU referred angles to head elevation and azimuth angles relative to the cockpit. In the simulator a further stage of axis transformation had to be performed to convert these cockpit or aircraft axes angles to ground axes. The ground referred head azimuth and elevation angles were then simply added to the normal aircraft heading and pitch angles respectively, and then fed to the outside world camera optical probe. Whatever the attitude of the aircraft, the optical probe responded as if it were a two degree of freedom sensor platform mounted on the aircraft. With the camera output presented on the Honeywell helmet mounted display, the pilot had an instantaneous field of view of 40° of the outside world at unity magnification, focussed to infinity. This outside world image was superimposed with the flight information developed during the flight trials and shown in Fig 2. The helmet display was mounted horizontally along the bottom edge of the right hand side of the helmet. The 25mm CRT contained within the unit was viewed via in-line collimating optics and a reflector plate as illustrated in Fig 5. As with all current designs this helmet mounted display was monocular, the outside world image only being viewed by the pilot's right eye. This not only gave rise to asymmetric weight problems, but also produced severe operating problems as discussed later.

5 EXPERIMENTAL DESIGN

In the sections below, a summary of the trials procedures used to assess each of the three night vision systems is given. Although differing in detail, the common factor in each case was the incremental approach adopted which ensured the trials successful outcome.

5.1 Fixed sensor assessment

To facilitate the slow progression in task difficulty, on the fixed sensor trials, two experimental flying areas were selected. The first of these contained reasonably flat terrain, free from major obstacles and power cables. A route was formed which followed the boundaries of this area. This was some 35 km in length and was considered to be the basic training and familiarisation route for the trials. The main experimental flying area which was used, once sufficient experience had been built up to undertake tactical flying and area navigation, contained much more demanding terrain with hills up to 500 ft above adjoining valleys, and covered a much larger area than the familiarisation route. Within this 'advanced' area, ten obvious ground features were selected to provide designated way-points. A number of different routes could then be formed using these as turning points.

In the test plan for the trials the flying was divided into four separate blocks. The first was a television familiarisation period. Here both the daylight TV and LLTV were used whilst the helicopter was flown along the training route at clearance heights of around 300 ft. These flights were all conducted in day visual meteorological conditions (VMC) with the LLTV fitted with neutral density filters to prevent light overload. On these flights the evaluation pilot compared the performance of the daylight and low light systems. In this block sufficient flights were undertaken to bring the pilots up a learning curve on flying the helicopter using a TV image of the terrain ahead, and to confirm the results of previous phases of the trials regarding required fields of view and ground feature resolution for the piloting and navigation task.

The initial objective in the second period of flying was to establish a performance baseline for low level flying and navigation in the Sea King over a known route. This was done because, although ideal as a flying laboratory, the large size and slow height response of this helicopter make it unrepresentative of the smaller lighter helicopters which would be used for operational low level piloting and navigation. The baseline performance measurements were achieved by flying the Sea King with the unaided eye in day VMC along the training route. Here the evaluation pilot attempted to maintain a constant clearance height of 300 ft agl, this being reduced to 200 ft agl and finally 100 ft agl, as experience and confidence increased. The airspeed flown was left to the discretion of the safety pilot but was not greater than 90 kn.

This exercise was then repeated in day VMC along the training route under the same flight conditions, but with the evaluation pilot flying on the TV picture of the terrain ahead. Initially, these flights were conducted with no flight information superimposed on the TV image. This was found to be essential however, once the evaluation pilot flew with a hood over his helmet, which obscured his forward and peripheral view through the windscreen. Both daylight and low light cameras were used for this flying. The zoom lens on the daylight camera allowed a wide range of fields of view to be investigated.

The third period of flying consisted entirely of night flying and ran concurrently with the latter half of the second block. The first exercise was to fly at 500 ft agl, using the LLTV system, around the training route. This was done in as wide a range of scene illumination as practicable. The main objectives of this exercise were to see if the conclusions drawn from the daylight flying remain valid and to investigate new problems created by the night environment. As experience and confidence increased the clearance height was gradually reduced. The final block of flying was undertaken in the advanced area. This permitted longer flights to be undertaken with a wide choice of different routes.

As experience and confidence increased during the trials, the evaluation pilots were requested to undertake the communications and engine management tasks as well as the piloting and navigation. This was done to establish if single pilot operation at low level would be feasible and, if not, how the responsibilities could be divided. This would in turn provide an indication of the skill level required from the second crew member.

5.2 Passive night goggles

Most of the trials of the night goggles were conducted after the fixed and sensor assessment, and the experimental design was largely the same. For daylight flying the goggles were fitted with neutral density filters to prevent light overload. The trials followed the general pattern described of flying on the basic well known routes by day at safe heights and then slowly reducing clearance heights as confidence and experience increased. It was anticipated at the start of the trials that low flying over unknown routes using the roller map system would be difficult if not impossible, due to the lack of colour cues, resolution and depth of focus when viewing the instruments and navigation system through the goggles. This was borne out during the trials as discussed in section 7.

5.3 Helmet mounted display

As in the airborne flight trials, the participating pilots were given a familiarisation period, both to learn to fly the simulator with its limited flight cues and to learn to use the helmet mounted display.

The pilots in the experiment had varied flying experience and, of course, different learning curves. This created the difficulty of deciding how much practice time each pilot required to ensure all the pilots were at the same level of performance before undertaking the tasks. As a simple measure of task proficiency participating pilots had to keep their height over the terrain to between 150 ft and 250 ft agl for five minutes, when flying a defined route. The route was 42 nautical miles long and took 35 minutes to complete at about 65 to 70 kn.

There were two major tasks given the pilots to fly. The first was a reconnaissance exercise and involved flying a specified route defined by way-points; the continually updated range and heading to steer readouts being displayed on the flight information overlay. To simulate a reconnaissance operation the pilot was required to spot and verbally identify as many off-track targets, *ie* simulated tanks, as possible. By tape recording the tasks a scoring could be taken of the number identified.

The second task was a simulated anti-tank operation, which was to locate and then fly to tanks in as short a time as possible. This simulated a target search operation with no defined route. The positions of the off-track tanks was not supplied to the pilots. The purpose of both tasks was to make the pilot look off track so that a study of the visually coupled display in its major role could be undertaken. Both tasks were flown in the height range from 150 ft to 250 ft.

6 FIXED SENSOR ASSESSMENT

6.1 Initial day TV flying

During the initial TV flights, it was found to be difficult to assess aircraft height or speed by reference to the two-dimensional TV image. Frequent reference had to be made to the aircraft's conventional instruments, particularly the radio altimeter, and slowly a mixed form of instrument/TV flying was developed. The instrument layout around the pilot's TV monitor was not felt to be ideal for this, the widely spaced instruments making rapid scanning very difficult. Also the pilots were reluctant to take their eyes off the TV screen because ground features were best recognised during the few seconds when they appeared in the foreground of the picture. Once the flight information was superimposed on the picture the piloting task became much easier.

Although the evaluation pilots were thoroughly familiar with the training route, navigation from memory whilst flying on the TV still proved to be very difficult. There was a continual conflict between wanting the widest possible field of view to be able to see as many ground features as possible, and the highest resolution to identify those features, which only came with the narrow fields of view. A compromise had to be accepted, and because the pilots tended to favour wider fields of view for flight at lower clearance heights, a horizontal field of view of around 38^{o} was selected. When flying at 100 ft, foreground features became markedly larger than at 300 ft and hence some reduction in their subtense by increasing the camera field of view could be accepted without pilot performance loss. However, at 100 ft the whole aspect of the terrain was different. Groups of trees for example, instead of having a recognisable plan form took on a different vertical significance. Rising ground ahead could fill the picture with the resulting loss of the horizon. These effects are commonly experienced when low flying, but were greatly amplified when using the TV system. The overall effect of reducing clearance height appeared to be that height judgment was easier than at higher altitudes but navigation and orientation more difficult.

Apart from supplementing the image with the instrument information discussed below, collimation of the image may improve depth perception as has been experienced in flight simulation. Although not easily measured, this improvement may be a psychological factor due to the constancy of subtended angle of image features with fore and aft head movement.

6.2 Assessment of superimposed flight information

The requirement for superimposed flight information on the TV image during daylight practice flights, was increased once the evaluation pilot wore a flying hood which restricted his external forward and peripheral vision permitting only a view of the instrument panel and TV monitor. Flight information was assessed on two flights each consisting of six circuits around the training route. To minimise learning effects, repeated circuits were flown without and then with superimposed flight information. This also enabled the evaluation pilot to give a more considered view of what information was essential and what was useful.

The most important piece of flight information was felt to be radio height. With the hood fitted the pilot found his scan to the conventional radio altimeter too large so that his attention was away from the TV screen too long requiring some reorientation when returning to the picture. At only 100 ft agl this is unacceptable particularly if flying towards rising ground.

The second most important piece of information was felt to be heading. This became apparent after some pilots became 'lost' on a what was to them a well known route. With heading available the pilot would know the heading to steer to the next known ground feature without having to scan across to the HSI.

Flying on the TV image initially without attitude information (horizon bar, aircraft symbol and pitch ladder) was found to be difficult particularly when a large amount of drift was present on the aircraft which could be interpreted as aircraft bank on the TV image. With the attitude stabiliser and cyclic stick trim facilities on the Sea King the correct attitude could be accurately adjusted providing a 'hands off' control ability. In this situation the pilot was less likely to make unrequired stick inputs from misinterpretation of the TV image. However, for smaller lighter helicopters without stabilisation, attitude information would be necessary. Even in the Sea King, it was felt to be valuable particularly at low level when flying towards rising ground when the real horizon could be lost to view out of the top of the picture resulting in no immediate knowledge of pitch attitude. Alternatively, flying towards ground which slopes across the picture can give rise to a false bank cue.

In addition to the flight data already discussed, the following information was felt to be useful but not essential.

(i) Airspeed, this can be deduced from aircraft pitch attitude but pilot workload is reduced if it is presented on the picture. More importantly, groundspeed is needed during a hover to land to stabilise the aircraft's speed in the absence of a downward looking camera.

(ii) Vertical speed; although not felt to be needed by most pilots for the low level flying it was found very useful during an approach to landing.

(iii) Sideforce; with a head down display this can be presented immediately below the monitor. However, since this still requires a scanning away from the screen, albeit only a small amount, it would be useful to have it presented on the TV image if the symbol generation capability is available.

6.3 Night TV flying along the training route

Initial night flights in the third block were undertaken at 500 ft agl in order to compare the performance of the LLTV with the daylight TV under conditions which were not too demanding on the pilot. This also allowed the safety pilot to familiarise himself with the route by night so that he was able to establish the aircraft's position by reference to the features visible to the naked eye. Subsequent flights took place at much lower clearance heights. Qualitative pilot assessment by day was generally validated during the night flying and only the differences are discussed in this section.

The navigational task was more difficult by night due to the reduced image resolution and dependence on feature contrast for identification. This led to greater reliance being placed on the Doppler TANS navigation system as back-up, with the safety pilot reading off range and bearing of the next turning point. Some pilots however, would have preferred to have first hand real time information such as could be obtained from a moving map display. (This latter facility was not available at this stage in the trial.) All pilots found that at night they did not have the spare capacity to operate the TANS whilst flying on the TV picture. Although it was originally intended to maintain around 90 kn whilst flying at low level, the flexibility of the helicopter was not ignored and speed was frequently reduced when the pilot required additional time to assess a situation.

6.4 The total piloting task

After the very promising results achieved in the earlier stages it was decided to commence the final block in the advanced area. The earlier flying along the training route clearly demonstrated that the pilot would be unable to manage the full navigation and piloting task without aid. At this juncture in the trials the TANS moving map display was installed in the aircraft. Within the confines of the advanced area various routes were flown using waypoints. In addition tactical flying was undertaken along valleys taking advantage of ground cover. Another feature available at this stage in the trials was the 'heading-to-steer' director in the TV image as shown in Fig 1. This enabled the pilot to select the next way point previously entered in the TANS computer, the steering director when nulled providing the correct aircraft heading to this way-point.

Flights were undertaken at low level both by day and night. Although the workload and degree of concentration required were high, they were within the pilot's capabilities as evidenced by the fact that some monitoring of engine temperatures and pressures, and dialling in of new radio frequencies could be undertaken. It was felt that this was achieved due to the large amount of experience already built up on TV flying along the training route.

The moving map was found to be easy to use both by day and night. Its central position between the pilots (Fig 2) was not ideal for viewing by the evaluation pilot, but this only became a real problem when the aircraft's position was close to the edge of the map strip and the pilot's look ahead capability was temporarily lost. Because the aircraft's present position on the map was determined by the combination of roller and cursor positions, the map was not track orientated, and the pilot had to scan the map for several seconds to determine track departures.

Once the desired track and selected way-points were marked on the roller map, this problem was overcome to a large extent. For unplanned tactical flying, however, the pilot had to look away from the TV picture for several seconds to gain an impression of aircraft movement. This initially caused workload problems which disappeared as experience increased. When looking away from the TV picture the pilot's reaction was to increase height. Under some situations, height gains of 100 ft were experienced. This again was found to reduce with pilot learning.

With the addition of the heading-to-steer director on the TV picture the total pilot workload was further reduced when flying directly between way-points. In this situation the TANS computer only had to be referred to for the selection of way-points. When navigating using the roller map and steering director, the TV picture was used to confirm the aircraft's position and prevent the clearance height becoming too low. Thus the TV assumed a secondary role in the navigation task. This situation was reversed if a hand held map was used. Here so much time was spent undertaking the navigation task in conjunction with the TV picture that the aircraft height could not be monitored satisfactorily. This in turn demanded a second crew member to undertake the piloting.

6.5 Division of crew responsibilities

With the equipment available in this latest phase of flying the total piloting and navigation task over unknown routes by day and night was within the pilot capabilities. It was felt however, that little spare time was available for aircraft management tasks, *ie* monitoring of temperatures, pressures, fuel cross feed, or for continuous communication tasks and dialling in different radio frequencies. In addition the pilot could not afford the time to look away from the TV picture to enter new way-points into the TANS computer, without reducing flight safety if no safety pilot were present. Overall, the system assessed would require two crew members, one the trained pilot, the second requiring less skill to undertake engine and fuel management and communication together with updating the navigation aid. In the case where no navigation system is used, sorties over unknown routes down to 300 ft agl at night are feasible. Here however, two pilots would be required or one pilot and a navigator. The navigator would provide steering information whilst monitoring the TV image in conjunction with a hand held map. The pilot would fly the vehicle, being given steering and terrain avoidance information by the navigator. Vehicle management in this situation would be shared between the crew.

6.6 Camera performance

The performance of the low light camera was not a limiting factor in the presence of a clear sky and at least half moonlight. Below half moon, without ground lights, camera performance was still satisfactory but limited the flight profile since the pilot could not so easily judge terrain shape, tree heights, closing rates etc. With a crescent moon or no moon and a clear sky, picture quality was very dependent on ground lights, usually not allowing flight below 300 ft agl. With an overcast sky, unless the overcast was thin and a high full moon was present, the light level was low and contrast was also low. With no moon, low level piloting became difficult particularly if ground lights were present. Overall, flights could be undertaken in ambient conditions down to clear starlight (10^{-3} lux) provided that minimal interfering lights were present in the scene. Figs 6 and 7 demonstrate the LLTV performance under different ambient light conditions.

7 NIGHT GOGGLE ASSESSMENT

Due to a number of factors not least of which was availability, only limited flying was carried out in the course of the flight trials using the passive night goggles. This was insufficient to allow a full assessment to be made, but did identify some of the more important problems, which are covered briefly in this section.

7.1 Goggle mounting

This proved to be a major problem with the goggles. The initial solution was to attach them to the helmet with three straps which could be tightened. This drew the mask into firm contact with the face, providing good support and a reasonable degree of comfort as shown in Fig 3. However, donning the goggles was a two handed job which was very difficult in the dark. More importantly, they were difficult to remove and the pilot was therefore committed to the goggles, having no quick release facility. This was considered dangerous particularly in the event of a failure at low level. Various solutions were tried using hinged mountings attached to the helmet visor track. The quick release facility was thereby provided but two new problems were introduced. The first was that with the goggles in the operating position their full moment was applied to the helmet so tending to rotate it forwards. The full weight came to bear on the pilot's forehead just above the eyebrows and had to be braced by the pilot using the muscles in the brow. This caused severe discomfort and pain after about ten minutes of use. The second problem arose with the goggles in the raised position, where they became a hazard in the cockpit with some risk of their fouling controls on the overhead panel when the pilot moved his head. A better solution appears to be strapping the mask of the goggles firmly to the helmet as in the initial technique but with the ability to detach the main working section of the goggles rapidly.

7.2 Ease of use

In general, many of the problems of the TV system caused by the fixed camera and limited field of view can be overcome with the night goggles. However a whole new range of problems was found. The pilot still required information from the instruments. With the ITT 40° field of view bifocal goggles, this could be acquired using the lower near focus section of the goggle optics. However, the depth of focus was not adequate to allow the pilot to use all the instruments without leaning backwards or forwards to bring them into focus. Some illumination of the instruments were required and in many cases the minimum settings were far too bright to be usable with the goggles. It was necessary for some lighting to be on for the safety pilot to monitor the flight and engine instruments. This lighting caused reflections in the transparencies which under some conditions could obliterate the pilot's view through the goggles.

Towards the end of the trials a new system for viewing the cockpit instruments was devised which eliminated all the problems described above. The second generation image intensifier tubes fitted to the ITT goggles are most sensitive to light with wavelengths towards the red/infrared end of the spectrum. Fortunately, light reflected from the terrain at night is predominantly towards the same end of the spectrum. The addition of a red (minus blue/green) filter to the objective lens of the passive night goggles does not result therefore in a serious loss of performance. In addition the low sensitivity of the goggles to the blue/green end of the spectrum means that this colour can be used to illuminate the cockpit at a reasonably high level without overloading the goggles. To implement this concept, the goggle objective lenses were fitted with a red filter containing a small clear convex lens in the centre. The focal length of this lens was chosen so that the instrument panels and consoles in the aircraft would be in focus. The cockpit instruments were then floodlit by green/blue light. This light was accepted by the small lens into the goggle objective and rejected by the red filter. Because of the small size of the convex lens relative to the total goggle objective (0.2 of the goggle diameter) and the insensitivity of the image intensifier to the blue/green light, the lighting level in the cockpit could be high enough to read a standard 1:50000 map without difficulty for the copilot who was not wearing goggles. Also because of the small size of the convex lens, a large depth of focus was achieved, some 0.25 m compared with 0.05 m for the previous bifocal arrangement. The total advantages of this system were as follows: without refocussing, the instruments and outside world stayed in focus over the complete field of view, stray internal reflections did not effect goggle performance, the depth of focus when viewing the instruments was so great that no adjustment of the filter or lens characteristic was needed to cater for variations in aircraft configuration or pilot size.

7.3 Performance

Comparison between the Isocon camera and night goggles was difficult because of the different intensifier sizes. Laboratory tests revealed that on a comparable field of view for field of view test the goggles' performance in terms of resolution was equal to the camera performance down to 10^{-1} lux (half moon). Below this level the goggle performance fell continuously. In addition below 10^{-3} lux (starlight) the image became noise limited and very dim. However, with the larger intensifier format of the camera and the ability to adjust the TV monitor gain and brightness the system gave adequate performance down to 10^{-3} lux.

The ability to fly at low altitude with the goggles down to almost the same light levels as with the television despite this disparity of performance suggests that the ability to see an image at unity magnification and scan rapidly over a large area was of great importance.

8 HELMET MOUNTED DISPLAY

Although this concept was assessed in a fixed base simulator without representative motion or feel characteristics, the results obtained demonstrated the operational advantages and highlighted the potential physiological and psychological problems of the system. Conceptually, the visually coupled system provides the pilot with a full look-around capability and this was adequately demonstrated during the trials. The aspect which was particularly liked was the ability to look into a turn before executing it.

One of the early problems discovered was that platform slew rates and accelerations were critical in maintaining orientation. In the simulator, platform motion was simulated by the optical servo system on the closed circuit television system. The response of this servo could be easily altered to represent different platform response. It was found that in order to prevent perceivable lag the platform required an angular acceleration capability of the order of 900°-$1000^\circ/s^2$ to reach a rate of $120^\circ/s$. The system had also to be critically damped to prevent overshoot or undershoot. When system lags were present, the pilot was forced to reduce his head rotation rate to keep the platform in step, and this not only added to the general task level, but prevented the pilot identifying targets of opportunity. This problem was highlighted when flying at very low level, since small undetected descent rates could quickly increase whilst the pilot was looking off track, resulting at best in large uncontrolled collective inputs, and at worst in a crash. Even with the system optimised, where platform lag for an off axis glance at 90^{o} was no more than 0.1 s, there was a tendency for the pilot to instinctively increase height due to the lack of peripheral vision. Although this problem reduced with familiarisation, it was not solved until the overlay symbology was modified as described below.

8.1 Overlay flight information

Apart from platform head following rate, another source of disorientation was the fact that pilots had initial difficulty in resolving the difference between aircraft heading changes and head azimuth movements, since both produced the same effect on the image presented to the right eye. In addition when looking far off axis, although the inside of the cockpit could be seen by the left eye, the concentration on the display image was such that the pilot could be unsure which position to return to, to establish the aircraft attitude. When the overlay flight instrument display was added (as shown in Fig 1) this resolved some of the problems, but there then arose the question of whether the flight information should move with the head, or remain boresighted to the cockpit in some manner. It was quickly established that the latter procedure minimised any disorientation effects. To implement this, the head offset angles in azimuth and elevation were used to drive the overlay information across the CRT face to correspond one for one in angular subtense to the offset of the optical servo on the camera. To prevent the overlay information disappearing off the CRT for large head offsets, the drive signals were limited so that one edge of the flight information could always be seen. In this way the pilot always knew in which direction to move his head to re-establish the boresight. The only refinement made to this concept during the course of the trials was that the aircraft radio height was not driven in this way, so that it always remained in the same position in the pilot's instantaneous field of view of the CRT. With the height readout always present the pilot knew immediately if the ground clearance was reducing when looking to the side.

Navigation was not a problem using the helmet display when a preplanned route was followed, and the way-point number, range to that way-point, and the heading to steer were presented on the overlay flight information. Unplanned navigation proved to be very difficult due to the problems arising when attempting to view a map with the left eye and relating this to the image in the right eye. This aspect is explored more fully in section 8.3.

8.2 Helmet mounting

The mounting of the helmet display along the right hand side of the helmet gave rise to an asymmetric weight problem. Although the unit was fitted just below the head centre of gravity to reduce its effective moment, it still tended to roll the pilot's head to the right. The compensatory muscle power needed to hold the head upright produced slight neck ache in some pilots after an hour's sortie. In a separate experiment it was found that compensating weights on the left side of the helmet improved wearing comfort considerably without increasing total head inertia to the point where rapid azimuth movements became difficult. Another problem which effected performance was cable drag. Apart from the normal earphone and throat microphone cable, the head sighting cable and helmet display drive cable ran from the back of the helmet to their respective drive electronics. To prevent any significant restriction on normal head movements, the cable weight was fully supported by rubber straps fixed to the cabin roof. Operationally this may be feasible, provided the design includes a provision for rapid release in an emergency situation.

8.3 Ease of use

In order to minimise the weight of the helmet display, the size of the display objective lens, intermediate lenses and combiner glass were kept as small as possible consistent with the 40° field of view requirement. It was found in practice however, that the very small image exit pupil and eye relief that the design philosophy produced, made it very difficult to adjust the display on the helmet, for particular subject pilots, to achieve the full field of view without vignetting. This posed particular problems for the subject pilots who wore glasses, most of whom were unable to establish a satisfactory adjustment. The criticality of this optical design would obviously cause serious problems when the helmet display was used with any form of chemical or biological defence mask. It should be stated that the unit tested was early generation equipment, and that more recent displays have a larger exit pupil and eye relief. Nonetheless, to achieve a totally acceptable design requires an optical design where the element nearest the eye had some optical power. One way of achieving this is to use the helmet visor, as this optical element acting as a holographic lens.

8.4 Binocular rivalry

Helmet sighting systems which inject weapon or flight data into the right eye have been in use for some considerable time with great success. In this case, both eyes can see the outside world and because the disparate flight data into the right eye is a relatively small proportion of the total field of view and consists of low spatial frequency information the brian accepts this without difficulty. This is not the case for the visually coupled system however, where totally disparate information is fed to the foveal areas of each eye. This situation gives rise to a physiological effect called binocular rivalry which proved to be the most significant problem found during the simulator trial. In normal operational flying the pilot would be expected to view the image of the outside world with the right eye and then switch his mental attention to the left eye when anything needed to be monitored in the cockpit. In the simulator, the cockpit was darkened to simulate night conditions and the display set to comfortable viewing brightness of 2-3 ft lamberts. After a certain period (which varied greatly from a few minutes to half an hour depending on the subject), the pilot found it more and more difficult to concentrate on the outside world as the scene in the left eye would keep breaking into their attention. The only way to stop this effect, once started, was for the pilot to shut his left eye. By experimentation, it was found that equalising the light level into each eye caused the rivalry problem to occur fairly soon after the start of the flight and the pilot would be constantly distracted by the left eye scene resulting in severe pilot fatigue after a half hour sortie. If the light level into the left eye was reduced to a minimum by using a darkened visor with a patch over the foreal region, this increased the time to the onset of the rivalry problem, but then when it did occur it was more dramatic, causing the outside world information into the right eye to be lost temporarily. Operationally, at low level by night this could be disastrous.

It was concluded overall from the experiment that the visually coupled system was viable provided that a bi-ocular or binocular viewing system could be developed to overcome this rivalry problem.

9 CONCLUSIONS

The trials on the night vision system described in this paper demonstrated the feasibility of using an indirect view of the terrain ahead, to pilot and navigate a helicopter at low level, over known and unknown routes. Specific conclusions on each system are given below. In summary, it is believed that each system could have an application in helicopters having different role requirements.

9.1 Fixed sensor

The trials on this system demonstrated the capability to pilot and navigate a helicopter over essentially unknown terrain by night, in a wide range of ambient light levels. Unaided navigation by the pilot using the LLTV was only possible over a known area. The provision of a moving map or other pilot interpreted navigation aid is essential for single pilot operation over an unknown area.

For operations in a known area one qualified pilot is required to pilot and navigate at low level. However, the pilot stress and concentration level is such that when considering sorties of significant length a second crew member is required to undertake vehicle management and communications. Low level operation in unknown areas only requires a single pilot if an automatic navigation aid is used. A second, less skilled crew member, is still required however to undertake vehicle management, communications and also update the navigation system.

Low level flying using the night vision system demonstrated the need for superimposed flight information on the TV image. Radio height, attitude and heading were felt to be essential. In addition vertical speed, airspeed and sideforce were felt to be useful.

9.2 Night goggles

The flying undertaken with the passive night vision goggles demonstrated that they offer a viable alternative solution to the night piloting problem. Although having a theoretically lower performance capability than the LLTV they could be used down to comparable lighting conditions, possibly due to their unity image magnification and the ability to scan the scene.

There are a number of problems requiring further investigation, one of the main ones being their mounting on the head. To be completely effective, it is essential that a comfortable mounting with a quick release facility be developed.

Viewing the instruments using the bifocal goggles gave rise to problems, and a shared aperture system based on the use of a complementary filter was successfully investigated.

9.3 Visually coupled system

The limited simulator trial demonstrated the feasibility of this type of system for piloting a helicopter at low level. The main advantage of the system is that it provides the pilot with a complete look-around capability, where the area of coverage is dictated solely by the platform freedom. In addition the night operating capability is determined by the platform mounted sensor, which is not constrained by aperture size and unit weight in the same way as the passive night goggles. The main human factors problem is that the image is injected into one eye. This causes binocular rivalry which could produce serious flight safety problems when operating at low level. It is concluded that the development of a bi-ocular viewing system is mandatory, if the visually coupled system is to be operationally viable. Overlay flight information was found to be essential if the pilot orientation was to be maintained.

0.7 m, the average instrument viewing distance, when the remaining upper 60% was focussed at infinity. The weight of the basic goggles evaluated was 0.825 kg, which posed some problems with helmet mounting, not only due to their basic weight, but also because of the forward moment they produced.

4 VISUALLY COUPLED NIGHT VISION SYSTEM

In the normal airborne installation, the visually coupled system comprises a head sighting system coupled to a slewable platform in the nose of the aircraft. Within the platform, a suitable night vision sensor is mounted, either low light television (LLTV) or forward looking infrared (FLIR). The sighting system measures pilot head angular orientation in elevation and azimuth, and these signals are fed to the platform so that the night vision sensor is locked to the pilot's line of sight. The sensor output is fed to a helmet mounted display which presents to the pilot a collimated scene image at unity magnification. As the pilot moves his head, the platform follows (up to the gimbal limits) giving a continuous view of the outside world as if the pilot were looking through the windscreen. Typically the system provides an instantaneous field of view of 40° with an area of coverage from the platform of $\pm 180^\circ$ in azimuth and $+ 20^\circ$ to $- 110^\circ$ in elevation. Because of the elevation coverage, the pilot can actually 'look through the floor' of the helicopter vertically downwards. Provided potential disorientation effects can be overcome the visual coverage at night is much greater than with passive night goggles. This can be very advantageous during search and rescue missions or when landing in a restricted site.

4.1 Helicopter simulation

The assessment of the helmet mounted display system was carried out using a fixed base digital simulation of the Lynx helicopter (WG 13). The mathematical model was programmed on a Redifon 2000A computer and was based on the full flight equations of a Lynx helicopter. This gave a full six degrees of freedom simulation from the hover up to 160 kn. The digital computer was coupled to an analogue to digital input and digital to analogue output system which handled stick and collective inputs etc, and provided output drives to a visual outside world presentation and the flight instrument displays. The simulator cockpit was a representative wooden mock-up of the front of the Lynx helicopter.

The simulated outside world was provided by closed circuit television system which comprised a camera viewing a contoured modelled belt scaled at 3000:1. This scaling was just adequate to provide realistic contouring and reasonable simulation of airfields, towns, woods etc. Helicopter forward velocity was represented by a combination of belt speed and camera lateral tracking. Height was represented by camera displacement above the terrain. The camera viewed the modelled terrain via an optical probe which reproduced aircraft pitch, roll and heading changes. The inputs to the various angular and linear servo systems was provided by ground axis transformation algorithms in the computer programme, via the digital to analogue converter interfaces.

The only instrumentation in the cockpit was an 0.28m diagonal television monitor which presented the terrain image, together with superimposed flight information provided by a programmable symbol generator. The initial display format used was identical to that shown in Fig 1. As the camera field of view of the modelled terrain was $40^\circ \times 30^\circ$ and the monitor only subtended $17.5^\circ \times 13^\circ$ at the normal viewing distance of 0.7 m, the outside world image was seen at less than half scale.

4.2 Helmet mounted display

The only parts of the normal airborne system which were used in the simulation were the head sighting unit and helmet mounted display and associated drives. The action of the platform mounted sensor was simulated by driving the camera and optical probe of the simulated outside world in a suitable manner as described below.

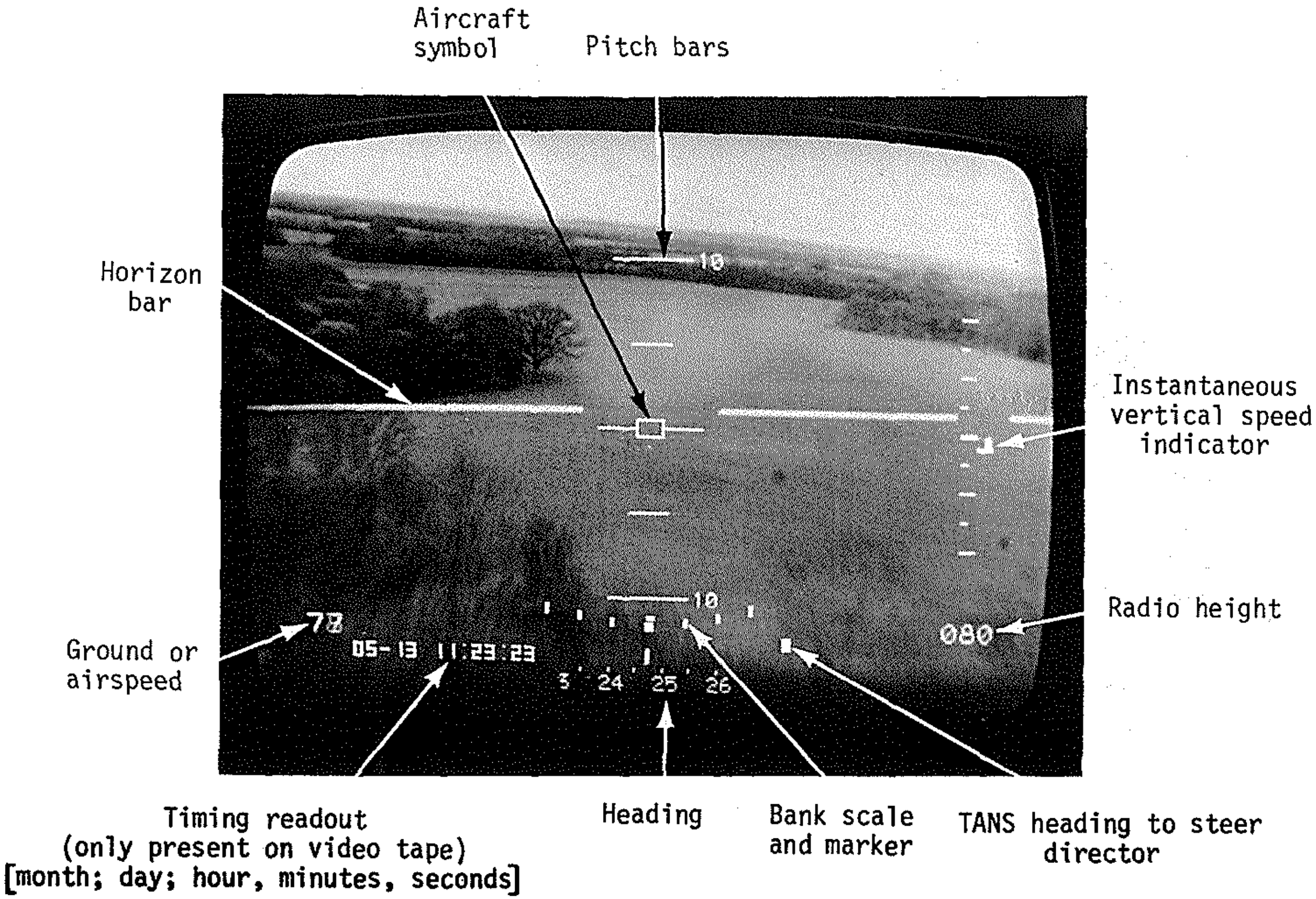
The head sighting system and helmet display were manufactured by Honeywell and are illustrated in Fig 4 in position in the cockpit. The head sighting system basically consisted of two sensor surveying units (SSU) mounted each side of the pilot's head which produced horizontal fan shaped infra beams, which swept in an arc downwards through the cockpit. These beams were detected by a pair of phototransistors mounted horizontally with a separation of 150 mm on one side of the helmet, together with a corresponding pair on the other side. Each SSU produced two synchronised infrared fans separated vertically by about 100 mm. The intersection of these beams with the phototransistors generated pulses whose timing relative to the start of the scan was used to calculate the helmet attitude relative to the SSU. Axis transformation calculations were then performed to convert the SSU referred angles to head elevation and azimuth angles relative to the cockpit. In the simulator a further stage of axis transformation had to be performed to convert these cockpit or aircraft axes angles to ground axes. The ground referred head azimuth and elevation angles were then simply added to the normal aircraft heading and pitch angles respectively, and then fed to the outside world camera optical probe. Whatever the attitude of the aircraft, the optical probe responded as if it were a two degree of freedom sensor platform mounted on the aircraft. With the camera output presented on the Honeywell helmet mounted display, the pilot had an instantaneous field of view of 40^{o} of the outside world at unity magnification, focussed to infinity. This outside world image was superimposed with the flight information developed during the flight trials and shown in Fig 2. The helmet display was mounted horizontally along the bottom edge of the right hand side of the helmet. The 25mm CRT contained within the unit was viewed via in-line collimating optics and a reflector plate as illustrated in Fig 5. As with all current designs this helmet mounted display was monocular, the outside world image only being viewed by the pilot's right eye. This not only gave rise to asymmetric weight problems, but also produced severe operating problems as discussed later.

5 EXPERIMENTAL DESIGN

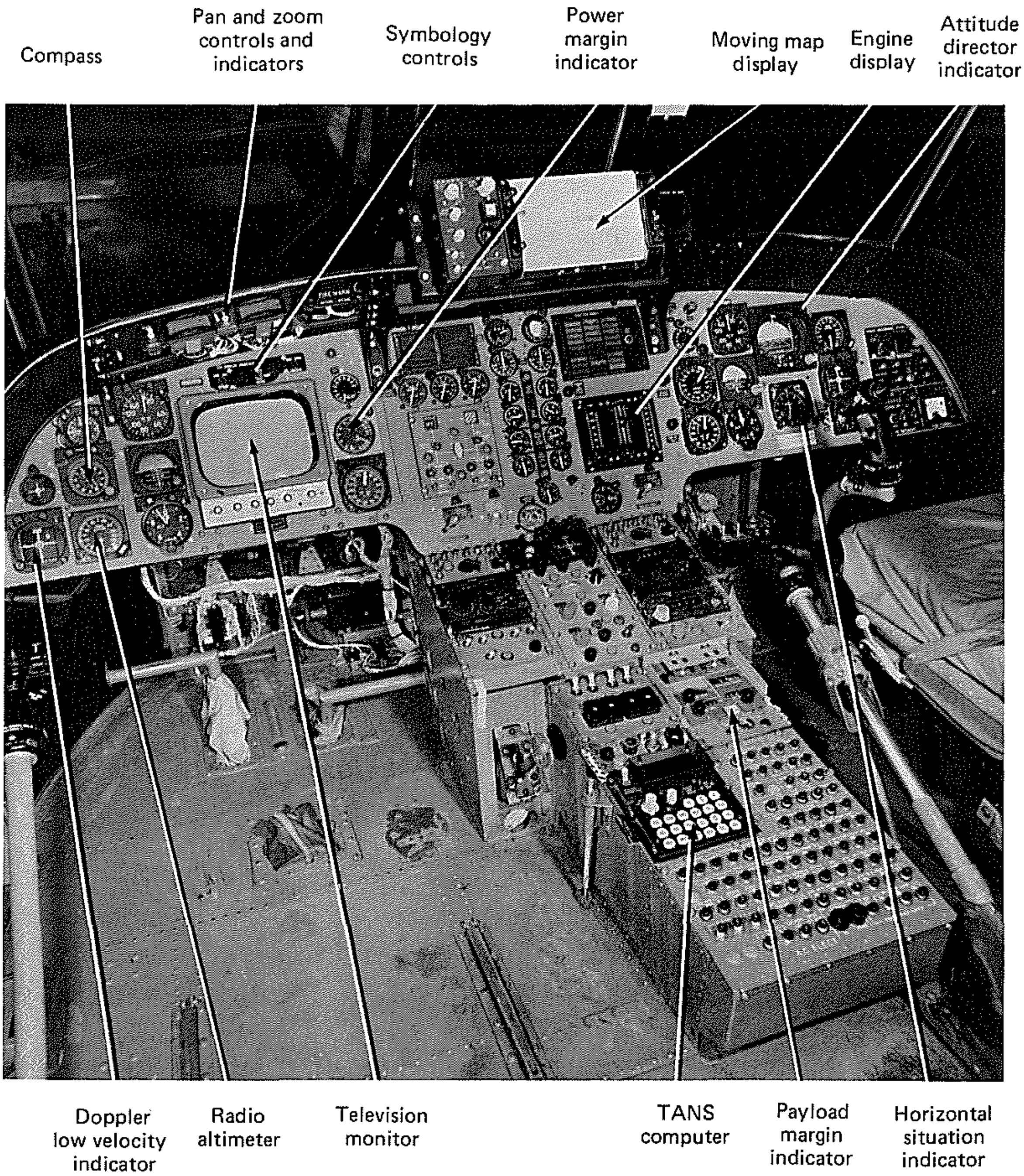
In the sections below, a summary of the trials procedures used to assess each of the three night vision systems is given. Although differing in detail, the common factor in each case was the incremental approach adopted which ensured the trials successful outcome.

5.1 Fixed sensor assessment

To facilitate the slow progression in task difficulty, on the fixed sensor trials, two experimental flying areas were selected. The first of these contained reasonably flat terrain, free from major obstacles and power cables. A route was formed which followed the boundaries of this area. This was some 35 km in length and was considered to be the basic training and familiarisation route for the trials. The main experimental flying area which was used, once sufficient experience had been built up to undertake tactical flying and area navigation, contained much more demanding terrain with hills up to 500 ft above adjoining valleys, and covered a much larger area than the familiarisation route. Within this 'advanced' area, ten obvious ground features were selected to provide designated way-points. A number of different routes could then be formed using these as turning points.



Figs 1 Flight symbol format shown superimposed on the TV image



Figs 2 Cockpit layout of the Sea King

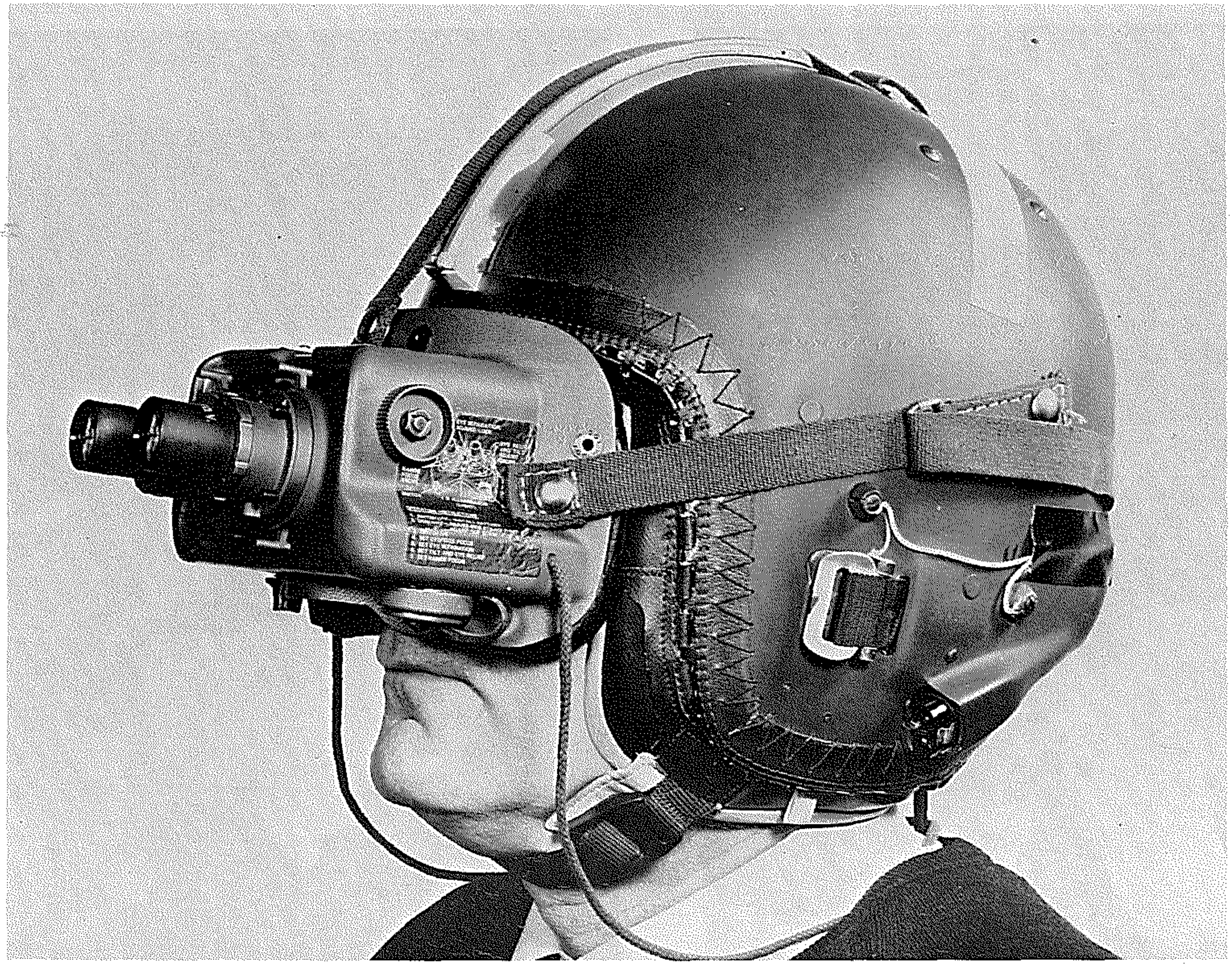
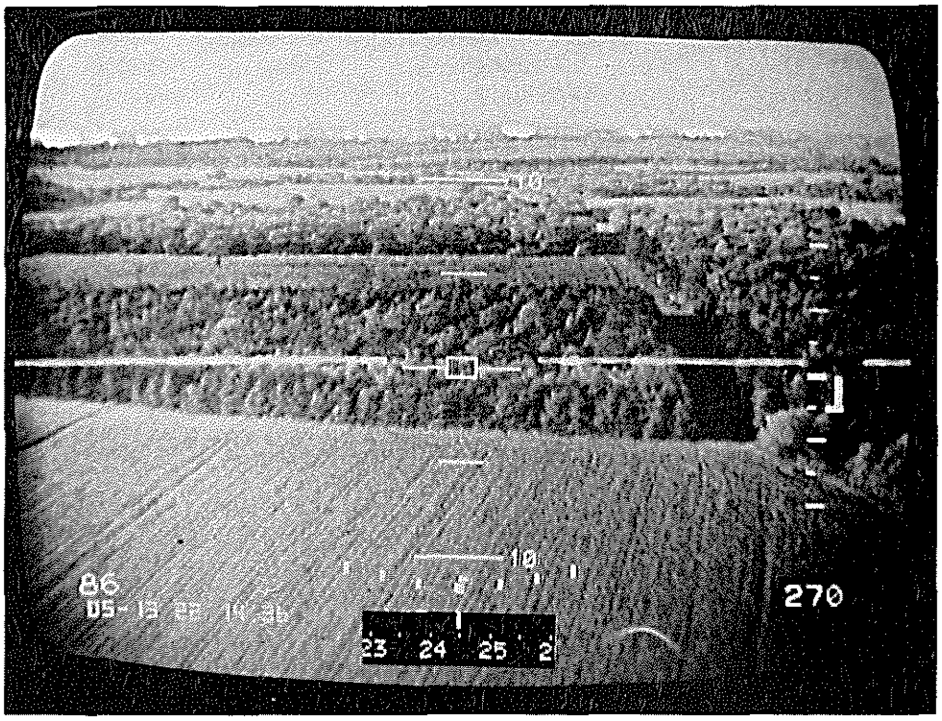


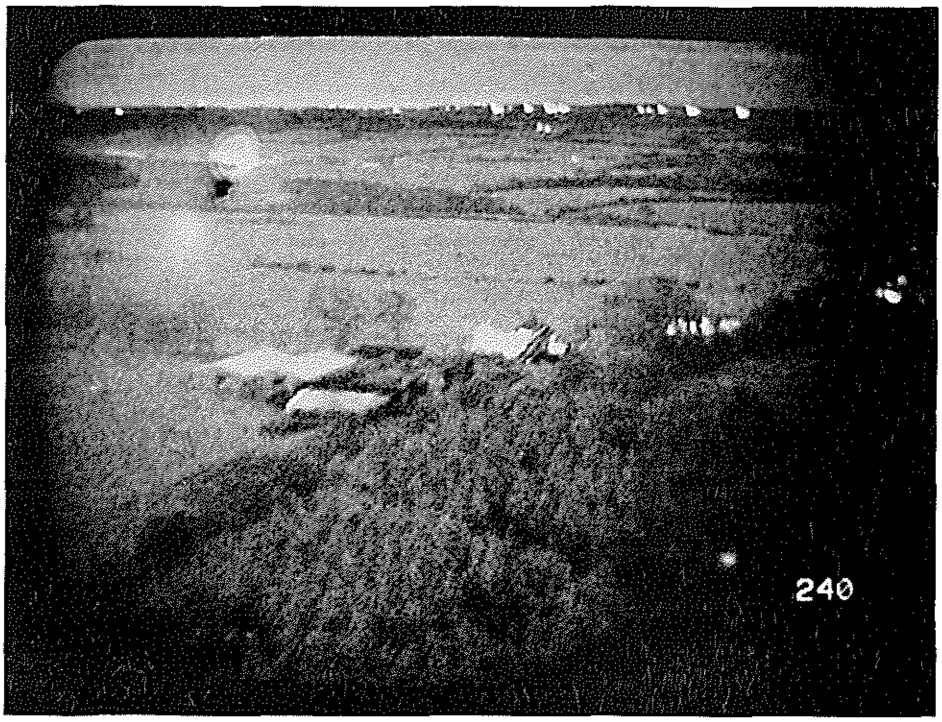
Fig 3 Initial three strap night goggle mounting system. The goggles have a 40° field of view and are manufactured by ITT

Fig 4 Helmet mounted display and sighting system installed in the simulator

Fig 5 Front view of the helmet mounted display



Figs 6 LLTV output under full moon clear sky conditions ground light only present at horizon (2×10^{-1} lux)



Figs 7 LLTV output under ¼ moon clear sky conditions some ground lights present (10^{-2} lux)