GEC AVIONICS

Wide Angle Raster Head Up Display

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INTRODUCTION

In recent years, the fighter aircraft designer has been faced increasingly with the need to present large and varied quantities of information to the pilot in a readily assimilable form, within the fixed confines of the cockpit. One of the most significant aids to this has been the introduction of the cursive, or stroke written, head up display, which combines flight instrumentation information with the full range of weapon aiming capabilities. This is now accepted as standard equipment for all but the simplest ground attack and fighter aircraft. A good example of a day cursive HUD is the F-16 system.

A development of the standard cursive HUD is the raster night vision HUD, which can display imagery from an electro-optical sensor in raster format, with conventional symbology overlaid. There have been two major fixed wing night vision programmes to date, the US Navy A-7 Corsair FLIR system, and the RAE Farnborough Hunter night low level system, initially using low light TV, and more recently FLIR. These systems both use a raster HUD to present an electro-optical image of the scene in front of the aircraft to the pilot, overlaid on the real scene. Trials have shown conclusively that there are significant advantages in displaying this imagery directly in front of the pilot, scaled one to one and positioned so that it corresponds with the normal daylight scene. Presented in this way, the electro-optical image permits the pilot to fly at low level by night in fair weather; it does not however allow continued operations in full IMC conditions. Because the image seen by the pilot relates directly to what he is used to seeing by day, he can continue to use his normal day low flying visual cues and techniques by night, thus increasing safety and decreasing workload.

The significance of this development is that it allows effective low level operations in VMC conditions by night as well as day. As shown in figure 1, in a European winter an effective electro-optical aid can increase capability by 200%, from 20% to 60% of the 24 hour period on average. This ability to penetrate hostile areas at very low level at night is further enhanced since the system is totally passive, with no emissions to forewarn enemy defences and give away the aircraft's position.

The other major benefit of such a system is that it adds to flexibility. The use of an electro-optical imaging system gives a realistic night capability to relatively simple

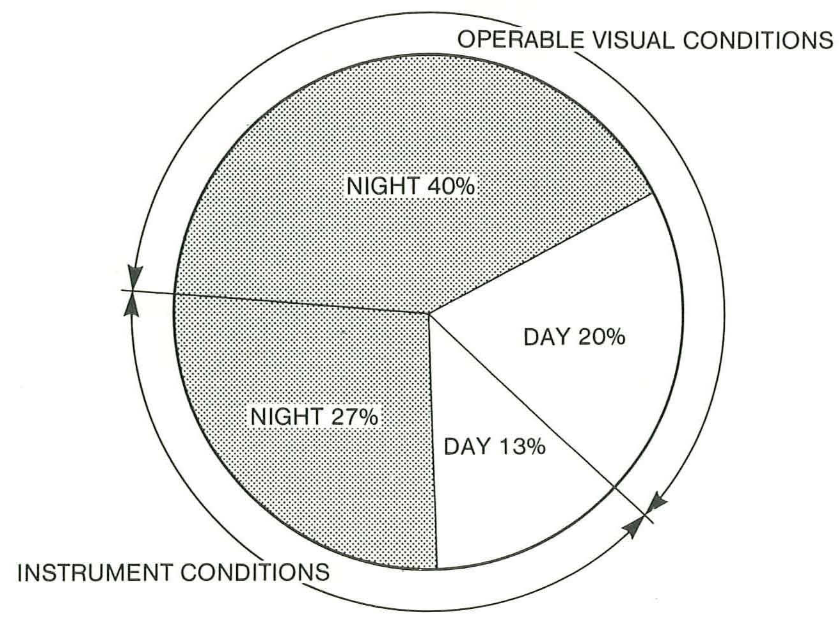

Figure 1 Central Europe in Winter

day ground attack fighters at a much lower cost than any comparable active terrain-following system. By the employment of a judicious mix of simple single-seat fighters with night vision systems and more sophisticated all-weather attack aircraft with terrain-following systems, the air force commander is given an optimum combination of a large force of day/night VMC aircraft and a smaller specialised force of sophisticated all weather aircraft. This combination allows the commander to maintain a realistic capability for the VMC portion of the day, and to reserve the limited number of expensive all weather aircraft for when they are really needed.

THE SIGNIFICANCE OF FIELD OF VIEW

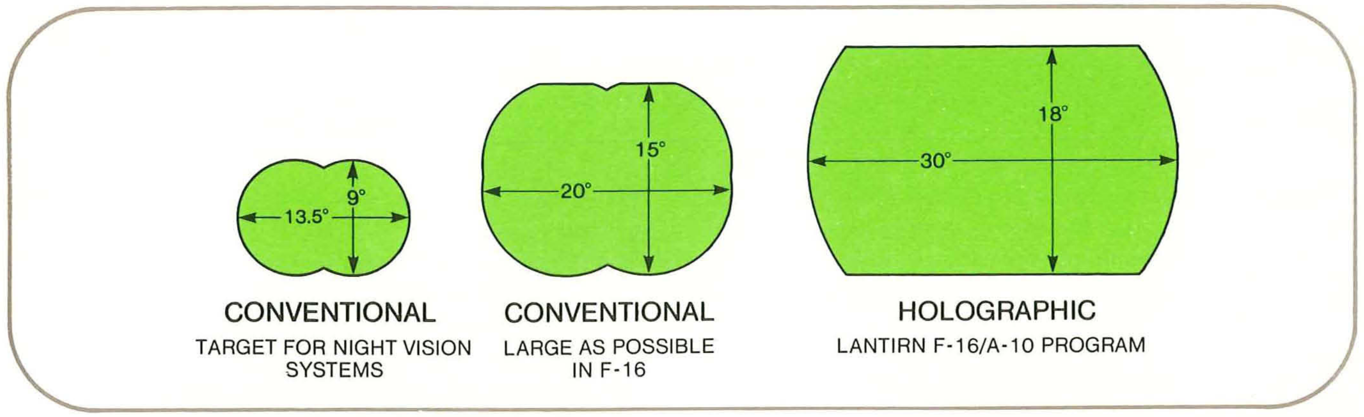

Figure 2 Fields of View achievable for F-16 using Refractive and Diffractive Optics

Widespread experience of operating at low level by night using electro-optical sensors has been accumulated on the US Navy A-7 and the RAE Hunter. The Hunter is particularly significant, since it is the only fixed-wing aircraft to have used the night vision sensor displayed one to one on a raster HUD as its only low flying aid. This experience has demonstrated the importance of field of view for a fixed forward-looking sensor. As shown in figure 2, a standard F-16 cursive HUD has an instantaneous field of view of 13.5° in azimuth by 9° in elevation. For the Hunter HUD, these figures were increased to 20° by 15°. It should be appreciated that this field of view represents the only area in which the pilot has a view of the "outside world" when flying by night, and consequently this HUD display is his only low flying reference. Subjective experience indicates that this latter field of view (20° by 15°) is the approximate minimum acceptable for night low level operations over a representative range of operating conditions. This opinion was formed empirically by early trials using various fields of view and image scaling. However there is also no doubt that a larger field of view in both azimuth and elevation is highly desirable.

There are two main reasons for wanting a wide field of view in azimuth. Firstly if too narrow a field of view is used, the pilot will have difficulty in maintaining his visual orientation, and in appreciating his instantaneous relationship with the ground. This forces him to increase his height above the ground for safety reasons, which in some circumstances can exacerbate the lack of orientation. Secondly, the pilot relies on an adequate azimuth field of view to acquire targets and navigational features, and hence to navigate and operate effectively. Figure 3 demonstrates why. If we assume a 20° azimuth field of view, a navigational system drift rate of 1.5 nautical miles per hour and a target or waypoint acquisition range of 3 kms, the pilot will have to update his navigation system at least every 11 minutes. A reduction of the azimuth field of view to 15° would require an update every 8 minutes, which would be unacceptable operationally in most environments.

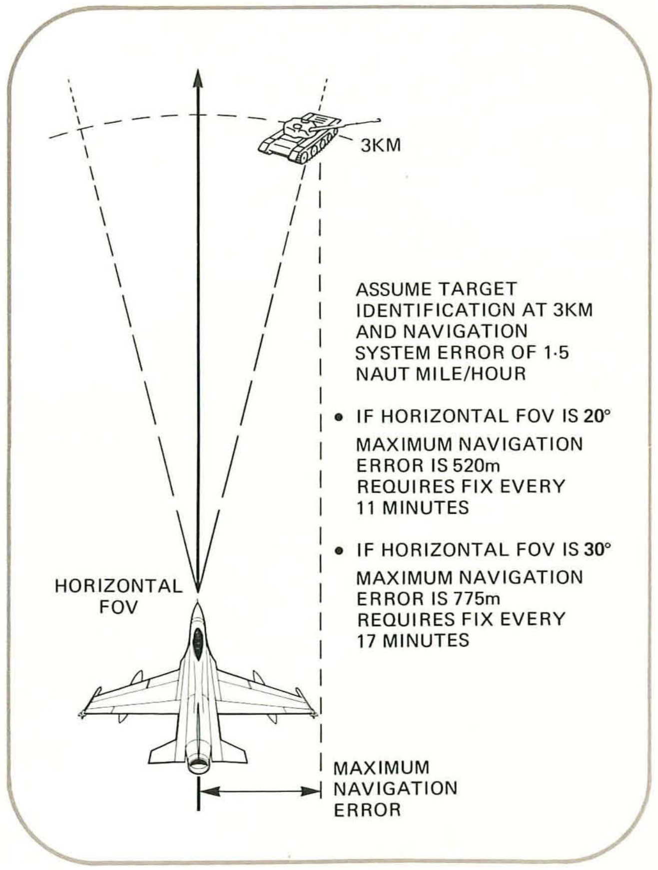

Figure 3 Significance of Horizontal Field of View

Conversely an increase to 30° azimuth angle eases target acquisition, and requires an update every 17 minutes. In practice updates would be required more frequently than indicated above to allow for error.

The need for a large vertical field of view is dictated by a combination of manoeuvring requirements and operational factors. The lower limit of the vertical field of view is defined by either the sight line over the nose, or the weapon aiming release point for the highest drag weapon employed, or the need to provide the pilot with an adequate sight line for orientation and terrain avoidance. The vertical field of view available defines the upper limit. As shown in figure 4, a 15° vertical field of view, giving an average coverage from 12° below the velocity vector to 3° upward field of view, is adequate for straight and level flight. However, as shown in figure 5, when the aircraft is manoeuvred hard at low level, this upward field of view is transformed into the look angle into the turn. A 3° look angle into the turn is marginal for ensuring obstacle avoidance at high turn rates; the aircraft is consequently limited to about 45° of bank in a steady turn. However, if the vertical field of view is increased to 18°, this transposes into a 6° upward look angle. This 100% increase in look angle means that the aircraft can be turned at large bank angles with adequate obstacle avoidance, as shown in figure 6. Vertical field of view is therefore clearly critical in permitting freedom to manoeuvre hard at low level in safety.

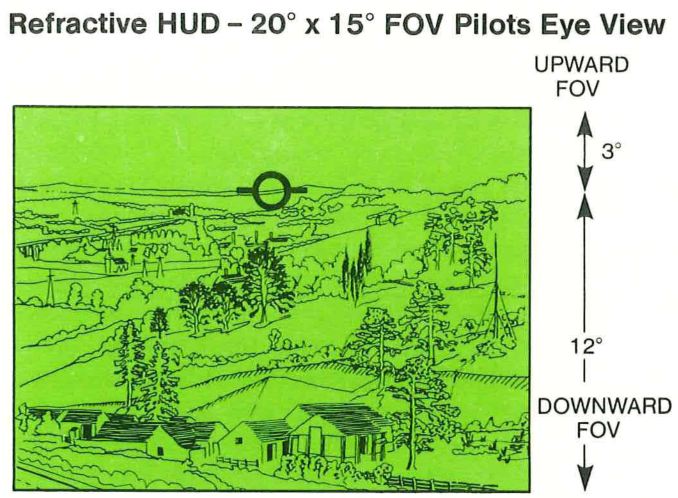

Figure 4 HUD Field of View – Straight and Level

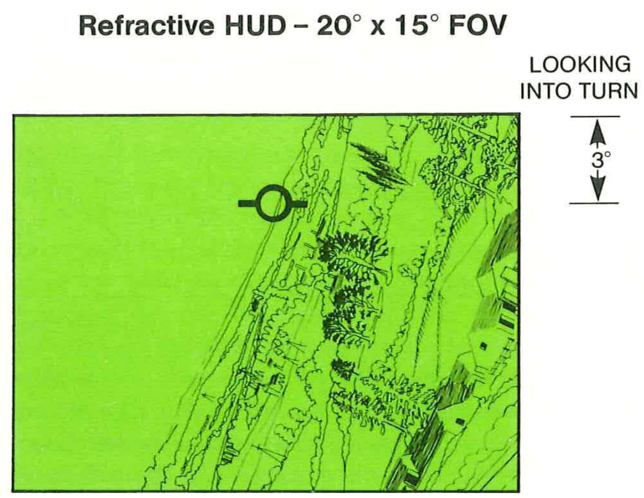

Figure 5 HUD Field of View – Turning Flight

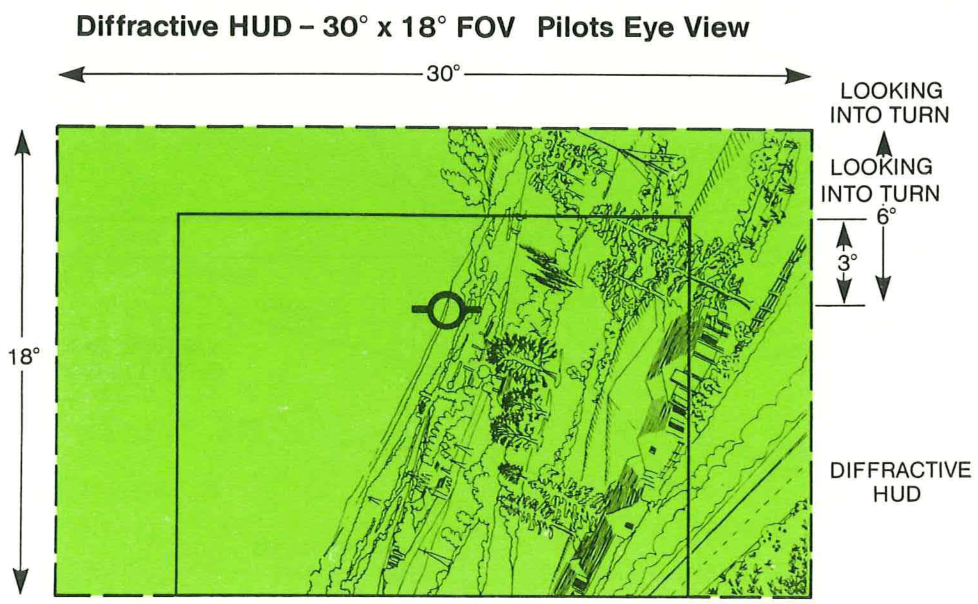

Figure 6 HUD Field of View – Turning Flight

DESIGN FOR WIDE FIELD OF VIEW

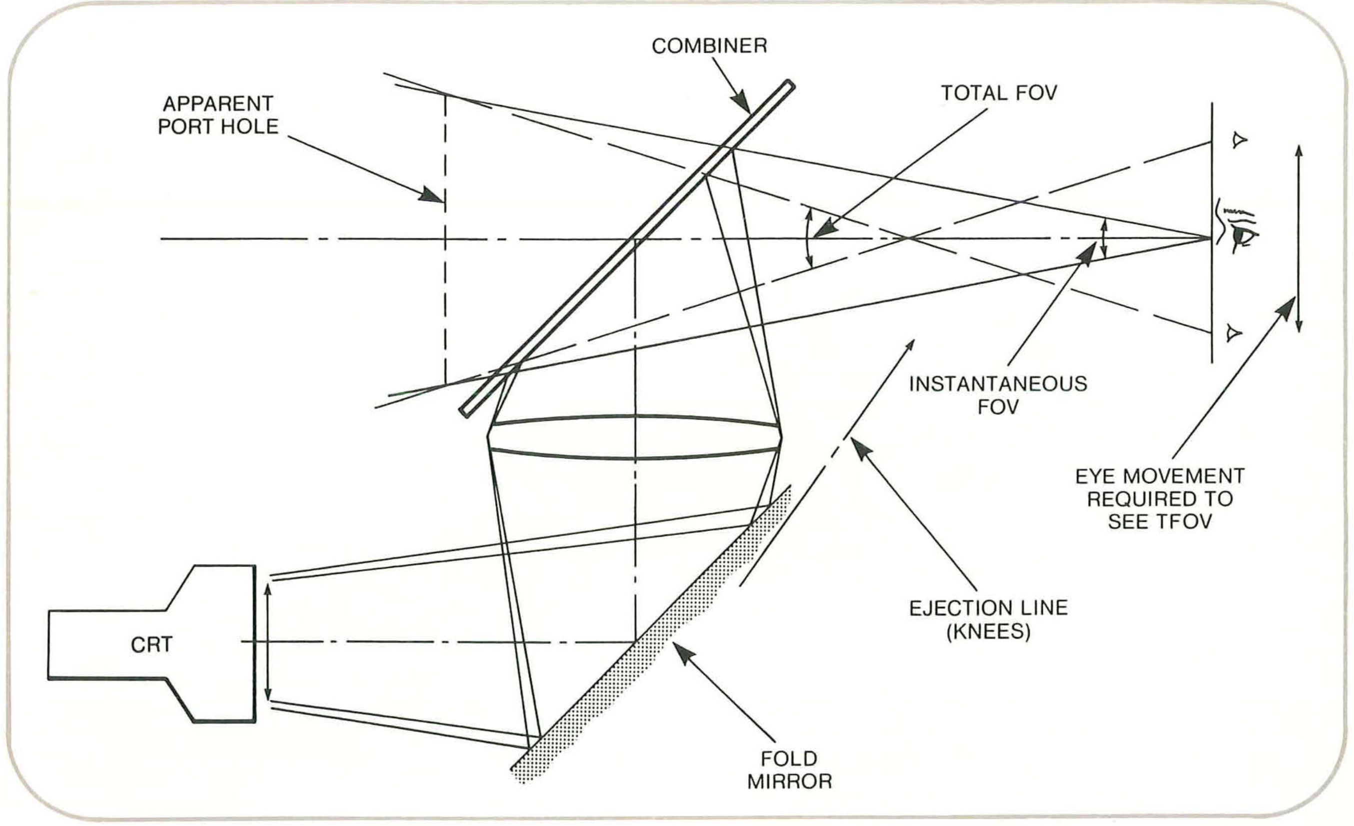

Figure 7 Conventional Refractive HUD

It has thus been shown that field of view is critical. Using a conventional refractive HUD design, field of view is a function of two primary factors: eye-to-combiner distance, and collimating exit optic diameter, (see figure 7). In any given cockpit, the distance from the pilot's eye to the combiner is fixed as the display unit position is effectively defined by the ejection line. The only way to increase field of view is therefore to increase the collimating lens diameter. However practical considerations in instrument panel and canopy design dictate that maximum field of view for a refractive HUD will be limited to about 20° by 15° in a conventional cockpit. In order to significantly improve these figures, a radically new optical approach is necessary, using diffractive (or holographic) optics. This approach uses diffraction gratings, which are essentially holograms of mirror surfaces, made by exposing a photo-sensitive material to an interfering pattern of light produced by that mirror surface. They can be thought of as semi-silvered mirrors, such as are produced by conventional optical coatings but with unique properties. First, they will reflect light only of a certain bandwidth (i.e. colour). We choose the colour produced by a narrow bandwidth green phosphor on the CRT. They do, however, reflect this light very efficiently (typically about 90%), while still allowing all other light to pass straight through (see figure 8). Because of the narrow bandwidth in which they operate, white light is effectively transmitted at about 90%. In other words we have found one of the rare conditions in life where we are getting something for nothing: a surface which transmits 90% of the light hitting it and yet apparently also reflects to similar value!

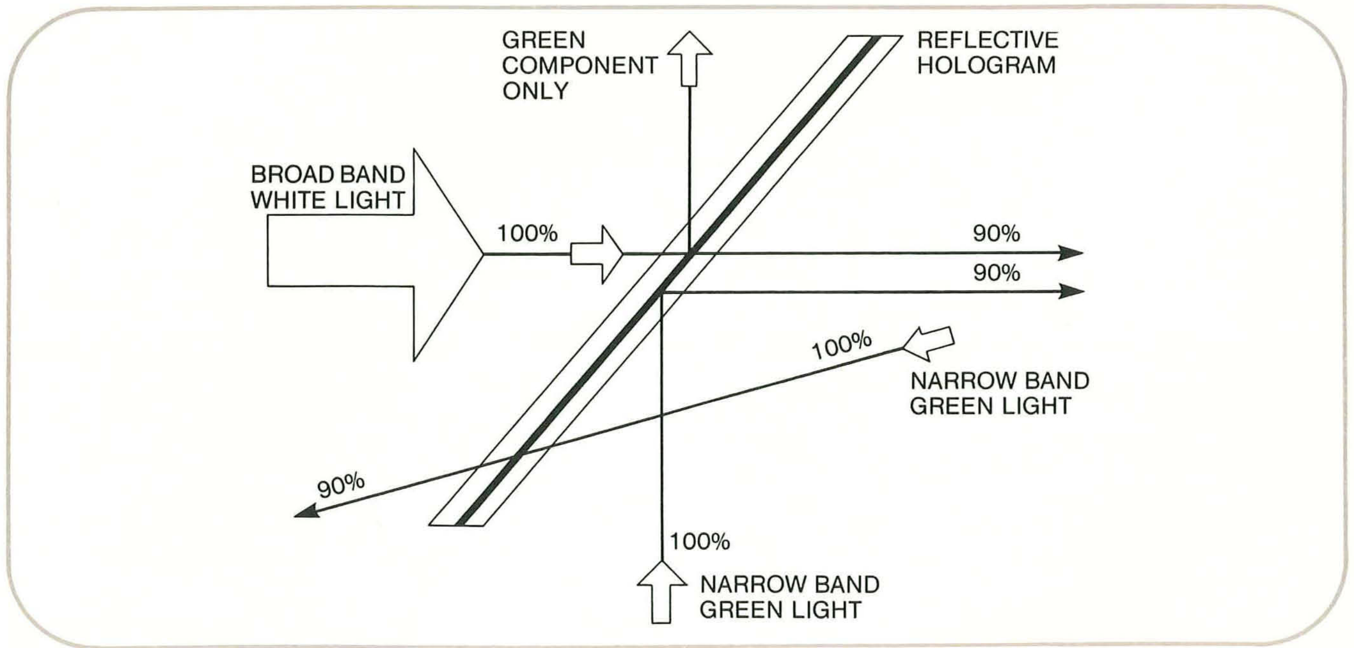

Figure 8 Reflectance/Transmission Properties of Holograms

In addition to this useful phenomenon such holograms can, over a fairly limited range of angles, go from reflecting nearly all light of this phosphor bandwidth to transmitting (with some change in the angle of incidence), nearly all of the same light. Thus for some angles, a green ray will reflect from the hologram whilst at other angles it will pass through unimpeded. These features allow us to greatly improve the efficiency of the optical arrangement used.

THE WIDE ANGLE RASTER HEAD UP DISPLAY

In 1980, the USAF issued a requirement for a wide angle head up display for the LANTIRN (low altitude navigation and targetting by infra red at night) system. This required a HUD with a hitherto unattainable field of view to display FLIR information in raster format with conventional symbology overlay. The HUD had to be made in two versions, for the F-16 and the A-10 aircraft, to give them a realistic anti-tank night attack capability. Following a long and detailed evaluation, the design described in this paper was selected to meet the very demanding requirement. The Wide Angle Raster HUD fully meets the USAF requirement, and provides an instantaneous field of view of 30° azimuth by 18° elevation, or just four times the field of view of the existing F-16 HUD.

To achieve this, the design team had to go back to first principles. The space envelope available for the HUD was defined by the ejection line to the rear, the cockpit canopy above, the glareshield and mounting tray below, and the instrument panel cut-out laterally. The team considered a number of optical configurations to meet this requirement (figure 9).

On the left is a class of diffraction optics we have designated 'off-axis'. It represents one of the earliest attempts to apply the technology in the most direct way but it suffers from a number of penalties. The curvature of the combiner in such a system provides the principal collimating function but is too great to allow the use of a planar doublet to sandwich the diffraction coating. The necessary protection is provided by two pieces of curved glass which reduce the thickness of the element and thus its weight to an acceptable level. The curved combiner not only introduces certain practical manufacturing problems but also contributes to the apparent distortion of the real world seen through it. However, the three major drawbacks are more immediately apparent: the lower mirror tends to intrude into the ejection clearance path, restricting how close the combiner may be brought to the pilot and hence limits the FoV available; a further restriction in elevation is contributed by the windshield clearance, reducing the further forward the combiner is located; and the large off axis angle causes very large optical aberrations. It is impossible to reduce the off-axis angle in this configuration since to do so would shift the combiner even further from

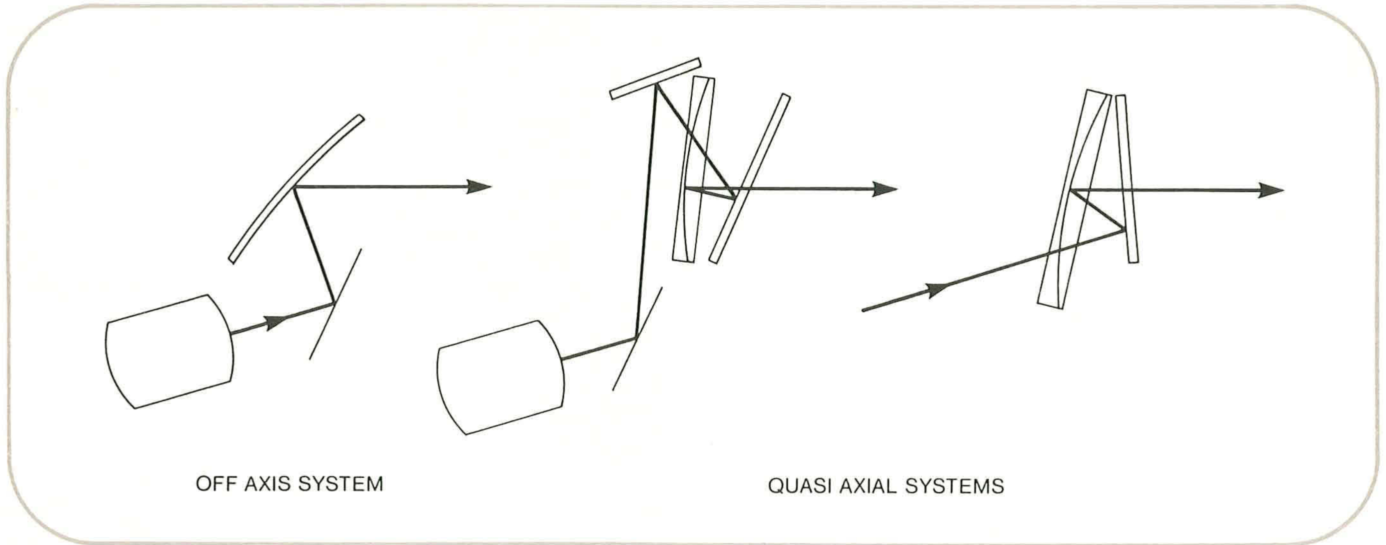

Figure 9 Alternative Optical Designs

the pilot. The intrinsic aberration must be corrected by introducing compensating aberrations in the hologram itself and in a complex relay lens. Such a design still has problems since it is only practicable to correct an inherently highly aberrated system for one eye position, the view from a different eye position will remain highly aberrated.

By comparison with the off-axis systems, the other class, termed quasi-axial, have much reduced critical angle of incidence for reflection. Aberrations are minimal and do not require compensating aberrations in the diffraction coating itself: the limited corrections necessary can be implemented in a simple relay lens. Indeed, in the case of the system on the right of figure 9, no relay lens at all is provided and the residual errors in the unaberrated design, although slightly larger than desirable for high accuracy HUD, are acceptable for certain applications. Such 'lensless' designs have been built and evaluated.

The central system of figure 9 of course represents the Wide Angle Raster HUD which is the subject of this paper. If the collimating element is placed on the corner of the glareshield at the intersection with the ejection safety line, one can achieve the biggest field of view with the smallest possible size of collimating element (figure 10). This optical system, however, requires the CRT image to enter from the pilot's side. This is not readily achieved as we have already moved next to the ejection line. Our team evolved therefore a method of folding the light around, using a variety of flat mirror-type surfaces, to achieve a condition where the CRT would fit back into the location available for it. This optical system uses a combination of three holographic surfaces to present the imagery to the pilot (see figure 11). This leaves the collimating element back on the ejection line, which ensures maximum vertical field of view, since the canopy is highest there. It also maximises the azimuth field of view by keeping the collimating element as close as possible to the pilot's eye. Two further advantages are that the radius of curvature of the collimating element is large, allowing it to be sandwiched between two planar elements, and that the small angle of incidence and long focal length dramatically reduce the abberations present in the off-axis systems. This design does not suffer from the sun reflecting off the rear surface which can create a problem with the 'lensless' design, and it embodies the principal advantages of the quasi-axial design class. The diffraction surfaces do not require 'power', allowing them to be made easily, while residual aberrations are compensated in a simple relay lens. The cross section of the body of the HUD mounted behind the instrument panel is small in both height and width, simplifying installation in a wide variety of cockpits. Full advantage of this economy in the use of prime panel real estate can be taken in new cockpit designs, allowing the instrument immediately beneath the HUD to be located much higher than might otherwise be possible.

A number of snags remained with this approach, however. First, as the various optical rays are always off-axis to the collimating element, a complex relay lens was required to position the image of the CRT in a position where it

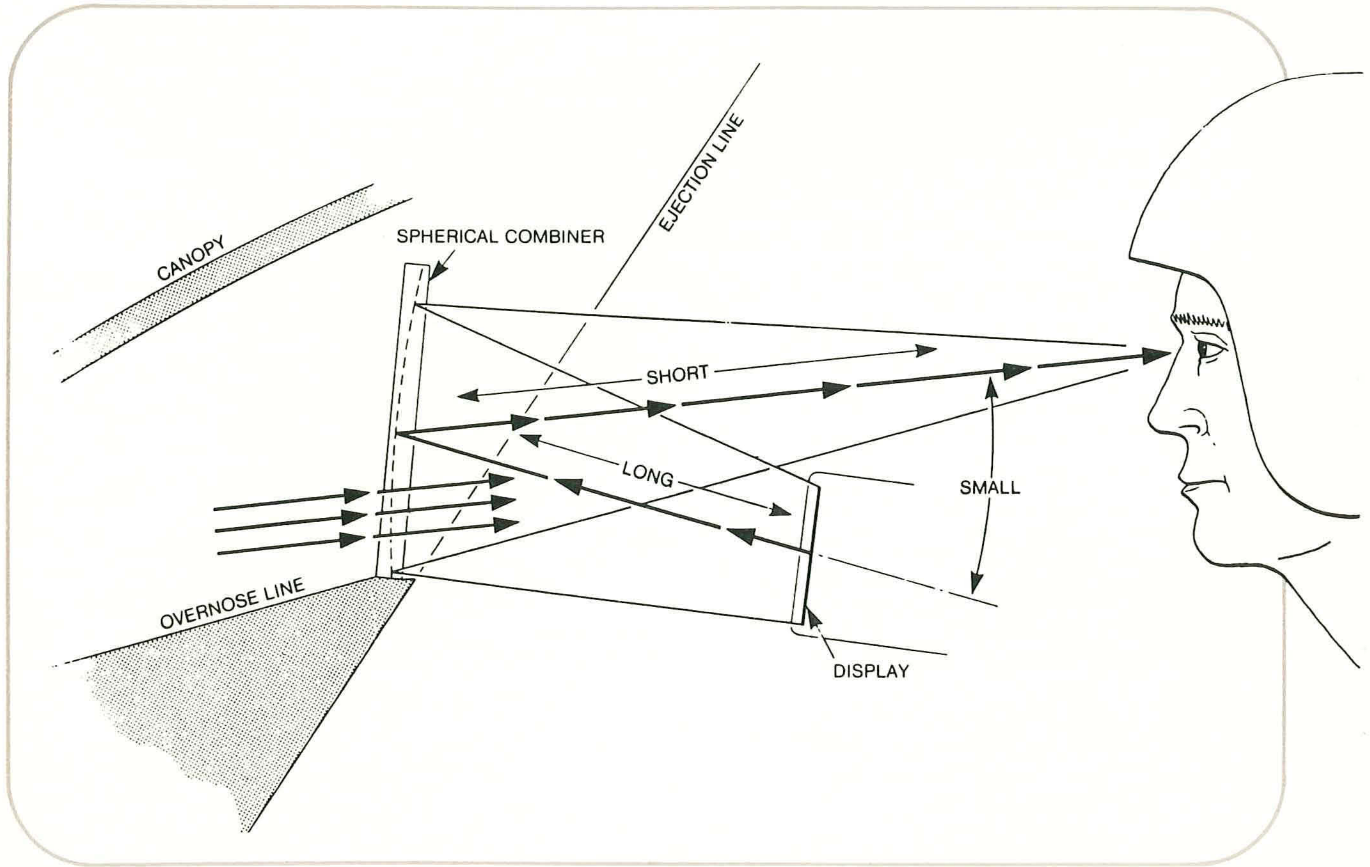

Figure 10 Idealised Optical Configuration

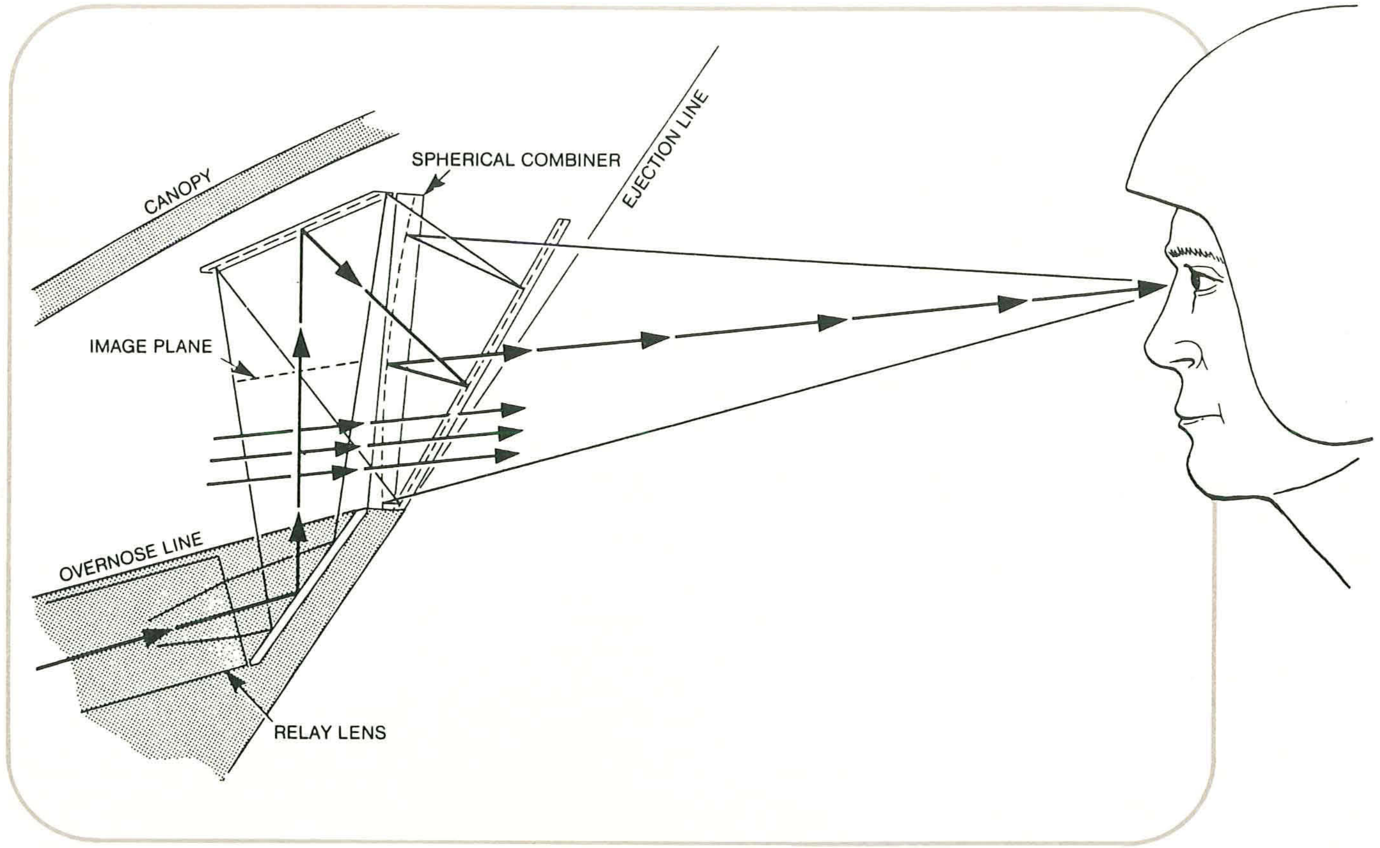

Figure 11 Quasi Axial Optical System

would be truly infinitely-focussed by the collimating element. Secondly, it is necessary to minimise distortions due to being off the true optical axis.

The main remaining difficulty was that, with conventional refractive optical coatings, whilst the design would work theoretically, its efficiency would be completely unacceptable (about 2%). Under such conditions, a pilot would be quite unable to see the CRT image against the outside world background and his view of the outside world would also be attenuated. However, the ability to use holograms (or, to be more technically precise, diffraction gratings), instead of conventional reflective coatings, transforms the situation and makes the whole optical layout feasible.

HOLOGRAM MANUFACTURE

All methods of manufacturing holograms involve exposing a thin film of photosensitive dichromated gelatine to two coherent beams of laser light. Due to the coherent nature of the incident beams, a series of interference fringes are formed throughout the depth of the gelatine film. During the developing process, these fringes are converted to planes of high and low refractive index parallel to the film surface, thus producing a diffraction grating. To a first approximation the refractive index change between adjacent planes is sinusoidal. The designer can specify the characteristics he requires from the hologram, determining the critical angle of reflection and the frequency response of the holographic surface. It is thus possible to make rays reflect from holograms at angles which are not the direct reflection of their incidence angle. Indeed, the effect of such altered reflection angles can be controlled across the area of a hologram. Such optical shaping or power characteristics would create an aberrated hologram.

If we elect to use an off-axis system, we have to produce aberrated holograms in the optical system. This would require the laser beam we use for hologram exposure to be split into two and brought together again to interfere on the element under exposure – see figure 12. With a sizeable difference in the two path lengths, a controlled wavelength difference can exist in the two beams. The total energy which can be put into the element being exposed however, would be low and the exposure time therefore fairly long (of the order of 20 minutes). The problem of holding two beams stable to fractions of a wavelength over such a time would be considerable.

If however we use a quasi-axial optical system, then we do not need to use aberrated holograms. This allows the use of a greatly simplified manufacturing process, as shown in figure 13. This process achieves the necessary interference pattern by a single beam of light, back-reflection from a

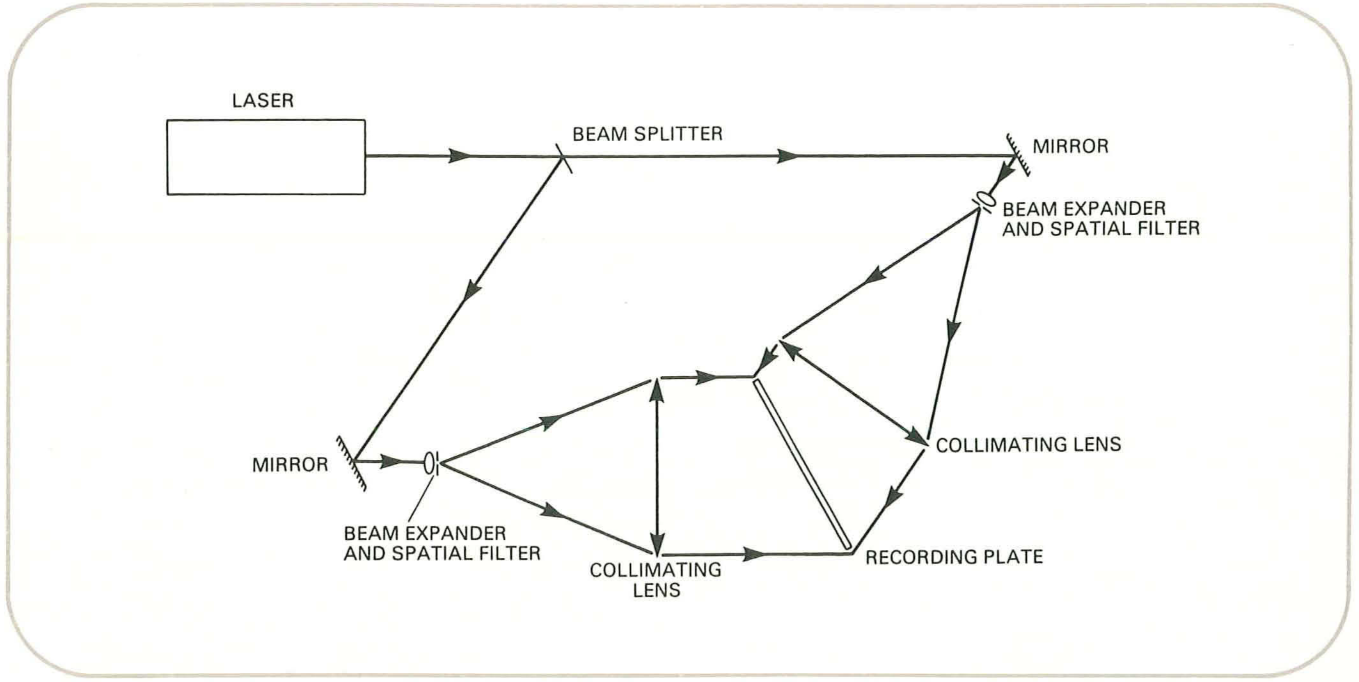

Figure 12 Production of Reflection Holograms Using Separated Beams

mirror in close contact with a element being exposed. Fringes are then created by the interference of incident and reflected rays. This technique also allows an order more laser energy to be focussed into the element, drastically reducing exposure time and stability requirements to a level where they no longer create manufacturing yield problems.

The quasi-axial WARHUD thus provides the largest practicable instantaneous field of view without impact to the cockpit installation, provides transmission and reflection characteristics superior to conventional HUDs, and allows straightforward hologram manufacturing techniques to be used. Interestingly enough, in addition to its other virtues and almost as a side effect, it rejects the bulk of sunlight reflections which can cause problems with other HUD designs, both refractive and diffractive.

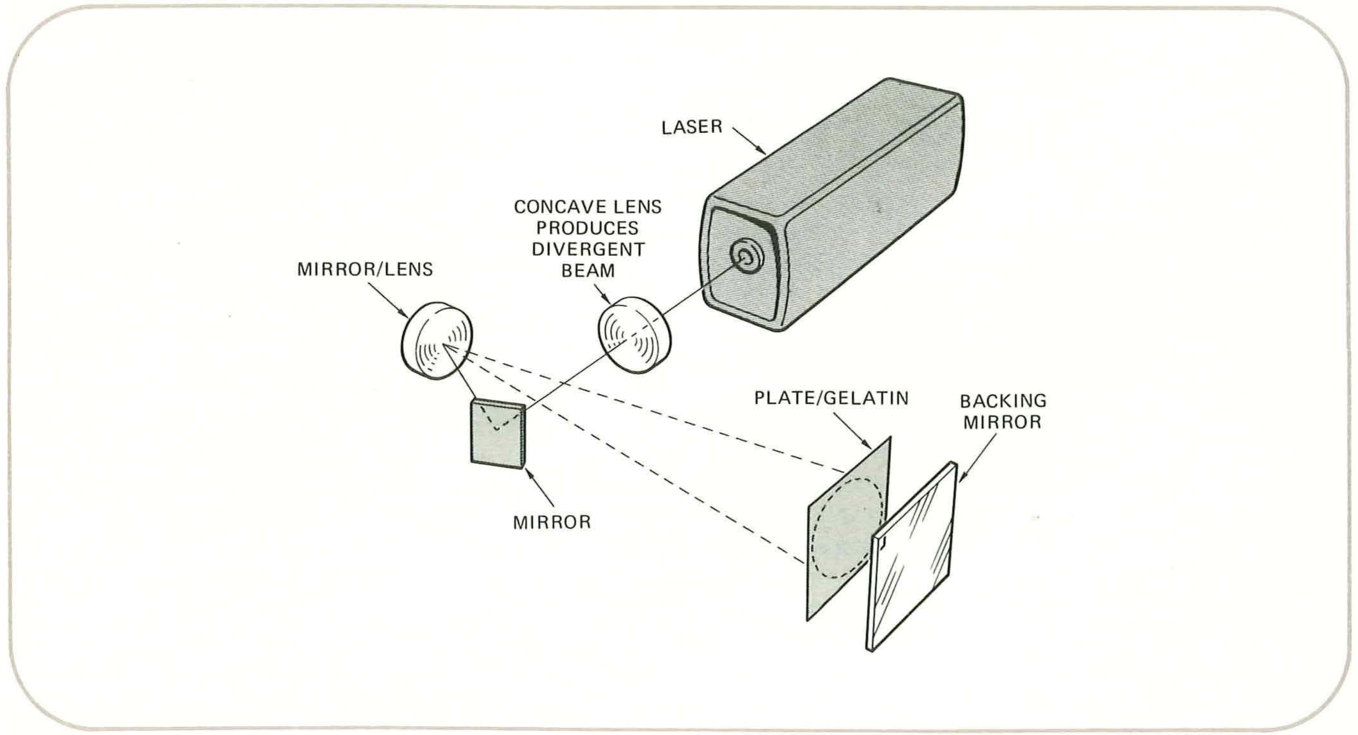

Figure 13 Hologram Generation Using Back Reflection

Although for obvious reasons the optical design of the Wide Angle Raster system has attracted the most attention, it is only one part of the overall system. Electronic and software design are equally important in ensuring operational effectiveness, ease of manufacture, and reliability and maintainability.

In particular, maximum use has been made of the important design standards evolved by the United States Air Force. The three MIL standards making up the so called "TRIAD" have been successfully brought together, for the first time, in this equipment. These are:—

MIL-STD-1553B
: Standardised Electronic Data Highway. This reduces aircraft wiring and would enable additional equipments to be installed in an aircraft more flexibly.

MIL-STD-1750
: Standardised Computer Architecture, ensuring compatibility with international high level language development such as ADA.

MIL-STD-1589A
: Standardised Jovial J73 Computer language, to allow ready support or modification by the USAF during the life of the system. Pending the long term availability of ADA, Jovial J73 will be the standard USAF language.

The equipment makes use of a wide variety of "state-of-the-art" electronic devices; large scale memory, programmable array logic and microprocessors and includes many custom designed hybrid micro circuits. To improve maintainability, it comprises convenient replaceable modules, which also ease manufacture. The raster requirement for the night scene demands that a different approach be adopted from the usual daytime slow speed high brightness cursive scan. Two basic alternatives are possible, bearing in mind that the CRT has one gun and can carry out only one display task at a time. Either the daytime symbology must be converted to a synchronised raster video and mixed electronically with the sensor video prior to display or the complete night symbology must be written at high speed in the only available time, the vertical retrace period of the raster. In the event, the latter approach has been preferred because of the overall economy of having a single symbol generation technique, albeit one with a night mode writing requirement some eleven times faster than the day mode, and because of the consistency in the high quality of the symbology achieved by this means. Special features are included to reduce the power dissipation normally implied by a high bandwidth deflection amplifier design.

A frequent HUD requirement is to provide a collimated depressible standby sight, available in the event the electronic system fails, and totally independent of it, although the case for such a sight is reduced as improved technology extends equipment reliability. The most successful method of injecting the standby reticle into the optical path has been used on a very large number of conventional HUDs, A-7D/E, A-4M, F-16, etc. A red reticle image is injected via a dichroic beam splitter. It is particularly efficient because it reflects most of the red light without significant attenuation of the green CRT light. With a diffraction HUD that only operates at a very narrow band of green wavelengths a different approach is necessary. The obvious technique using a neutral density beam splitter and a green standby reticle is inefficient because it would cause significant attenuation of both light sources. As a result, the Wide Angle Raster HUD can be provided with an electronically generated standby sight using a microprocessor in the Display Unit. Its operation is completely independent of the separate main Symbol Generator Unit.

To relieve the pilot of the manual tasks associated with display brightness and contrast control, particularly when he is flying low at night, beneath cloud or in bright moonlight, an advanced autobrilliance control is provided, sharing the same microprocessor as the standby sight. Where current day HUDs provide automatic control over 3 decades of ambient scene brightness, the WARHUD control extends this through a further 2 decades, down to a 1 foot lambert night scene. Clearly it would be quite unreasonable to expect a pilot already trying to cope with multiple complex tasks to also be concerned with anything quite so mundane but nevertheless potentially disturbing.

The HUD camera recorder presents problems with any diffraction HUD. Because of the limited range of positions from which the display can be seen, the recorder cannot be mounted in the conventional position, looking through the combiner glass. To see the display satisfactorily, it needs to be co-located with the pilot's head. The only really viable alternative is to provide a scan converted version of the display symbology, achieved relatively efficiently using currently available digital technology. The synchronised raster video output is then mixed electronically with either a CTVS camera video, now mounted forward of the combiner, in the day mode, or the sensor video at night. The mixed video is passed to an airborne VTR with all the attendant benefits of this now widely preferred recording method.

Another interesting implication of the wide angle HUD design is that it allows the normally closely clustered HUD symbols to be distributed over the larger FoV, reducing display clutter.

The Wide Angle Raster HUD system was originally developed to meet a specific requirement for a wide angle night vision retrofit system. As such it required a flexible optical system, which makes it readily adaptable to fit into a wide variety of existing aircraft cockpits. Preliminary design studies have shown it to be suitable for installation, for example, in the Jaguar, Tornado, Harrier, F-18, A-7 and F-15 aircraft, as well as the F-16 and A-10. As such it can be applied to a number of different roles.

There are three main mission applications: night ground attack or interdiction, day ground attack and day air combat. In each of these missions the use of a wide angle HUD offers many advantages. As already discussed, in the night low level mission a wide angle HUD eases pilot workload, improves the manoeuvrability potential and reduces the navigation up-date requirement.

For daylight ground attack, a wide angle HUD offers two advantages. Firstly it allows target acquisition and attack within a wide azimuth coverage. This permits use of a target cueing system with a FLIR or laser marked target seeker over a significantly greater field of view. It can also make attacks from a turn on a laterally displaced target practicable. Studies have already been made of the possibilities of such an attack system which show considerable potential for the future. Secondly, the wide angle HUD allows the symbology to be spread wider, decluttering the display and enabling the displaying of more symbology if required.

Finally, a wide angle HUD is of considerable benefit in air combat. The latest missiles have a large aim-off capability against a manoeuvring target. To take full advantage of this, the HUD needs to display the missile seeker head circle scaled one to one, together with a target indicator driven by the radar. Only a HUD with a large field of view, particularly in the aircraft's vertical axis, can give this display capability.

F-16 Development Installation

CONCLUSION

The requirement for the wide angle HUD originated in the need for a capable system for displaying electro-optical sensor information. This demands a very wide angle raster HUD, with good display quality, displaying the imagery scaled one to one in front of the pilot and overlaid on the outside scene. The new Wide Angle Raster HUD achieves this without the loss or degradation of the normal day HUD facilities. The first development models have now been delivered, and demonstrate the capability of this system. Although originally conceived to meet the night vision requirement for ground attack aircraft, the Wide Angle HUD has great potential for retrofit to a wide variety of existing aircraft to give them a much more capable day HUD system as well as a fully realistic night capability.

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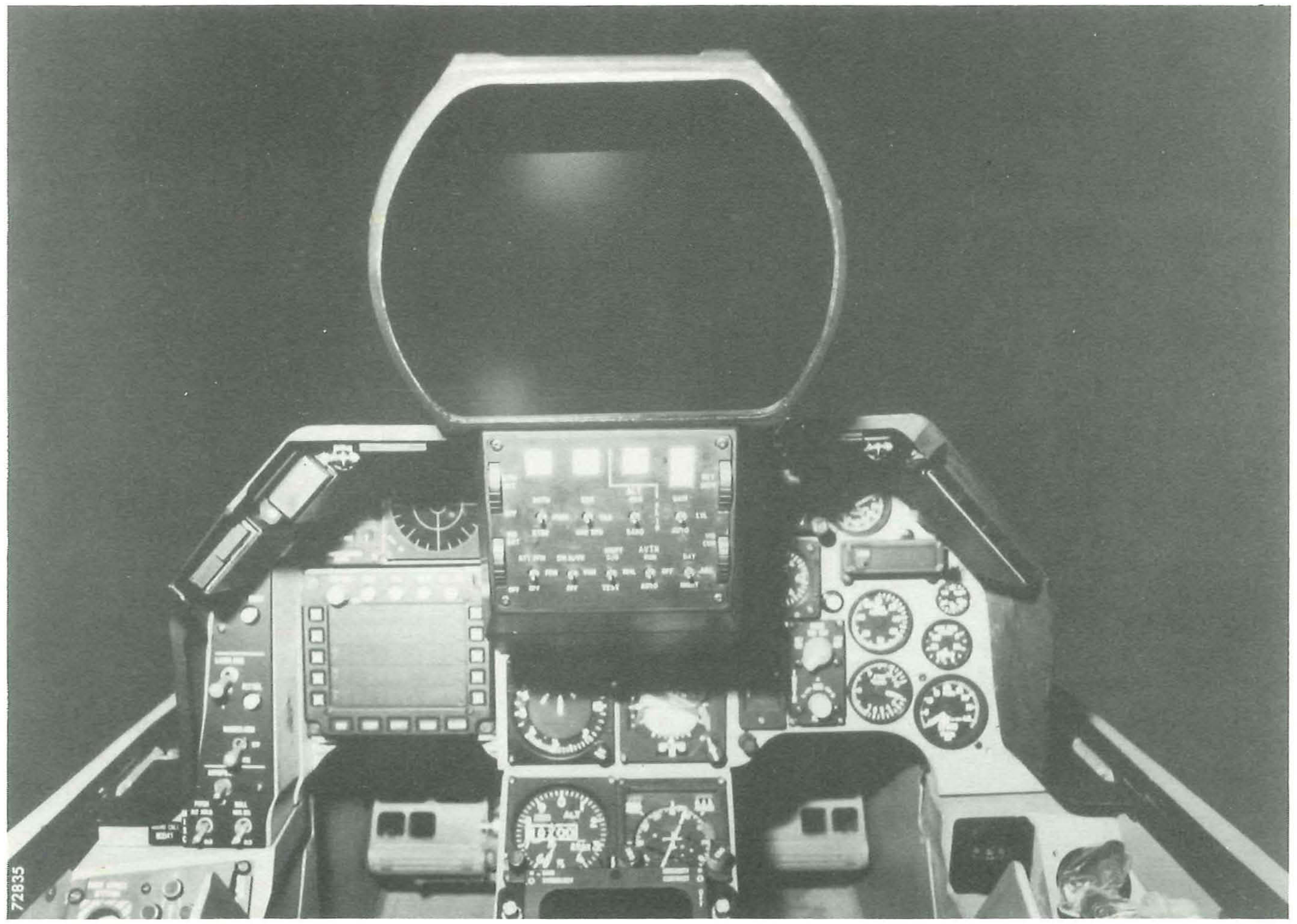

F-16 MSIP 2 Production Installation

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