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REPORT 405

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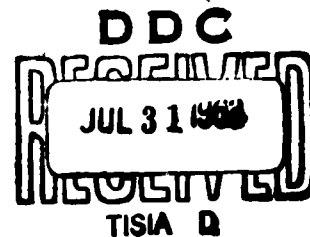
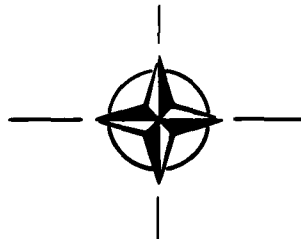


**RECENT DEVELOPMENTS IN THE U.K.
IN FLIGHT INSTRUMENTS**

by

K. R. HONICK

JULY 1962



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NORTH ATLANTIC TREATY ORGANIZATION

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ADVISORY GROUP FOR AERONAUTICAL RESEARCH AND DEVELOPMENT**

**RECENT DEVELOPMENTS IN THE U.K.
IN FLIGHT INSTRUMENTS**

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K.R. Honick

**This Report was presented at the Twenty-First Meeting of the Flight Mechanics Panel
of AGARD, held in Paris, 6-10th July, 1962**

SUMMARY

Developments in panel mounted ('head down') flight instruments are described. The achievement of increased integration of instrument indications together with the use of a flight director indicating demanded action by the pilot by instrumental techniques which separate the functions of sensing, computation and display are discussed.

Further simplification of the pilot's task by super-position of essential elements of the instrument field on the external field, using optical projection of collimated information onto a reflector plate or the windscreen ('head up' display), is also described.

The addition to normal flight instrument indications of a pictorial topographical display of ground position and track by optical projection of micro colour transparencies of maps as a continuous automatic plotting facility is described.

SOMMAIRE

Dans ce rapport sont exposés les travaux de mise au point relatifs aux instruments de vol montés sur un tableau (présentation obligeant le pilote de baisser les yeux). La réalisation d'une intégration accrue des indications fournies par ces appareils, ainsi que l'utilisation d'un indicateur de vol, qui indique l'action demandée au pilote par des techniques instrumentales permettant de séparer les fonctions de captation, de calcul et de présentation sont examinées.

L'auteur décrit également un moyen supplémentaire destiné à simplifier la tâche du pilote et qui consiste à superposer, sur le champ externe, les éléments essentiels du champ des instruments, par projection optique d'indications collimées sur une plaque réfléchissante ou sur le pare-brise (présentation au niveau des yeux).

La présentation, sous forme d'images, en dehors des indications normales des instruments de vol, d'indications topographiques de position par rapport au sol et de route par projection optique de micro-diapositives de cartes en couleur, comme possibilité automatique en continu d'enregistrement de paramètres est décrite.

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RECENT DEVELOPMENTS IN THE U.K. IN FLIGHT INSTRUMENTS

K.R.Honick*

1. INTRODUCTION

This paper describes the evolution and development of flight instruments in which an attempt has been made both to co-ordinate the information displayed and to present it in ways which match the increased demands imposed on the pilot by increased aircraft performance and more exacting operational procedures. The governing principles followed in the choice of presentation methods are discussed generally and with respect to the individual instruments.

2. METHODS OF PRESENTATION OF PRIMARY FLIGHT DATA

Figure 1 illustrates an early example of the array of flight instruments known as the 'Standard Blind Flying Panel', which was introduced in British aircraft about 1936. The quantities measured and presented were:

Top row, left to right:	Airspeed, attitude, vertical speed (originally termed rate of climb or descent)
Lower row, left to right:	Altitude, heading, rate of turn and sideslip ('turn and bank').

All of these instruments were separate, self-contained, mechanically operated devices in which the functions of sensing, computing and presentation were performed within the instrument case. For example, the altimeter comprised an evacuated pressure capsule stack sensing static pressure, a mechanical linkage (computing) and the display. The very small forces available restricted the display to the rotation of low inertia pointers over a circular scale. Similarly the artificial horizon was operated by an air driven gyroscope within the instrument case. In order to obtain reasonable performance, parasitic torques on the gyroscope had to be minimized and only a very simple mechanism such as the horizon bar could be operated mechanically.

Two rate indications, turn and rate of climb, were provided. The remaining instruments, within the limits of their response, showed the prevailing value of the quantities measured at any instant.

The pilot was required to scan this array, mentally to integrate their separate indications, rates of change and direction and from this assessment to translate the information into control movements giving stable flight along the desired flight path. Assuming no automatic control, the pilot's task with such a system was, therefore, both varied and onerous, since he had to combine from a knowledge of raw data the functions of a computer and a servo system.

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Although limited in scope, the early blind flying panel at least had the merit of standardizing the relative positions of the instrument indications provided, which simplified the task of scanning.

With the advent of new aids, such as automatic control, auto stabilization, I.L.S. (Instrument Landing System), etc. and the growing complexity of aircraft systems the need arose not only to present fresh information but also to supply primary flight data to other systems in the aircraft, such as the automatic pilot, A.I. radar, bombsight, etc.

This requirement has been made compatible with improvement in the instrument display by centralizing the sources of primary flight data and computation and providing servo-operated power outputs of the required quantities both to the aircraft systems requiring them and to the instrument displays, which then become servo-operated repeaters. The three principal sources of data are:

- (a) An air data computer in which, by measurement of pitot and static pressures together with air temperature, indicated airspeed, barometric altitude, vertical speed, Mach number and true airspeed may be computed.
- (b) A master reference gyroscope or stable platform containing both vertical and azimuth gyroscopes, the azimuth gyroscope being stabilized by the vertical gyroscope, thus avoiding gimbaling errors during aircraft manoeuvres. The azimuth gyroscope may be magnetically monitored. The gyros themselves are mounted in low friction gimbals having only small angular freedom (15° or less), which in turn are mounted in a main gimbal system which is servo operated from detectors operated by the inner gimbals. By providing effectively four degrees of freedom in the gimbal system, three are always operable at any attitude of the aircraft, so that gimbal lock cannot occur. Presentation of all attitudes and heading are therefore available from this source.
- (c) A guidance or automatic flight control computer from which programmed demands requiring a change of flight path, such as a climb to a given altitude or a change of heading, may not only be fed to the automatic control system but may also be presented to the pilot as a director associated with the visual instrument display in such a way as to indicate the manoeuvre required to satisfy the demand.

By providing a direct display of flight data together with a director index the pilot can operate the aircraft in one of three modes:

- (a) Fully automatic control with pilot monitoring
- (b) Pilot control through the flight director with monitoring
- (c) Pilot control independent of the automatic control (with the possible exception of the auto stabilizer).

The importance of the second mode is that the pilot can, if required, exercise judgment in a difficult situation, being able at will to deviate from the demand indications of the flight director and revert to direct pilot control; at the same time his task in

flying the aircraft is made as easy as possible and he can revert to fully automatic control without discontinuity.

The easing of the pilot's task by means of computed signals on a flight director does not remove the need for a readily interpretable display of primary flight data. Monitoring under automatic or director control should be simple and the association of the director with the primary display is important. If necessary, the primary display must be usable under adverse conditions without automatic control or flight director.

For certain phases of flight, e.g. landing, transition from instrument to visual flying is required with minimum discontinuity. This aspect of the problem becomes relevant in the choice of frames of reference for the presentation of attitude, heading and ground position and has also been a significant factor in the development of the 'head up' presentations which will be described.

The concept of centralized measurement, computation and servo-operated power transmission of the required variables permits the following improvements to be achieved in flight instrument presentation compared with the earlier self-contained instruments:

- (a) Since the displays are now power driven, restriction of choice of type of display is virtually removed and may be of any desired form.
- (b) Since the load caused by operating the display mechanically from the sensor has now been removed, accuracy and response may be improved by the elimination of frictional effects.
- (c) Accuracy may also be improved by the possibility of more elaborate computation. For example, in the case of those quantities such as barometric height and Mach number derived from pitot and static pressure measurements, pressure errors incident on directly operated instruments may be corrected in the central computer by applying known corrections programmed as a function of Mach number.
- (d) Better integration of the whole array is possible by a reduction in the total area of the displays with consequent easing of the scanning problem, both by engineering displays which economize in frontal area, and by using a given instrument area to present different sets of information by mode selection. It is also possible to display quantities which are relevant to one another in improved juxtaposition.

An example of reduced area tailored to fit the whole array is the combined indicated airspeed and Mach number indicator shown in Figure 2, which also presents the corresponding values of these two quantities simultaneously related to each other by a common index. Another example of combination is the presentation of the flight director index on the attitude indicator (Fig.4). The best example of mode selection is the navigation display, which may either appear as a simple display of heading of the rotating card type (Fig.2) or may present the range of a Tacan beacon or of a point offset from the beacon combined with heading, or displacement displays of the I.L.S. glide-path and localizer beams combined with heading (Figs.3 and 4).

In this instrument the advantages of power operation are particularly apparent, since not only are relevant quantities combined with the heading indication, but also these only appear when required and selected. The central area of the instrument may therefore be likened to a theatre proscenium where by means of scene shifting the required display is revealed.

Reduction in area and increase in sophistication are, however, achieved at the expense of increased weight, depth and complexity. Servo operation has been considered essential in order to match the display to modern requirements, but the change of primary flight indications from directly operated devices to repeaters is a potential hazard unless equivalent reliability can be achieved. The development of the new displays has therefore been accompanied by the provision of miniature standby versions of self-contained instruments using modern techniques which will be described briefly. An array of these, mounted for exhibition and not necessarily in appropriate panel positions, is shown in Figure 5 and comprises indicated airspeed, barometric altitude, azimuth directional gyro and artificial horizon.

A comparison of the early panel shown in Figure 1 with the later developments of Figure 2 indicates the effect of human engineering studies during the period between the two on the technique of dial marking and numbering, which has been embodied in the later development. This may be summarized as a general increase in size and clarity of significant graduations and numerals and the suppression of much irrelevant detail, notably superfluous intermediate subsidiary graduation marks, since the ability of the eye to interpolate accurately between major graduations has been demonstrated. Integral lighting is also embodied in the new instruments.

Altering current synchro-data transmission in the control transmitter/control transformer configuration with transistor amplifiers and miniature two-phase servo motors is used for operating the displays.

3. SERVO-OPERATED FLIGHT INSTRUMENT PANEL

The appearance of a representative panel is shown in Figure 2. The frontal area occupied by the presentation is 15 in. x 9 in. (38 cm x 23 cm). Within this area the following quantities are displayed:

1. Indicated airspeed
2. Mach number and command value of Mach number
3. Barometric altitude, ground pressure and command value of altitude
4. Vertical speed
5. Attitude with flight director index
6. Sideslip
7. Heading with compass annunciator or directional gyro indication

- 8. Range and bearing of Tacan beacon or of an offset point
- 9. Range and bearing coordinates of an offset point
- 10. I.L.S. glide path and localizer beam displacement display
- 11. I.L.S. beam on-off indication
- 12. Desired heading.

3.1 Altitude and Vertical Speed

It is not intended to discuss within the scope of this report all of the alternative presentations, the assessment of which lead to the choice of those now described. A full account of this work has been given by Stratton¹. Reference will, however, be made to the type of presentation shown and brief reasons given for its choice.

In the case of altitude the best compromise was found to be a combination of the well established merits of a digital counter presentation, for ease of reading and freedom from ambiguity, with the properties of a single pointer making one revolution of a circular scale per 1000 ft in providing angular and rate information necessary in height holding or descent. This solution avoided the ambiguities inherent in multiple pointer instruments while retaining the superiority of the circular scale and pointer over vertical strip presentations of the moving scale type in supplying angular rate clues.

Digital counter displays of command heights are provided above the dial in thousands of ft. The usual ground pressure setting is also provided in millibars as a counter indication.

The large height counters are arranged to change indication rapidly while the pointer moves between the 950 and 1000 ft graduations on the dial. A simple conventional dial-pointer presentation of vertical speed is provided beneath the altitude presentation. Zero is at the 9 o'clock position on the dial, which produces a natural sense of pointer movement for small rates of climb or descent. The scale is non-linear, giving a more open scale at the lower rates for which the indication is principally used during the let down. The scale is not extended beyond 6000 ft/min, though for higher rates the pointer is arrested beyond the scale maximum but short of the 3 o'clock position in order to avoid ambiguity. No operational need has been established for the quantitative presentation of higher rates, although the precise response rate of this instrument appears to be a matter of individual pilot preference and considerable work has been done in varying the processing of the data to achieve an acceptable compromise.

3.2 Speed and Mach Number

The advantages of presenting the whole range of a quantity within one revolution of a pointer moving over a circular scale are well known. Once the range presented is familiar the user derives an immediate clue to the prevailing value by sensing the angular position of the pointer without necessarily reading the instrument quantitatively, while the angular velocity of the pointer affords an indication of rate of change.

In the case of a moving scale type of indicator read against a fixed index in which only a portion of the range is visible in the viewing aperture at any instant, the instrument must be deliberately read to interpret it and the user is deprived of any immediate clue to his position within the limits of the range presented. If such an instrument is arranged vertically difficulties arise in harmonizing its direction of motion with that of a similar altitude indicator and the attitude indicator of the earth reference or moving horizon type to be described. A conflict occurs between requirements for quantitative use and for control purposes.

If vertical moving scale types of altitude and speed indication are used and the aircraft is pitched up, harmony with the height and attitude indications requires that the speed scale should also move downwards. However, the speed decreases as the aircraft is pitched up and a human operator expects the scale to increase in an upwards direction. It can be demonstrated that when the direction of scale increase is contrary to expectation errors of interpretation are likely to occur under conditions of stress. It is also desirable that different quantities should be readily distinguishable from one another. The possibility of confusion occurs if quantities such as altitude, airspeed and Mach number are all presented on adjacent vertical strip scales.

The choice of the combined horizontal presentation of indicated airspeed and Mach number shown in Figure 2 was therefore made with the following considerations in mind.

- (a) It fits into the complete array economically.
- (b) It is readily distinguishable from the altitude display.
- (c) The horizontal configuration increasing from left to right avoids similarity with the attitude indicator movement.
- (d) Since the instrument can be longer than if it were vertical, it is possible to retain in part the advantage of the dial-pointer instrument by presenting the whole range of indicated airspeed on a fixed scale, the positional clue being strengthened by using the thermometer stem type of pointer, in which a white strip moves along the scale from left to right as speed increases. The scale is proportionately more open in the landing range below 200 knots and is non-linear and contracting above that value.
- (e) Since the range of Mach number is too great to be presented adequately on a fixed scale the moving tape has been employed in which the tape moves from left to right with increase of Mach number. The greater width of aperture possible with a horizontal array permits the display of a reasonable range at any instant and meets in part the potential criticism of a moving scale indicator. By making allowance for movement of the airspeed index differentially the Mach number is read against the same index as indicated airspeed and the two values shown by the common index at any instant are therefore the appropriate equivalents at the prevailing height. The appearance of the indicator in a climb at constant Mach number, for example, would occur in such a way that the Mach scale and the white thread index would appear to move slowly together to the left as the Mach number chosen becomes progressively equivalent to a lower indicated airspeed with increasing altitude.

A digital counter presentation of command Mach number appears in the lower left hand corner and is also arranged to appear on the Mach scale as a circular index with a diametral line θ which moves with the Mach scale.

3.3 Attitude and Flight Director Index

3.3.1 Attitude

The problem of attitude presentation has been fully treated by Stratton¹, who has also given an account of the development and appraisal of the instrument illustrated in Figure 2.

Summarizing, two possibilities exist for attitude display:

- (a) The moving element is identified with the outside world and the instrument case with the axis of the aircraft being controlled. This is the so-called 'natural' or 'earth reference' presentation.
- (b) The moving element is identified with the axes of the aircraft being controlled and the instrument case with geographic axes. This is the so-called 'aircraft reference' presentation.

The arguments for the earth reference are the pilot's known ability to control the aircraft in attitude under visual flight conditions by using the outside world as a reference and the absence of discontinuity when making the transition from instrument to visual flying, since both the angular position of the instrument simulation of the horizon and that of the natural horizon are then in agreement.

It will be seen that this factor becomes preponderant when the super-position of the instrument field upon the external field is considered. The arguments for compatibility are then strong enough to resolve any controversy possible in the choice of a head down instrument presentation.

A schematic diagram of the instrument illustrated in Figure 2 is shown in Figure 6 and is known for obvious reasons as the 'roller blind' indicator. It consists of a frame operated from one servo-mechanism repeating bank angle, the frame carrying a moving blind operated by a servo-mechanism repeating elevation angle. The surface of the blind is divided into two regions, one painted white or grey (sky) and the other black (earth), the two-tone presentation giving a much stronger clue of the outside world than the simple bar of the conventional horizon; zenith and nadir points are also marked at distances from the 'horizon' equivalent to rotations of $\pm 90^\circ$ of the elevation mechanism. The scale of the elevation drive is chosen so that the zenith appears in view at the top of the instrument before the horizon disappears at the bottom. By this means, an earth reference type of display is also obtained near the vertical, the zenith (or nadir) occupying the same position relative to the frame of the instrument as a zenith star would occupy relative to the aircraft.

Concentric circles 20° apart with intermediate 10° divisions marked on the cover glass enable elevation to be assessed quantitatively either with relation to the horizon or to the zenith or nadir marks, which are in the form of stars with an elongated tail directed towards the horizon. These give an additional clue to the direction of the horizon in extreme attitudes when the horizon is not visible on the display.

A bank scale is provided in the lower half of the instrument which then indicates in the natural sense.

The limits of elevation movement correspond to $\pm 90^\circ$, so that a continuous blind is not required. By appropriate increase in the rate of response of the bank servo as elevation increases, accurate following can be achieved to within $2\frac{1}{2}^\circ$ of the zenith or nadir. At these points the indicator will execute a rapid inversion, which will be accompanied by a simultaneous 180° change of heading indication.

A series of illustrations showing the appearance of the indicator at various angles of elevation and bank are shown in Figure 7.

An indication of sideslip is provided above the attitude display by a simple lateral accelerometer of the ball in liquid type. Unlike the more common arcuate variety, the sensitivity of which increases with elevation, the glass envelope of the instrument illustrated is barrel shaped, having the same curvature in all planes. Its sensitivity is therefore independent of attitude.

3.3.2 *Flight Director Index*

Flight director control for the two degrees of freedom of the control column controlling roll and pitch is naturally associated with the display of attitude, so that attitude can be readily maintained while tracking the director. The system therefore follows normal practice in presenting the director index on the attitude display.

A choice of convention similar to that of the earth or aircraft reference in attitude display exists in the case of the director index and the frame of reference with which it is to be visually associated. The index may either be interpreted as the direction in which to fly the aircraft in order to satisfy the demand (known as the 'fly to' convention) or it may be considered as a pointer to be brought back to a given point by means of the control movement ('pointer' type).

Since the flight path index in an earth reference type attitude display is central and is associated with the aircraft to which it is physically fixed it is logical to use in association with it the 'fly to' type of director index, in which the index represents the required direction until it is nulled by making the appropriate attitude change. The control-index relationship with such a system is then harmonious in that a movement of the spot to the right demanding right bank is satisfied by moving the control column to the right. Since demand signals are arranged to be backed off by signals representing the control action, the director index will move in opposition to the direction of control movement until the demand is satisfied, when it will remain central. Thus in making a desired finite change of heading, say, to port, the appropriate bank will be demanded by the director index moving out to the left. This will be centralized on applying the demanded bank, but on approaching the new heading the bank angle will have to be progressively decreased to maintain the director index central until on reaching the new heading the attitude will again be straight and level. The action is similar in the vertical direction in, for example, a demanded climb to a command altitude.

The director index consists of an annular ring operated in Cartesian coordinates with respect to the instrument case. The ring has concentric black and white circles

so that it is visible against either the light or dark background of the roller blind representing sky or earth. The ring is suspended on two thin stretched filaments which intersect at the index. Since physical connection with the case lessens the illusion of the index as a 'fly to' indication the supporting filaments are made as inconspicuous as possible.

It must be noted, however, that the frame of reference for flight director displacements in this instrument is an aircraft framework which will not always coincide with the geographical framework of the attitude display.

It will be seen that this feature, together with the choice of convention, are significant when similar data are presented in superposition on the external visual field by optical methods where it has been possible to harmonize the two frames of reference more readily than with the mechanical instrument. The solution in the roller blind case would involve mounting the director index system on the blind carriage or resolving demands which produce complex mechanical problems.

4. NAVIGATION DISPLAY

As indicated earlier, advantage has been taken in this instrument of the flexibility of servo-operated presentations to combine with heading navigation information in the azimuth plane, which is conveniently displayed in relation to the compass card.

The instrument is basically a compass repeater of the moving card type consistent with the choice of earth reference presentation for the other two attitude angles on the roller blind indicator. There is also a logical reason for this choice for tracking purposes, since with an aircraft reference (moving pointer) display of heading the control-index relationship is reversed when a heading is indicated at the bottom of the display. Heading is therefore read against the fixed vertical datum mark on the display and an adjustable barbed pointer is provided for marking selected heading. This pointer is servo operated and can be remotely driven.

The centre of the display consists of a roller blind mechanism similar to that used in the attitude indicator. The blind is divided lengthways into three parts, each of which may be brought into position automatically by selection on the mode switch on the right of the instrument. The first part contains the markings for display of navigational position information, the second the markings for I.L.S. lateral displacement and the third is blank, in which case the instrument appears as a simple heading display (see Fig.2).

4.1 Display of Range and Bearing

The position display (Fig.3) gives both a pictorial and a quantitative display of range and bearing from a point such as a TACAN beacon. The central fixed circular index of the display represents the aircraft. The roller blind is driven along its length according to range from the beacon, which is shown by the numbered concentric circles on the blind. The range is also shown accurately to the nearest nautical mile by the digital counter in the top left hand corner of the display, this counter being covered in other modes. The frame carrying the blind is rotated with respect to the compass card and a diametral line passing through the concentric range circles and their central index, which represents the beacon, shows the bearing of the beacon from

the aircraft and of the aircraft from the beacon. In Figure 3 these bearings are E. (90°) and W. (270°) respectively. If the aircraft continued without wind drift on the easterly heading shown, the centre of the concentric circles representing the beacon would move down the face of the instrument. When the range decreased, so that the beacon index reached the centre of the display, and as the aircraft passed over the beacon, the blind mechanism would rotate through 180° , giving correct bearings as the aircraft flew away from the beacon.

In Figure 3 the bearing of the beacon and the aircraft headings are already shown coincident. If the beacon bearing were shown, for example, as N. in the illustration, when the line would be horizontal, a 90° turn to port would bring the aircraft onto the required heading to fly towards the beacon and both the Northerly heading and the diametral line would be aligned with the vertical datum mark of the compass.

Although the description above has been given in terms of the beacon as the reference point for range and bearing, it is possible, by means of a simple computer, to transfer the reference point for the whole display to another point (such as an airfield) by setting into the computer the range and bearing from the beacon of the chosen offset point. The two digital counter indicators with cranked knobs above the navigation display (Figs. 2 and 3) are provided for setting in the range and bearing of an offset point in this mode.

4.2 Display of Beam Displacement

The presentation of the beam display (Fig. 4) has been chosen to avoid, as far as possible, any confusion in interpretation of the elevation component. The double line azimuth index is carried on the roller blind and is rotated and translated by the blind mechanism. This display appears and takes up its appropriate azimuth position when I.L.S. is selected on the mode switch. At the same time the single line elevation index bar, which is servo operated, appears in the display; this should, strictly, rotate with the blind mechanism, but for simplicity it is attached to the instrument framework and remains horizontal. When the aircraft is flying near the beam, however, the difference involved is negligible.

The index system against which displacement and azimuth are read is viewed through a slot in the blind.

This display can be visualized in two ways:

- (a) as a cross pointer display showing the position of the aircraft longitudinal axis (centre index) relative to the beam (intersection of the pointers), the whole being framed by a compass against which azimuth can be read,
- (b) as a true plan view in which the two line index represents the runway, the transverse index line represents the point at which the desired glide path intersects the runway, and the central circle index represents the intersection with the ground of a glide path of the correct angle but passing through the present position of the aircraft.

For either method of visual interpretation the position of the aircraft relative to the beam is read in the same way. In Figure 4, for example, this would be below and to the left of the beam.

In this mode of operation the heading knob is used in two positions (push and turn or pull and turn) to operate both the roller blind carriage for setting runway azimuth (Q.D.M.) and the heading index to set drift angle. When the glide and beam signals are being received indication is given by flags in the two marked apertures at the top right hand corner of the display, and an indication of the I.L.S. marker appears by a signal light in the aperture at the bottom centre.

It will be appreciated that when using the complete system shown in Figure 2, with the I.L.S. mode selected, the user has simultaneously the displacement situation displayed with respect to the beam, as described above, together with computed flight director signals displayed on the attitude indicator showing the manoeuvre required to bring the aircraft in a stable manner on to the beam. This situation is shown in Figure 4, where the attitude and navigation display are shown together in the I.L.S. mode where the navigation display shows the aircraft below and to the left of the beam, and the flight director index is showing a demand for a climbing turn to the right in order to correct this situation.

4.3 Compass Display

In the simple heading display the centre of the indicator is blank (Fig.2). Synchronization is provided by the knob in the bottom right hand corner. The usual dot and cross indication compass annunciator, which indicates that magnetic monitoring is proceeding, appears in the lower left hand window above the heading knob, while provision is made for operating from an unmonitored azimuth gyroscope by the push button switch (upper left).

5. STANDBY INSTRUMENTS

The standby instruments are conventional in principle and may be regarded as miniature versions of the earlier directly operated indicators, in which an attempt has been made to supply the smallest minimum usable facility in the event of failure of the servo-operated presentations. These are shown in Figure 5.

5.1 Airspeed

The instrument is a pressure operated capsule pitot-static differential pressure gauge working directly from the aircraft pressure supplies; it is housed in the international standard flangeless 2-inch case. The presentation is of the single pointer type making an approximately 330° revolution over the range. The scale is non-linear, contracting above 200 knots. Below 200 knots the scale is reasonably linear and is subdivided in tens of knots for approach and landing; it can be read to the nearest 3 knots without difficulty and is accurate to this tolerance below 300 knots. Accuracy above this value is $\pm 1\%$ of indication.

5.2 Altimeter

The problem of providing a reasonable presentation of height in miniature form without ambiguity is more difficult than that of airspeed, since it is necessary to include means of adjustment for ground pressure variation and presentation of ground pressure set for landing purposes.

At heights above the range in which let-down or landing procedures would be operated a very simple indication will suffice.

The instrument illustrated aims at meeting these requirements. The indicator is, in principle, an aneroid capsule barometer operating from the aircraft static pressure system and is housed in the international standard $2\frac{3}{8}$ in. flanged case with a knob for ground pressure adjustment.

Two concentric scales of height are provided with separate pointers, only one of which is normally visible at a time, the inoperative pointer being concealed behind a radial mask plate marked with the word 'ALT', which also bears the index mark for setting ground pressure.

A relatively open scale of at least 5000 ft is needed for let-down and landing purposes. Since an additional range of 3000 ft is required for ground pressure adjustment, the outer scale of height, which is linear, covers a range of -1000 ft to +10,000 ft. The inner scale, which is much less open, extends from 10,000 ft to 60,000 ft, height in this range being indicated by a smaller pointer which does not emerge from behind the mask plate until a height approaching 10,000 ft is reached as the outer scale pointer disappears.

A ground pressure scale graduated in millibars is marked on the lower rim outside the height scale and rotation of the adjusting knob rotates the radial mask with its setting index together with the whole movement of the instrument, the inner scale and its pointer and the outer scale pointer, so that the outer scale pointer is moved over the fixed outer scale by the appropriate change of height due to ground pressure adjustment made. Ground pressure adjustment therefore affects only the outer scale indication and the inner pointer always indicates pressure height to the standard convention. This expedient has been adopted because, as already stated, the indication above 10,000 ft need only be approximate and because the difference in magnification between inner and outer scales would cause considerable mechanical complication if ground pressure settings were attempted on both.

There may be, therefore, an apparent hiatus between the upper end of the outer scale and the beginning of the inner scale which will always commence at a pressure height of 10,000 ft.

An accuracy and legibility to within 100 ft is aimed at on the outer scale.

5.3 Artificial Horizon

The standby horizon is a miniature version of the moving horizon bar type of electrically operated instrument and is housed in the international standard $3\frac{1}{4}$ in. case. The three-phase a.c. gyroscope has complete freedom in roll and $\pm 85^\circ$ in pitch. Since reversion to standby indication might be necessary at any time, the instrument is provided with a rapid settling system within the same limits as the main instrument sources (within 20 sec) so that it is available at the outset of take-off. Fast erection facilities are also provided by push button. The instrument is normally operated from the a.c. supplies, but failure of these automatically switches operation to a transistor d.c. inverter operating from the emergency d.c. system.

5.4 Standby Azimuth

The indication of azimuth for emergency use has been developed to provide a relatively short-term memory indication of heading with a reading accuracy of approximately 2° suitable for flying the legs of an approach pattern, but which is free from the turning errors associated with magnetic compasses and which has a superior presentation to the extremely simple, small standby magnetic compass normally provided.

For this purpose an indication from an unmonitored azimuth gyroscope is suitable, given initial synchronization with some heading reference, which could, in the last resort, be the standby magnetic compass. The precession errors of the azimuth gyroscope would be tolerable in the approach case, but the indication could, of course, be used for longer periods provided that synchronization is periodically checked. The frequency of checking depends upon the precession rate and quality of the azimuth gyroscope.

In order to minimize the size of the indicator, electrical transmission from a remote azimuth gyroscope is employed, but the transmission is as simple as possible, using a.c. synchros in the torque mode without servo operation. Power supply, both for the gyroscope and transmission, normally comes from the a.c. supplies, as in the case of the standby horizon, but a.c. failure causes automatic switching to the same transistor d.c. inverter that supplies the standby horizon in an emergency. The instrument is housed in the international $2\frac{3}{8}$ in. case like the standby altimeter and is of the rotating card type graduated in 10° divisions and read against a fixed vertical index. Its presentation as an earth reference instrument is therefore compatible with the main indication of heading on the navigation display.

Synchronization is effected by turning the knob in the lower left hand corner. On reversion to this instrument in the event of an emergency, it is essential to verify that the remote azimuth gyroscope is in a usable condition before synchronizing, i.e. that it has not recently been toppled by any manoeuvre and is erected within usable limits.

By pushing the synchronizing knob on the indicator the azimuth gyroscope is interrogated as to its condition. If the spin axis is more than 5° from the horizontal a warning light appears in the top right hand corner of the indicator and fast erection is automatically applied to the gyroscope. When the spin axis is erected within 5° of horizontal the light goes out and synchronization may proceed. It is not necessary to hold the knob down during the fast erection process.

The azimuth gyroscope has a wander rate of approximately $10^\circ/\text{hr}$, so that the necessity for resynchronization is sufficiently infrequent for the purpose required.

6. INSTALLATION

In order to facilitate installation removal and maintenance, the main elements of the servo-operated display are mounted in a rack or hollow crate which carries all fixed wiring. Spigots on the back of the display units ensure accurate location on insertion in the rack before electrical connectors mate with each other. Units can therefore be withdrawn without trailing connecting cables.

7. TOPOGRAPHICAL NAVIGATION DISPLAY

The navigation display of range and bearing already described with respect to a beacon or offset point can be regarded as a step towards pictorial display. Although a scaled representation of the horizontal plan situation is displayed within a quantitative indication of heading in a conformal manner, the symbols displayed bear no resemblance to the outside world.

A much higher degree of realism can obviously be achieved by presenting the aircraft's ground position and track against the background of a conformal topographical map in colour. All natural or man made features such as sea, coastlines, rivers, lakes and mountains, towns and railways may be indicated by familiar conventions of line and colour but the information content can be made much higher than that of the outside world by naming the features and adding data such as contours, spot heights and latitude and longitude values.

Some experience has been gained with roller map devices in which a predetermined track strip cut from the paper map is driven on spools by groundspeed data resolved along the aircraft's track, while the ground position is shown by a cursor driven across the strip by groundspeed resolved across track. The principal limitations of such devices are the necessity for preparing the full scale map strip before a flight and the inflexibility of the plan. Even with the provision of limited storage or 'memory' facilities in the unit beyond the width of the strip there is virtually no tactical freedom for changes of flight plan or diversions. The presentation is also somewhat lacking in realism.

If a sufficient geographical area in the form of map coverage can be stored in an instrument of acceptable size to be compatible with operational range and the instrument can be arranged to produce an image of a reasonable area at the original map scale it is apparent that the advantages of a pictorial display of present ground position can be combined with practically complete tactical freedom within the area stored in the instrument, which can then be operated in geographical coordinates instead of along and across track.

The instrument illustrated in Figure 8 has been developed and produced to assess the value of such a presentation and to gain flight experience in operating techniques. Flights of up to 1500 nautical miles have been made in the U.K., Western Europe and North America with no other navigational aid and excellent results have been achieved.

The maps are condensed by micro filming in colour on standard 35 mm perforated motion picture film, the maps used being the standard series of 1:500,000 Topographical Charts on Lambert's modified conformal projection (5 km/cm).

Using refined copying techniques and high quality 35 mm equipment it is possible to achieve a reduction of 20 diameters in colour and yet preserve all detail, so that a small area of the microtransparency can be optically projected back to the original scale with acceptable quality and definition. This means that a standard 1:500,000 map sheet covering 2° of latitude and about 180 nautical miles in longitude can be reduced to the dimensions of one standard miniature camera frame, 24 mm x 36 mm, with a scale on the film of approximately 140 nautical miles per inch (100 km/cm).

An example of the area covered on this scale by 70 frames is shown in Figure 9, from which it will be seen that practically the whole of Western Europe can be stored on approximately 3 metres of film, providing complete tactical freedom within that area on the relatively large scale of 1:500,000. Since 3 metres of film occupies a spool of the order of only 1 in. (2½ cm) in diameter it is clear that a much greater area can be stored without space problems.

7.1 Data Sources

The instrument can be regarded as a visual repeater operating from the navigation computer from which it receives resolved ground mileages in Northings and Eastings and track angle.

For self sufficiency, the data sources operating the system are preferably airborne and self-contained. For example, groundspeed and drift angle derived from a Doppler radar system may be combined with a heading reference to give track and the ground speed appropriately resolved. Alternatively, the instrument could derive its information from inertial sources. The presentation is readily operable either from analogue or digital computers. Since the gear ratios involved are very high, little power is required for the traction system driving the film and the complication of servo loops and amplifiers can be avoided by the use of miniature d.c. stepping motors, provided that the number of steps per nautical mile is sufficiently high to preserve the illusion of continuous motion.

7.2 Projection System

The instrument illustrated (Fig.8), projects a circular image 6½ in. (16½ cm) in diameter onto a translucent screen covered by a plastic Fresnel lens which intensifies the image and produces even illumination. A high level of screen apparent brightness of the order of 500 to 600 ft Lamberts is required for bright daylight use, but this can be achieved with a high efficiency high aperture optical system with a light source of the order of 100 watts. Dimming facilities are provided for overcast, dusk or night conditions. The area of film projected at any instant, therefore, at the 1:500,000 scale is a circle 0.35 in. (approx. 9 mm) in diameter, which corresponds to approximately 50 nautical miles. Present position is shown by the cross in the centre of the screen and track by the diametral line marked off with a distance scale every 5 nautical miles from the centre.

By providing a dual lens turret with a mechanical hand-operated lever change control a second scale of 1:1000,000 (10 km/cm) is available. By this means four times the area of the microtransparency is projected at half the original magnification, so that a diameter of 100 nautical miles can then be seen. The drive to the film is unaffected by this purely optical expedient which has been found to be an extremely valuable facility in flight for looking ahead.

The advantages of an automatic continuous plot of ground position within a geographical context have been more fully appreciated as a result of flight experience. Not only is present position displayed continuously without any delay or work load on the user, but the track line extrapolates or produces this to provide a pictorial plot ahead showing where the route will lie if the prevailing track is maintained. If this does not pass over the required place or fix point the course change necessary to bring the

track line over the required point can be called up by visual reference to the degrees scale surrounding the screen. Similarly it is possible to lay off a track to any point visible within the range of the 1:1000,000 scale presentation without plotting by turning the aircraft to bring the track line over the point.

7.3 Frame of Reference

A choice somewhat similar to that discussed in the presentation of attitude exists with the presentation of topographical features. Although in this instance the cross index is invariably identified with the aircraft, the image may either be track orientated or North orientated. In the case of North orientation the surrounding track scale is stationary with North at 12 o'clock and the user visualizes his aircraft travelling over the map with its track shown by the angular orientation of the track line on the scale. Track stabilization, however, is most nearly compatible with the earth reference presentations used elsewhere in the instrument system. In this mode the track line is locked vertically and the track input to the device is applied to the image and degrees scale, both of which rotate with change of track.

The detail ahead of the user is then invariably in a vertical direction from the centre of the display corresponding to forward view and its orientation with respect to topography will be in agreement with the outside world as seen through the windscreen by the pilot.

For pilot operation, particularly at low level, operation in a track stabilized mode requires minimum rationalization with ground topography if recognition of physical features is the main aim, though in this mode printed words may appear at any angle. Navigators, however, usually prefer to work with North stabilization. Since the instrument is intended for use by either pilot or navigator and a dual installation may be run with two displays in parallel, it has been thought desirable to allow for both modes of operation and the track input may optionally be applied either to the track line which is marked on the screen or to the image and degrees scale, which is capable of complete rotation together with the film traction system.

A dual installation may be operated with one display North stabilized and the other Track stabilized.

Discontinuities are imposed upon the instrument by the storage system and by the geometrical problems of map drawing projection inseparable from any attempt to represent the near spherical surface of the earth on a flat sheet.

Even with the scale of reduction achieved of 20 diameters, which gives, in effect, a micro-map with a scale of 40 nautical miles per inch (100 km/cm), a distance of 1400 nautical miles would be 10 inches (25.4 cm) in length. It is obvious that if distances of this order are to be considered, the area of any form of sheet coverage and the area swept out by moving it would be far too great to accommodate in any acceptable size of instrument. Some division of coverage and storage either in separate areas or serially in a strip is therefore necessary for this reason alone.

The principle of pictorial map display is not related to any one map projection and a full discussion of the methods used to minimize map projection convergence errors and to achieve map changing are not within the scope of this report.

The system described has been developed initially as a dual pilot-navigator installation in which control of both displays can be centred with the navigator, relieving the pilot of the task. It is likely, however, that the development of fully automatic map changing and fixing facilities will provide a presentation capable of being used by the pilot alone.

The provision of a storage or 'memory' facility in the associated navigation computer, enabling resolved ground mileages to be switched from the display into store and subsequently discharged from store into the display, enables the display to be stopped and adjusted either in relation to a direct ground fix, or, for the purpose of map changing from one frame to another, without loss of position.

Changes N.S. are readily made automatic, so that on going into store, for example at a Southern parallel of latitude on a given sheet, the instrument is automatically wound on by the requisite number of frames and simultaneously to the Northern edge, so that the North edge of the new frame is entered at the same longitude and on the same parallel as the position at which the previous frame was left.

Flight experience both with and without ground visibility has confirmed the value and ease of interpretation of a topographical display.

The ability to anticipate features ahead and the rapid recognition of ground features, with consequent orientation after breaking cloud, are examples of the potential of this type of display.

8. 'HEAD UP' DISPLAY

The improvements in integration, rationalization and information content so far described relate to instrument presentations mounted in an orthodox position, i.e. within the cockpit. The fact remains that the conventional instrument field of view is completely separated from and adjacent to the pilot's external field of view, the instrument field being closer to the pilot and below the downward limit of his external forward sight line.

This separation of the two fields may not be highly significant in those modes of flight in which reliance is placed either wholly on instrument indications or on external visual clues, but clearly becomes important in modes where external field information is required to be augmented by instrument information from the internal field, as in the approach.

Under these circumstances the physical separation of the two information fields involves the following complications of the pilot's task:

- (a) The spatial separation of the external field from the instrument field requires a movement of the sight line downwards in order to read or scan the instruments.
- (b) Since the instruments are relatively close to the pilot while his external field of view is effectively at infinity, there is a need to re-focus when transferring attention from one to the other.

- (c) The instrument field is within the cockpit and is shielded by the structure. There is usually a considerable separation in the brightness levels between the two fields, which demands adaptation in changing from one to the other.

Transition, therefore, from instrument to visual flight, as in the approach, or reversion from visual to instruments, involves these discontinuities if the instrument field is located in the orthodox position.

Since it is clearly desirable that the pilot should, ideally, be capable of performing concurrently the visual tasks associated with the external and internal visual fields, a system of presentation in which the effect of location of the information has the least effect on the pilot's performance is best.

The difficulties associated with the angular and distance separation of the visual information fields are eliminated if both are located in the same direction and at the same distance from the pilot's eye position. This can be achieved by collimation or projection to infinity of the instrument information in the direction of the flight vector. This method has been successfully used for many years for weapon aiming in the form of the reflector gun sight.

In such an instrument, the image of a graticule is reflected by a transparent plate, or possibly by the windscreen itself, in the direction of external observation and is projected to infinity by a lens system. It is possible by this means to present to the pilot fiducial marks related to the axis of the collimator, and hence with the direction of the aircraft, which are seen in the same apparent visual plane as details in the external world.

By collimation and superposition of the two fields by reflection it is therefore possible to acquire information from both fields simultaneously at maximum visual acuity and without accommodation or deliberate scanning.

The effect of location of the instrument display on combined instrument and visual flying has been investigated by Naish², who compared quantitatively uncollimated peripheral, uncollimated central and collimated central presentations with respect to a dual task capability and who has confirmed the advantages of central collimated presentation.

An instrument of this type, termed a 'head up' display, can be realized technically by exploiting the flexibility of the cathode ray tube, the required symbols being produced by a suitable waveform generator on a high intensity cathode ray tube, a collimated image of which is seen by reflection from a transparent reflector mounted in the external line of sight. As mentioned earlier, reflection may take place from the windscreen itself.

8.1 Information Displayed

Priority has been given to the presentation of information which is most necessary for control of the flight path and which is compatible with the external field of view when both are visible. This results in the presentation of the horizon as a single line or bar providing a simple visual analogue of the real horizon, a fixed central circular fiducial mark identifiable with the aircraft and a presentation of demanded

flight path used as a flight director. The information content is therefore similar to that of the roller blind attitude indicator with flight director already described, but the form of information is different. The basic conventions are, however, the same, i.e. the earth reference for presentation of attitude and the 'fly to' convention for the director index.

In superposing the instrument presentation on the external field of view the obvious desirability of achieving conformity between the apparent movements of the natural and artificial horizon resolves the problem of choice of the frame of reference.

The appearance of the head up display of attitude and flight director information in the instrument described is shown in Figure 10. The horizon is represented by a single line. The flight director index, which was restricted by engineering considerations to a circular ring in the head down roller blind indicator, is now displayed as the apex of a series of parallel lines of diminishing length, which provides a semi-pictorial representation of the demanded flight path with some illusion of perspective. As previously pointed out, the identification of the director system with a demanded flight path is valid only until action is taken to satisfy the demand, when the deflection is cancelled. Moreover, the perspective path is not a simulation of a real visual situation but a synthetic device having compatible visual properties.

The greater flexibility of the cathode ray tube method of synthesis of the required symbols compared with the electro-mechanical roller blind indicator also permits the flight director displacement to be shown in geographical coordinates, unlike the director index of the roller blind. The parallel lines of the director 'ladder' therefore remain parallel with the horizon under all circumstances, as shown in Figure 10.

Simulator and flight experience has shown the ease of learning and accuracy with which a tracking task can be performed using the display.

The addition of symbolic or quantitative information of height and speed in a head up form are being studied. This information is clearly complementary to the attitude and flight director information and is not provided from the appearance of the outside world. The appearance of such information, however, while valuable in the head up context, is essentially artificial and has no natural relationship with the outside world, as has the horizon or, to some extent, the flight director.

For this reason this form of display is at present considered to be outstandingly suitable for the presentation of information which supplements and is compatible with the external field of view. Attempts to exploit the flexibility of the cathode ray tube method of generation of symbols, in order to add information of the full content and quantitative accuracy provided by the head down presentations described, might well overload the display and also interfere significantly with the view of the external world. These considerations are being evaluated.

The head up display may derive its indications from the same data sources as those used for the servo-operated head down instruments or from similar ones. A wide range of brightness and contrast control is required so that the brightness of display and external environment may be matched. This may be achieved automatically, using photo cell techniques.

9. CONCLUSIONS

Description has been restricted to the display of primary flight data, since priority has been given to the integration and improvement of this information. A similar field for development exists with the display of fuel and power plant data, particularly in the single-seat aircraft.

The development of head up display is a major step in dealing with the problem of transition from instruments to the outside world. It is believed that by producing displays that minimize contradictions with clues provided by the outside world and by supplementing natural information with pictorial-type display, such as the topographical unit, many sources of confusion formerly existing in conventional instruments have been removed. In simplifying the task of flying the aircraft the pilot's performance under difficult conditions and his ability to perform other tasks will be increased.

ACKNOWLEDGMENTS

Acknowledgment is made to Mr. A. Stratton of the Royal Aircraft Establishment for permission to use material from his paper on 'The Presentation of Information by Aircraft Instruments'¹ and to Mr. J.M. Naish, also of the Royal Aircraft Establishment, whose work on head up display² has also been used in preparing this report.

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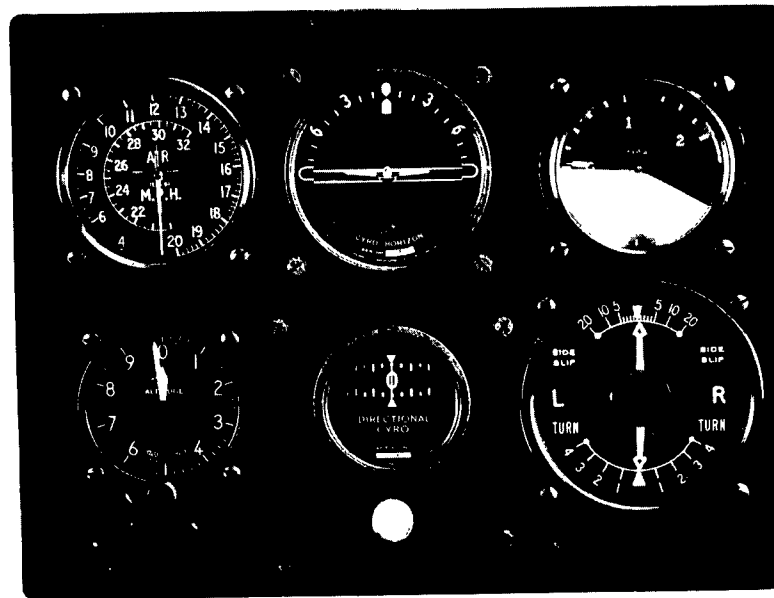


Fig.1 Standard blind flying panel, 1936



Fig.2 Integrated flight instrument system

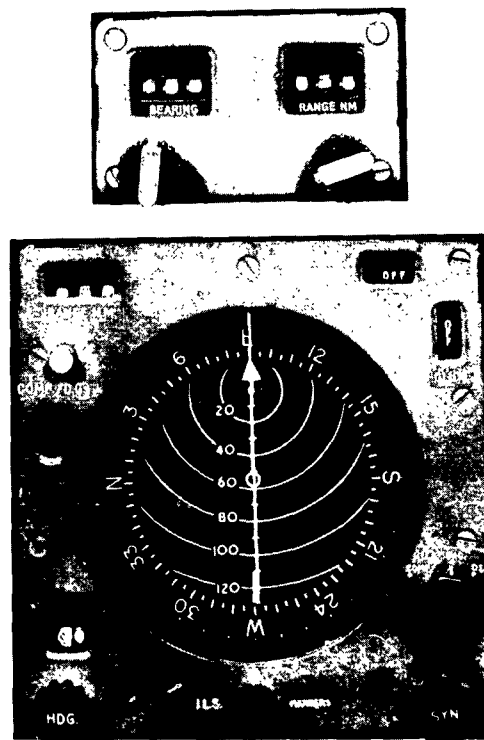


Fig.3 Navigation display range and bearing mode

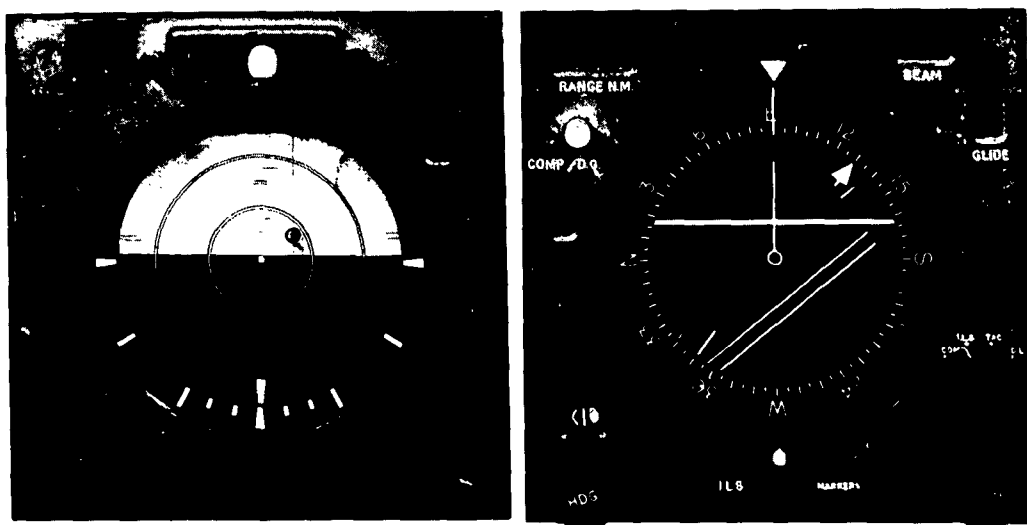


Fig.4 Attitude indicator with flight director index and navigation display
I.L.S. mode

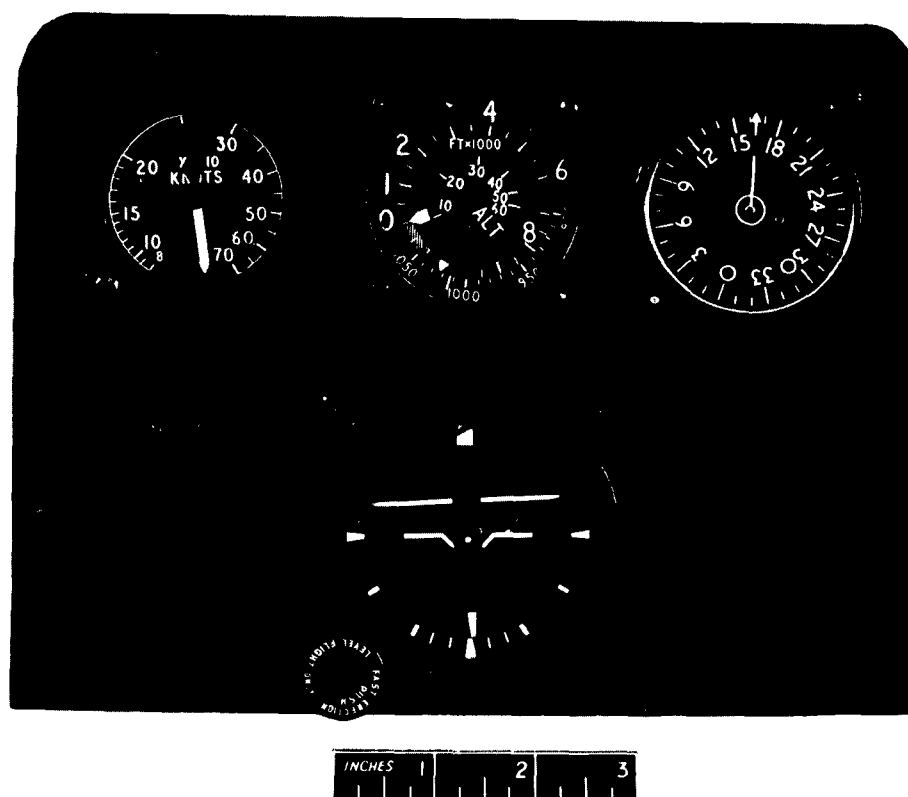


Fig. 5 Stand-by instruments

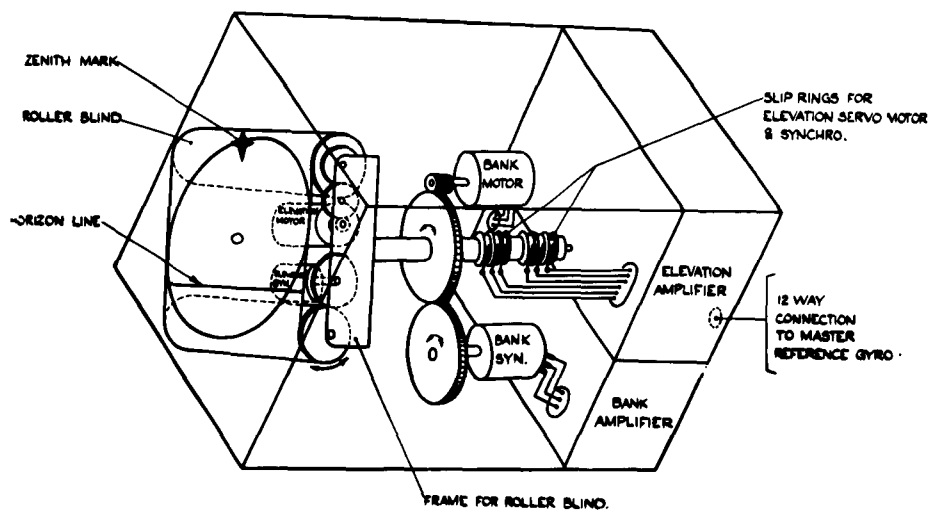


Fig. 6 Attitude indicator (roller blind) - schematic diagram

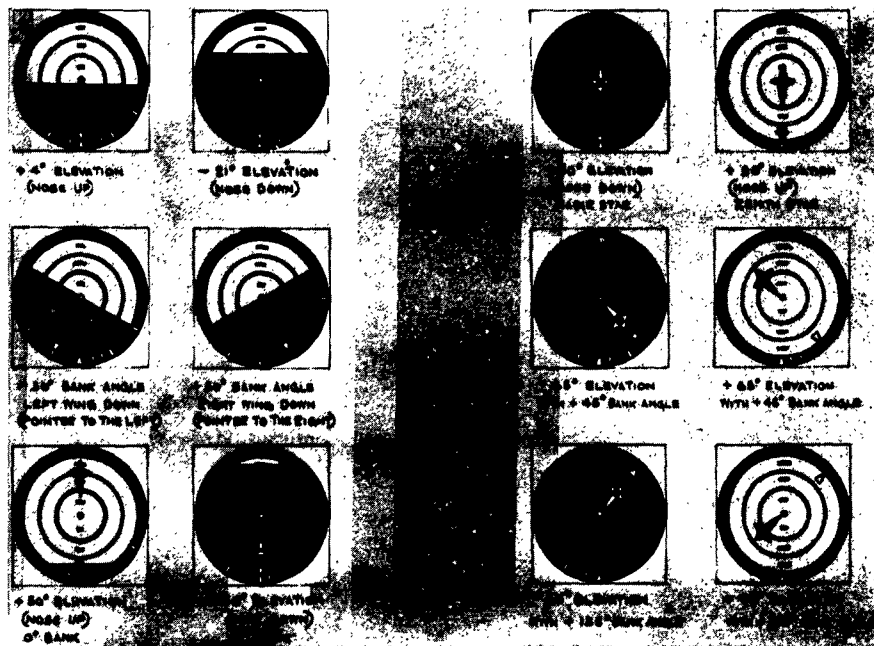


Fig.7 Illustrations showing various elevation and bank angle displacements of the 'roller blind' attitude indicator

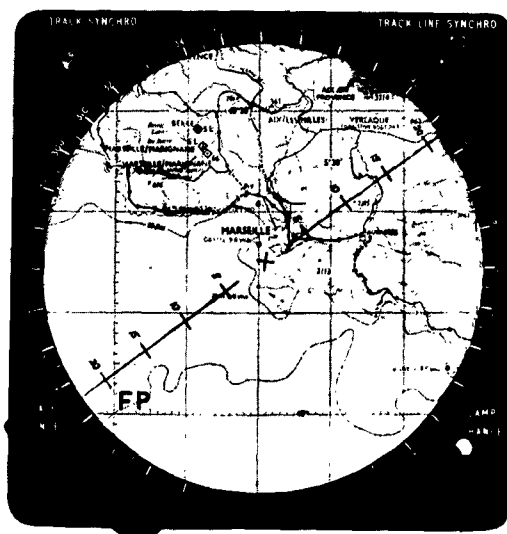


Fig.8 Topographical display

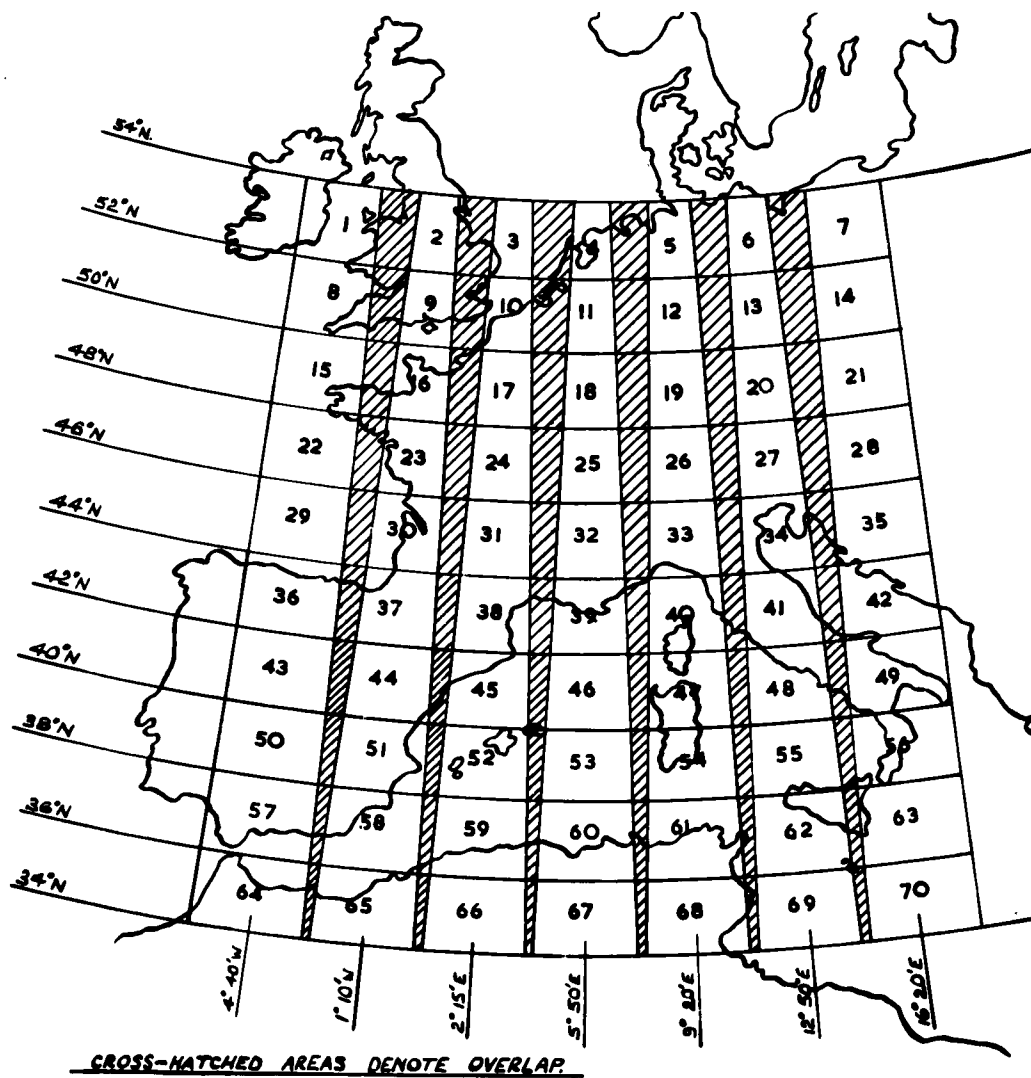


Fig.9 Area covered by 3 metres of film (70 frames)

THE HEAD-UP COLLIMATED DISPLAY

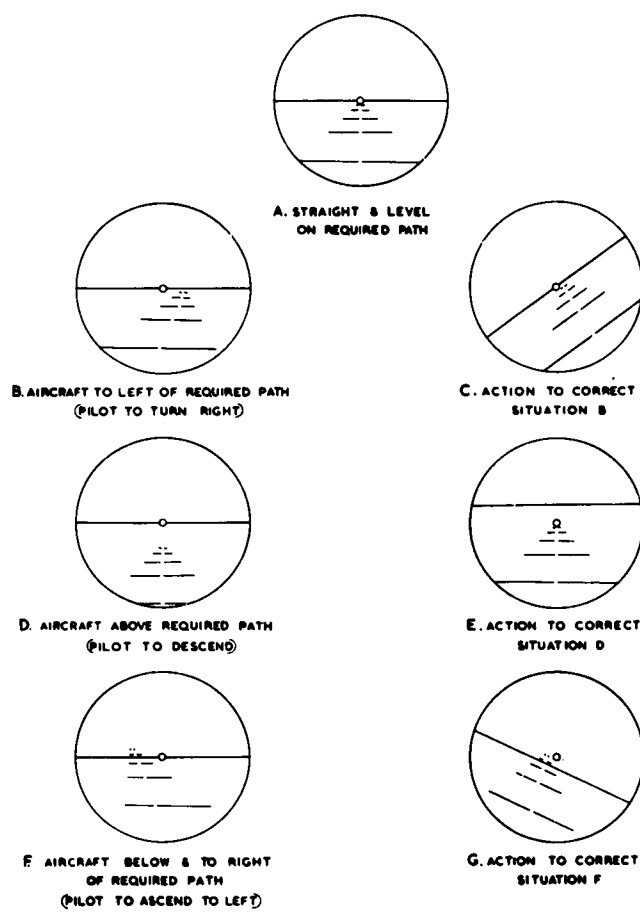


Fig.10 Presentation

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