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Simulation of Visual Flight, with particular reference to the Study of Flight Instruments

by

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SIMULATION OF VISUAL FLIGHT, WITH PARTICULAR REFERENCE TO THE STUDY OF FLIGHT INSTRUMENTS

by

J. M. Naish, M.Sc., A.R.C.S.

SUMMARY

The pilot's forward view in flight is discussed with a view to formulating the requirements for a visual background, to be used in the study of flight instruments. Systems of visual flight simulation are reviewed and it is shown that the appearance of the external world may be simulated in a very compact manner by extending the known principle of an edge-viewed ground pattern, using a novel television technique, with the addition of a simulated sky. The ground pattern is formed by projection from a transparency, representing the chosen terrain, which is endowed with movements of translation and rotation such as to permit complete freedom of manoeuvre within the area covered. An industrial television camera, mounted with freedom of rotation about two axes, is used to look across the ground pattern from a point of variable height and the resulting picture, which has six degrees of freedom - conveniently arranged to be compatible with the outputs of a conventional aircraft simulator, is presented on a large projection screen before the simulator cockpit, thus permitting head freedom and binocular viewing. Night or day conditions may be simulated and the visibility range is variable, but vertical ground features are not included.

Details of construction are given and values presented for the chosen field of view, scale and viewing distance. Picture quality for the moving scene is discussed in relation to the essential characteristics, which are texture, resolution, engineering accuracy, perspective geometry, contrast, depth of focus and horizon characteristics. Tolerances or values are indicated for these parameters and brief economic details are given.

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1 INTRODUCTION

It is well-known that the purpose of flight instruments is to provide that information concerning environment (or flight path) which a pilot has difficulty in acquiring by direct visual perception, the extent to which this auxiliary process is necessary depending on conditions of external visibility. It is thus desirable in the development of flight instruments to consider the assimilation of the information which they convey in conjunction with the direct perceptive process. In so far, therefore, as it is necessary to use a flight simulator for the assessment of flight instruments it is equally necessary to provide at the same time a simulation of the pilot's view during flight. The necessity for assessment under representative conditions is evident in the case of proposals, such as the Flight Director[1] and the Contact Analogue[2], which have been made to obviate the difficulties associated with reading individual instruments (reading times, transfer times and 'integration' times). These proposals should facilitate attention to other matters and the extent to which this becomes possible may be judged by making use of the visual background. Another case of immediate interest is the situation arising in poor visibility and at low altitude, when alternation between direct (visual) and indirect (instrumental) perception of environment assumes greatest significance; a proposed installation which may prove useful in this situation consists of a collimated, head-up steering display which will be seen superposed on the external world; clearly, an evaluation of such a system requires a visual background. The broad requirement in simulating visual flight for the study of flight instrument systems is, therefore, to provide a continuously variable perspective view in the forward direction for an aircraft which is supposed to be flying in an unrestricted manner over a given landscape of sufficient extent, under day or night conditions, with particular reference to conditions of poor visibility. Since the position of the pilot's head and the way in which he uses his eyes must be reasonably similar to that finally intended in the aircraft and since complete flexibility of approach to the problem of instrument presentation is essential to the type of enquiry to be conducted with the apparatus, unnecessary restrictions such as eyepieces are unacceptable and a free presentation of the environment is required. The significance of colour, under the visibility conditions of interest and for the type of work to be carried out, is very small.

The chief proposals which have been made for the serious study of visual flight conditions are broadly divisible according to the method of storing the information relating to the terrain and according to the method of presenting this information as a perspective view. Four main types are to be distinguished:

A The indirectly-viewed solid model.

B The indirectly-viewed flat model.

C The directly-viewed, projected transparency, and

D The indirectly-viewed, projected transparency.

A choice of scale must be made for the storage system and this leads to immediate difficulties in the case of a solid model. If the representative fraction (R.F.) is taken to be large it is possible to accommodate a considerable extent of country within a given building, but the accuracy required of the moving parts (to avoid spurious vibrations and discontinuities in the presented view) is then high. Conversely, a small R.F. eases the engineering problem but extends the installation. In practice, large installations, accurate engineering and temperature control are involved[3,4] and capital expenditure tends to be high. The use of a flat model is also possible and this may conveniently be made to move towards the viewing position, with some economy in space and mechanism[5]. In both methods it is necessary to obtain the view seen at the simulated eye-point and this may be conveniently done with a television camera, i.e. the viewing is indirect. In the method of the directly-viewed projection of a transparency a 'point' source is used to form an extended projection on a surface surrounding the cockpit[6,7,8,9] and it is then possible to move the cockpit, if desired. This method is chiefly applicable to helicopter studies, where the terrain limitations imposed by the finite size of the transparency are of little consequence. The transparency may also be of three-dimensional form if desired[7]. The principle of the projected transparency has also been used by Calvert[10], who has made use of a metal plate studded with holes representing runway lights, to form a ground pattern which may be viewed from one edge to obtain the necessary perspective scene. In this case the viewer's eye is placed before an ocular, thus defining the eye-point, and the scene is observed through deflecting systems giving rotations about the viewer's forward and lateral axes, the view of the projected pattern being more or less direct. Because of the system of deflection, a correction for apparent eye position is required and because of the use of an eye-piece, the system is not applicable to the general study of flight instruments. In addition, only lighting patterns are available, the horizon and sky are not represented and manoeuvres are restricted. It will be shown that by making the method of viewing indirect, i.e., by the use of a television camera, and by other innovations, it is possible at relatively low cost and without extensive installation space to extend the application of the principle of the edge-viewed projection to provide a view with all the characteristics required in the field of flight instrument research. The principal shortcoming of the system to be described is the absence of vertical features, which are, of course, obtainable with a three-dimensional scale model. However, the usefulness of the third dimension in visual studies appears to be limited, because the most frequent situation concerns the approach to a plane runway, and this omission is therefore tolerable, except where specific problems of terrain clearance are involved.

The essential features of the visual flight simulator to be described are: freedom of manoeuvre over flat, variable terrain of adequate extent, binocular presentation at a variable position, variable visibility, variable sky and ground brightness (night or day), compactness, relative simplicity of construction and flexibility of application to flight simulators. This system is of possible use in fields other than that for which it was devised, the extent of these fields having yet to be determined. The installation was first publicly demonstrated as a working model, in limited form, at the Society of British Aircraft Constructors' Exhibition held at Farnborough in September, 1958. It is the subject of Patents Branch Record No.951, dated 13th November, 1956.

2 BASIC PRINCIPLE OF VISUAL FLIGHT SIMULATOR

The essential property of the apparatus to be described here is the ability to provide the forward, perspective view of the terrain over which the flight is supposed to take place. The problem thus to be solved is to form a perspective view of countryside which moves towards the eye-position at appropriate speed, in the correct direction and along the desired track, whilst the view itself suffers angular displacements corresponding to such changes in bank and elevation as occur in the simulated flight, and the scale of the picture varies according to changes of height. In other words the visual field is to have six degrees of freedom and is to be tied to a datum (such as an agreed point on an airfield). This reference system is chosen for compatibility with flight simulator practice and ensures that the outputs X_N, X_E, h, θ, ϕ and ψ from a conventional type of analogue computer[11] are applicable to the visual flight apparatus; specifically,

X_N represents northing,

X_E represents easting and

h is height;

θ represents elevation,

ϕ represents bank and

ψ is heading,

these angles being the Euler angles of attitude. It is necessary to show first how the basic picture is formed and then to indicate how the motions are generated which correspond to changes in these variables. Finally, the picture so formed and thus animated is required for presentation in the simulator cockpit, where the pilot is able to make such changes in the controls as are required to effect the desired visual flight path, thus completing the loop. The overall system of the visual flight simulator is shown in Fig.1, where three main sections are distinguished by cross-hatching. Of these, the computer is that used in the R.A.E. flight instrument simulator (FISIM IA)[11] and incorporates an axis-transformation system giving outputs in ground axes (as defined above) after solving the forces and moments equations in airframe axes; the cockpit is essentially the flight simulator cockpit with the visual display added and the vision unit is thus the principal part of the equipment providing the visual flight simulation. The vision unit, whilst a simulator in itself, is better regarded as an auxiliary to the main flight simulator.

The basic picture used in the vision unit is formed by a simple extension of the well-known principle of perspective, first formulated by da Vinci[12], according to which a true picture of an object is formed by holding a transparent plate between object and eye, and marking on the plate the projection of the object. Thus, in Fig.2 if the observer's eye at E surveys a ground pattern which, for convenience, is taken to be an array of squares aligned with the horizontal direction of sight EH, and if the picture plane is the transparent screen PQRS which is normal to the sight line, rays to the eye from typical ground points such as B, C and D intersect the picture plane at perspective points, b, c and d. Furthermore, the same rays will intersect an auxiliary picture plane P'Q'R'S' which is also normal to EH at points b',c' and d', these points having the same geometry as b, c and d, apart from a scale factor, because of the rectilinear propogation of light. This fact is used in the visual flight simulator by making E the node of a television camera whose axis is, in the datum position, directed along the simulated line of sight,EH. The auxiliary picture plane is then formed by the photomosaic of the camera,on which is generated the perspective view of the ground pattern appropriate to an eye-position E. When the axis of the camera is turned into another direction passing through E the situation then corresponds to a new line of sight and a new picture plane, in other words the perspective view is then based on a new visual centre. By making the assumption that the pilot's line of sight is the forward direction of movement of the simulated aircraft, it is possible to simulate the pilot's view of the ground represented by the pattern offered to the television camera. When the line of sight does not coincide with the flight axis the perspective geometry is still correct because the picture plane does not have to be always perpendicular to the sight line. An allowance can be made for the effect of drift.

In Fig.1 the vision unit is shown as consisting of two parts with the separate functions of projecting and viewing the basic picture. The methods used for these purposes are indicated in Fig.3, in which the assembly TL forms the projector and the assembly NV is the viewing unit, the basic picture being formed on the intermediate screen GG' which is normal to the axis of projection.

In the projector, part of the transparency T is imaged by the lens L on the screen GG', thus defining the ground plane and forming a plan view of whatever ground pattern the transparency is intended to represent; then by suitable movements of the transparency in its own plane the projected picture can be made to move towards the viewing position, N, from whatever direction and from whatever point may be desired. To do this it is necessary to provide independent movements representing northing, easting and change of heading (the heading axis being conveniently the axis of L, which also passes through N), and the mechanism needed for this purpose accepts inputs appropriate to these variables from the computer (as shown in Fig.1). It is thus possible to provide at the viewing point a picture with the properties already defined in relation to Fig.2 and with the pictorial elements moving and changing in a way to represent movement over the ground along any desired track, over terrain of a very general nature; the picture is completed with the addition of a sky background which is produced by controlled illumination falling on the screen SS'. This picture is viewed by means of a television camera, V, whose node is at N and which has the facility for rotation about its own optical axis. It may also rotate independently about a perpendicular axis through N parallel to the ground plane, GG', so that the resulting picture can be made to simulate changes of both bank and elevation. The viewing unit is also movable as a whole in a direction perpendicular to the ground plane, to simulate the effect of changes of height. A similar effect is to be obtained by changing the scale of the ground pattern as may be realised by the use of a projection lens, L, of variable focal length, and in this case the fact that the viewing point, N is on the optical axis of L, which defines the simulated vertical, causes scale changes to be symmetrical with respect to a point immediately 'below' the simulated viewpoint. Both methods of simulating height variation are useful (although the zoom lens method calls for an unusual system of illumination if light losses are to be avoided) and the height input is shown in Fig.3 as being available at both lens and viewing unit, whilst the viewing unit also accepts inputs corresponding to bank and elevation. It then remains to make available in the cockpit the picture contained in the televisual system and this is most conveniently done by using a television projector (Rank-Cintel Ltd.) to throw the picture onto a screen in front of the pilot in such a way as to make his viewpoint the perspective centre of the picture. It will be appreciated that the resulting picture simulates movements corresponding to six degrees of freedom, is unrestricted in the nature of the terrain and, by reducing the contrast in the ground picture along the direction from G' to G, permits the simulation of a range of visibilities, whilst removal of the sky illumination and alteration of the contrast allow night conditions to be simulated. It will also be realised that the geometrical properties of the picture may be made as correct as the funds available for constructing the simulator permit (by seeking exact equivalence of the pilot's eye-point and the perspective centre, and by increasing the throw of the projected picture indefinitely); also, that the pilot's head is given complete freedom of movement.

3 DESIGN OF VISION UNIT

The technicalities involved in the practical realisation of the visual flight system do not require detailed specification, but the more important points will be noted. The perspective drawing, Fig.4, shows in schematic form the arrangement and functions of the components necessary to the projector unit. Light from a Xenon arc, X, (BTH Sound Equipment Ltd.) passes forward and upwards along the chain-dotted axis through the transparency carriage, ABCD, the zoom lens, Z,(W. Watson & Sons Ltd.) and returns in a direction parallel to the original, the optical axis being deflected by mirrors, M,N. The chief part of interest is the carriage, which is built around the optical path and consists in a standing part, D, (on which contacts are mounted to feed slip rings formed in the lower surface of the plate C) and three moving members, A, B and C, which divide the functions of forward and lateral displacement and heading change in the conventional manner. Since these movements must be continuous and must follow the computer outputs faithfully, careful attention is called for in designing the geometry of the moving parts and in providing appropriate feedback arrangements. Features found to be necessary, because of the optical lever implicit in the system, are kinematic movements[13], for both slides and heading ring, and position feedback potentiometers of high resolution (not shown). The lead screws controlling translations are driven through gearboxes by Muirhead Mark 8 servo motors, such as E, and the heading ring is actuated by a friction drive originating in a type 88X motor, W. Other features of the projector unit are the visibility slide, V, in which a variable-density filter is moved laterally, and the cooling fans (such as F) which, in conjunction with heat-absorbing filters and venting arrangements, dispose of excess heat. The projector unit is also shown in the photograph Fig.5 where the lamphouse with its air duct is seen in the lower foreground, the transparency carriage is seen edge-on in the central level and the zoom lens, together with the upper mirror, is observed in the upper section. The whole unit has been built up in a temporary structure of sufficient rigidity and when brought to a stage of reasonable finality will probably be housed in a casting.

In the viewing unit the problem is to support the television camera and provide the requisite movements without allowing the means so employed to interfere with the ability to bring the viewing (or nodal) point as close to the ground picture as may be required. Fig.6 is a perspective drawing which shows the scheme used to provide the camera mounting, and the photographs Figs.7 and 8 show the viewing unit as seen from one side and from the rear respectively. In Fig.6 the camera, C, is shown held in two circular plates, P, Q, with rims of semi-circular cross-section, these plates being used to provide rotation in bank about the optical axis. Because the camera lens is mounted somewhat off-centre in the industrial type of camera used (Pye Ltd.) it is necessary to use a comparatively large plate diameter (about 12 inches) in order to bring the lens to a central position. The toroidal rims of the plates are supported on five ball-races, two of these being used as 90° V-pair and one as a friction drive from the type 88X motor, M, through a single worm reduction. Rotation in elevation is provided by a more conventional (and less responsive) mechanism consisting of a shaft running in two races mounted within the cylindrical housing, H, which separates the plate, R, (carrying the bank mounting) from the base-plate, S. The elevation axis, which is normal to the bank axis, is shown chain-dotted and it is arranged that this may pass through the node, N, simply by moving the camera forwards or backwards in the plates P and Q. The drive to the elevation system is taken from another type 88X motor through double-reduction gearing and it is hoped to improve the relative sluggishness of this motion by alteration of the gear ratio. The entire mounting is movable on a slide below the base-plate, S, for the purpose of simulating changes of height, but this slide is not shown in the illustrations. In Fig.7 the features already described are evident together with electrical details (including switches to limit elevation) and this photograph shows clearly the space available in the immediate vicinity of the cone of vision of the camera. In Fig.8 the rear-mounted toroidal potentiometer which provides feedback in bank is easily recognised and it will be noted that changes of bank angle are limited to about ±90°, in order to avoid the use of slip-rings in bringing out the television camera lines. A further potentiometer, for elevation feedback, is seen mounted on the base-plate, and also, to the right, is a friction-driven potentiometer which was used unsuccessfully at an earlier stage as a bank pick-off.

The disposition of the projector and viewing units relative to the screen has been shown in plan form in Fig.3; it is further illustrated in the photograph Fig.9. Here the screen is seen with the plan view of a runway, which has been formed by the projector unit situated in the immediate right foreground. The viewing unit is to the right of the screen and from an adjacent position the sky illumination is thrown forward onto the left-hand part of the screen. The control unit shown in Fig.10 serves the purpose of housing amplifiers for the servo systems, provides local control of lighting, permits adjustment of the television system and makes available the various supplies required in the apparatus. The entire assembly, including projector, screen, viewing and control units is customarily housed in a room approximately 20 ft x 10 ft in area but it has been found possible to operate the apparatus within a room 9 ft 6 in. long, 7 ft 6 in. wide and 8 ft high.

4 OPERATING CRITERIA

(a) Picture quality

For the simulation to be judged valid it is necessary to establish criteria in respect of parameters affecting the issue. Little information is available on the subject, apart from some guidance on the scales suitable for Calvert's method[14], and this may well be through lack of definition concerning the objective. It is deceptive to state that the simulation must faithfully represent the pilot's view because this view cannot be known, except by inference, and any such inference must therefore be made clear. An early experiment showed that attempts at accurate representation of ground features such as fields and hedges were superfluous because pilots expressed lack of interest in such features and were almost entirely concerned with landing facilities. This suggests that the pilot's visual world is selective and implies, in a more general way, that although the simulation may include features of little interest to the pilot it cannot safely omit the essentials, which must therefore be known.

The second inference to be made concerning the pilot's visual world concerns definition of detail, or resolution. Since the region of high resolution is limited to about $2\frac{1}{2}^\circ$ in the human eye[15] a scanning process is essential to the assimilation of an extended scene. When the scene is static, ample time is available for scanning and it follows that for a photograph of the same scene to be convincing the resolution must be sufficiently good throughout a large part of the photographic field. When the scene is constantly changing it is no longer possible to assume that an equal degree of scanning can take place and the scene, if perceived as a whole, can therefore only be perceived at reduced resolution. It follows that where the simulation is mainly concerned with representing the broader aspect of visual perception, i.e., the perceptions of form rather than detail, some relaxation of the normal standard of visual acuity (1 minute of arc) is permissible. From the pilot's pre-occupation with judgement of apparent shapes and relative position of gross detail (to assess, respectively, his line of approach and attitude[16]), it is inferred that his visual world tends to lack detail, and this has been confirmed by experiments in landing an aircraft using a televisual presentation with degraded definition, landings being successfully accomplished when the definition is reduced five to ten times[17]. It must be stressed, however, that his ability to concentrate on a limited, high-definition field is not thereby excluded and the present simulator cannot be used in circumstances where the limited field is relevant.

It has been shown that the simulated view must present the principal features affecting the proposed flight path (usually an approach, for instrument studies) and need not be characterised by the same standards of resolution as are applicable to a photograph. The simulated view should also show the gradients of perspective, contrast and movement discussed by Gibson[18]. Experience with the simulator confirms that these qualities are essential parameters of the simulation, and criteria may be established by distortion of a gradient sufficient to destroy confidence in the presented view. A check may also be applied for geometrical accuracy by lowering the nose of the simulated aircraft and observing whether the ground appears to expand about the point of approach; this condition is met when the (height-dependent) change of scale matches the horizontal component of forward velocity. Gibson has also remarked upon the importance of 'texture' in perceiving the visual world, where texture evidently embraces those variations of light and shade by which the surface is made apparent and without which gradients of perspective, contrast and movement cannot be seen. Experiments in varying texture have shown that whereas a minimum texture is necessary for any simulation to be possible, this parameter is of secondary importance. The photographs, Figs.11-19, show the stationary aspect of scenes of different textures available in the simulator, together with transparencies from which the scenes are derived. In Fig.11 the forward view is shown for cross-country flight and this has been obtained from a photo-mosaic (a composite survey photograph) such as is shown in Fig.12. A random texture is shown in Fig.13, the transparency for this scene being a photograph of scattered confetti, which is shown in Fig.14. Fig.15 shows the view of a runway obtained from a transparency which is a photograph of a black and white drawing, the surrounding country having been painted in quite roughly by hand, as shown in Fig.16. Fig.17 shows the effect derived from a transparency consisting merely of two intersecting lines on a ground of slightly varying density. The view of a runway lighting pattern shown in Fig.18 has been formed by Calvert's technique[10] of projecting from a drilled metal plate, but with the addition of horizon and sky. Extensive use of these views has shown that all give adequate sensation of forward flight over a ground surface, so that the gradients of perspective, contrast and movement which are common to all (when animated) are essential qualities, whilst the texture need only be minimal. It has also been found that the illusion is preserved if the field is emptied of detail except for the most pale lateral shadows (suggesting flight over barely visible ground or over stratus cloud). Also it has been found essential to merge ground into sky (by contrast and brightness control), to avoid the feeling that the ground and sky are different pictures, and this merging is characteristic of most visual flight conditions. It is interesting to note that the cross-country view, Fig.11, has been found to be usable for map-reading, in spite of the poor resolution, although the simple runway scene, Fig.15, is the most useful for general purposes. Another use which may be made of these views is to attempt to define the minimum information content necessary to preserve the illusion of flight.

Picture quality is also affected by the depth of focus of the television camera lens. It might appear that the unconventional manner in which the camera is used would lead to such a restricted depth of focus as to render the simulation useless, but it must be remembered that the intermediate screen can be made fairly small (GG', Fig.3) and that the contrast gradient further reduces the depth of field to about 4/5 of the screen width. The use of a Xenon arc (which can be run continuously at 65 amps with the cooling arrangements in use) and a sensitive camera tube (Cathodeon, type C.936) enables the camera lens to be worked at f/4, without undue 'trailing', and under these conditions the picture quality is poor but acceptable, the effective depth of field being about 24 inches or 2/5 of the screen width. It would be desirable to work at f/8 or f/11 however, for the size of screen in use, and experiments have shown that this condition may be met with an image orthicon camera. The highlight brightness is of the order 20 ft lamberts under working conditions at the screen (which is a diffusive, white surface) and the darkest parts of the projected scene have a brightness of the order of 2 ft lamberts.

(b) Field of view

The field of view must include those features of terrain most closely affecting the flight path. The more rapidly an observer moves through a featured environment in a given direction, the greater is the tendency to restrict attention to a cone centred on that direction. It is therefore necessary to know the angle of the cone of attention during flight, especially during the approach, when the visual world assumes the greatest interest. It is also necessary to be able to restrict the field of view as much as possible since, with a television system comprising a finite number of picture elements, an increase of field means a loss of resolution. A preliminary experiment was carried out in a motor car using an indirect visual sight, due to E. R. Webb, with a total field of 30° and this field was found to be adequate for steering purposes except in dense traffic[19]. Flight trials with an indirect televisual viewing system[17] have led to the recommendation that the visual field needs to cover 36° in the horizontal plane. Investigations of pilot's eye movements during bumpy conditions[20] show that the head then tends to remain fixed in azimuth, and it is known[21] that the line of regard then lies within a field of 35° to 40°. A field of this size corresponds roughly to the area of the forward facing panel and it is expedient to restrict the view in this way so as to avoid seeing the windscreen struts, as will be discussed later. If the total field angle for the simulated view is taken to be 30°, and if the televisual system has a maximum of 300 line periods (600 T.V. lines), the apparent resolution cannot exceed 6 mins. of arc. This means that the definition is degraded six times from the optimum value of 1 minute of arc, in agreement with the B.L.E.U. findings[17], and it is interesting to note that the visual acuity at the edges of a 30° field is about one sixth of the central value[22], so that the simulation will appear correct if viewed as a whole. The camera lens used in the simulator is of one inch focal length (Angénieux) and covers approximately 28° in the horizontal plane.

(c) Scale

When a model is used to produce a simulated view the choice of scale is governed by considerations of cover (including height range) and the displacement of moving parts, so that a compromise must be made between the conflicting requirements of installation space and engineering accuracy, as mentioned above. A more flexible approach is possible with the present system in that the ground picture is formed by a projection system in which the size of transparency, focal length, projection distance (throw) and screen size (GG', Fig.3) can be selected. The design of the transparency carriage entails adequate clearance for the moving parts and the focal length cannot, therefore, be small. Conversely, a large focal length leads to a large throw and increases the size of the installation. A convenient choice of focal length is 4 in. (or a zoom lens whose range includes this value) and it is then possible with a throw of 8 ft to fill a 5 ft screen (magnification approximately 24 diameters) without exceeding the field angle of the lens, whilst preserving a compact installation. Since the magnification is then fixed, the tolerance on inaccuracy of translational movement of the transparency is also fixed (irrespective of scale factor) for a given image displacement on the screen just discernible as a jump from line to line in the television picture. The resulting movement tolerances are discussed in Section (e). The screen must also be covered across about 4/5 of its width, or 48 in., by the visibility distance. This determines the scale of the transparency, which can conveniently be 2 miles to the inch (R.F. 1/126,720) for 4 miles visibility or approximately 3/5 mile to the inch (R.F. 1/36,000) for a visibility of 1⅕ mile. The smaller R.F. is used for low-level simulation, when the height range is from 10 ft to 650 ft and the larger value is useful for medium-altitude work in the range 30 ft to 2000 ft. These values, together with the speed ranges possible with the servo-systems in use, and the ground cover available with a 9 in. x 9 in. transparency, are collected in Table I.

(d) Viewing distance

It is clearly undesirable to produce a projected, real image at a range approaching infinity, as perfect simulation would demand, and in practice a smaller viewing distance must be used. Thus, although perspective geometry can be preserved under such conditions, binocular convergence, accommodation and parallax are affected. Since the pilot's forward visual field is essentially void of objects closer than several hundred yards, convergence can only play a minor role in the visual process of flight and this view is supported by the known ability of one-eyed airmen. For the same reason parallactic displacements of ground objects, consequent upon head movements, are insignificant and the chief effect of this kind is likely to be the parallax between windscreen struts and background, which may be avoided, as already mentioned, by keeping the struts out of sight. The principal effect of reducing the viewing distance is thus alteration of the state of accommodation, and it is necessary to have the screen at sufficient distance from the pilot's eye to ensure adequate change of accommodation when the attention is transferred between the instrument panel and the simulated view of the outside world. For this reason a picture monitor cannot be used but a television projector is necessary and the available viewing distance, which is approximately equal to the projection distance, lies in the range from about 5 ft to about 50 ft. Using the smaller type of projection system (Rank-Cintel Ltd.) it has been found that a minimum viewing distance of 6 ft is admissible for flight instrument research, but a larger system and larger throw would be preferable if the additional expense were justified.

(e) Summary of leading particulars

Leading particulars of the visual flight simulation are summarised in Table 2 and the values given relate to the chosen configuration of the projector unit, for a 30° field and for the mean operating height. Movement tolerances have been found experimentally and agree with values calculated on the basis of a detectable **shift** of one T.V. line. The tolerance on lateral displacement is finer than for forward displacement but since the motions are interchangeable, with 90° change of heading, the lateral tolerance is applicable to both motions. No tolerance is given for height movement because this is a slowly varying quantity. The permissible value given for perspective distortion is that for (static) landscape photography. In practice, a larger tolerance is acceptable in a moving scene, since a mental allowance is made for consistent distortions, e.g. as occur when a televised picture is viewed on a screen which is not flat, and an object of given shape is still perceived to have the same shape, whilst its position is varied continuously over the screen. Except for depth of focus, the values given have been achieved and the simulation is successful in the application to research in the field of flight instruments. It will be appreciated, however, that the given viewing distance is dictated more by expediency than by exact knowledge of the permissible minimum and it is hoped to improve on the value given, as well as to increase the depth of focus, in future developments.

5 USE

In laboratory use the simulated view of the external world is presented to the pilot on a screen placed in front of the cockpit of Flight Instrument Simulator IA[11], and this general arrangement is shown in the photograph Fig.19. The screen is situated within a darkened enclosure, which has been removed to enable the photograph to be taken, and this enclosure surrounds the instrument panel seen in the centre of the picture. The computer is seen behind the cockpit in this photograph and outputs pass from it to the separate room in which the vision unit is housed. The television picture, also monitored on a small screen in the vision unit room, is passed back to the television projector situated above the pilot's head (upper right centre, Fig.19). He is thus able to 'fly' himself throughout the area covered by the transparency, and is only limited by restrictions on bank (±90°) and elevation angles (±13°). Since the field of view is insufficient to enable the pilot always to keep the runway or other datum in view, it is necessary to provide navigational guidance and this may be provided by a flight director or a map, according to the transparency used. After mastering the art, there is little to be learnt by continued 'flying' of the system and the chief interest then centres around the combination of visual and instrument flight techniques.

The visual apparatus has been constructed for a component outlay of approximately £3500 to which must be added approximately £3000 for labour costs and overheads. In use, the value of the visual simulation varies between £400 and £2500 per hour, according to the scope of the simulation. The economical advantages to be gained are therefore very apparent.

6 ACKNOWLEDGMENT

A project of this nature calls for the closest co-operation of all concerned in the diverse fields from which help has been drawn. It is a pleasure to record the ready, and often enthusiastic assistance which has been given both inside the Establishment and in industry, and it is necessary to state that without the continuous and skilful work carried out by the IAP Model Shop the project could not have been successfully completed.

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TABLE 1

Scale and cover for chosen configuration of projection unit (magnification 24 dia., effective screen width 48 inches or 4/5 full width)

Scale	R.F.	Visibility	Height range	Speed range	Cover
2 miles to 1 inch	1/126,720	4 miles	30 ft - 2000 ft	0-1385 m.p.h.	18 miles × 18 miles
3/5 mile to 1 inch	1/36,000	1 1/5 mile	10 ft - 620 ft	0-415 m.p.h.	5 2/5 miles × 5 2/5 miles

TABLE 2

Leading particulars of simulation for chosen configuration of projection unit, for 30° field and mean operating height

Parameter		Criterion	Tolerance or Value
Picture quality	Texture	Minimal, except for major flight features (runways).	-
	Resolution	Adequate for viewing moving scene as a whole and enabling shapes (e.g. of runways) to be judged.	Not worse than 6 minutes of arc.
	Movements of components	Free from disturbances causing picture movements of unconvincing nature, i.e. less than 1 T.V. line interval.	Transparency slides 0.0013 in. Heading ring 1/1000 rad Bank bearing 1/500 rad. Elevation bearing 1/300 rad.
	Geometry	Free from distortions causing falsification of perspective.	2% on static picture viewed on flat screen.
	Contrast	Diminishing to zero at horizon.	2% on viewed picture.
	Horizon	Equality of sky and ground brightness.	2% of sky brightness on viewed picture.
	Depth of focus	Adequate to preserve resolution over 4/5 distance to horizon.	48 inches.
Field of view		Including principal features affecting flight path.	30° minimum.
Scale		Adequate to cover 4/5 of screen with visibility range.	Table 1.
Viewing distance		Correct for perspective geometry and sufficient to require adequate change of accommodation.	6 ft minimum.

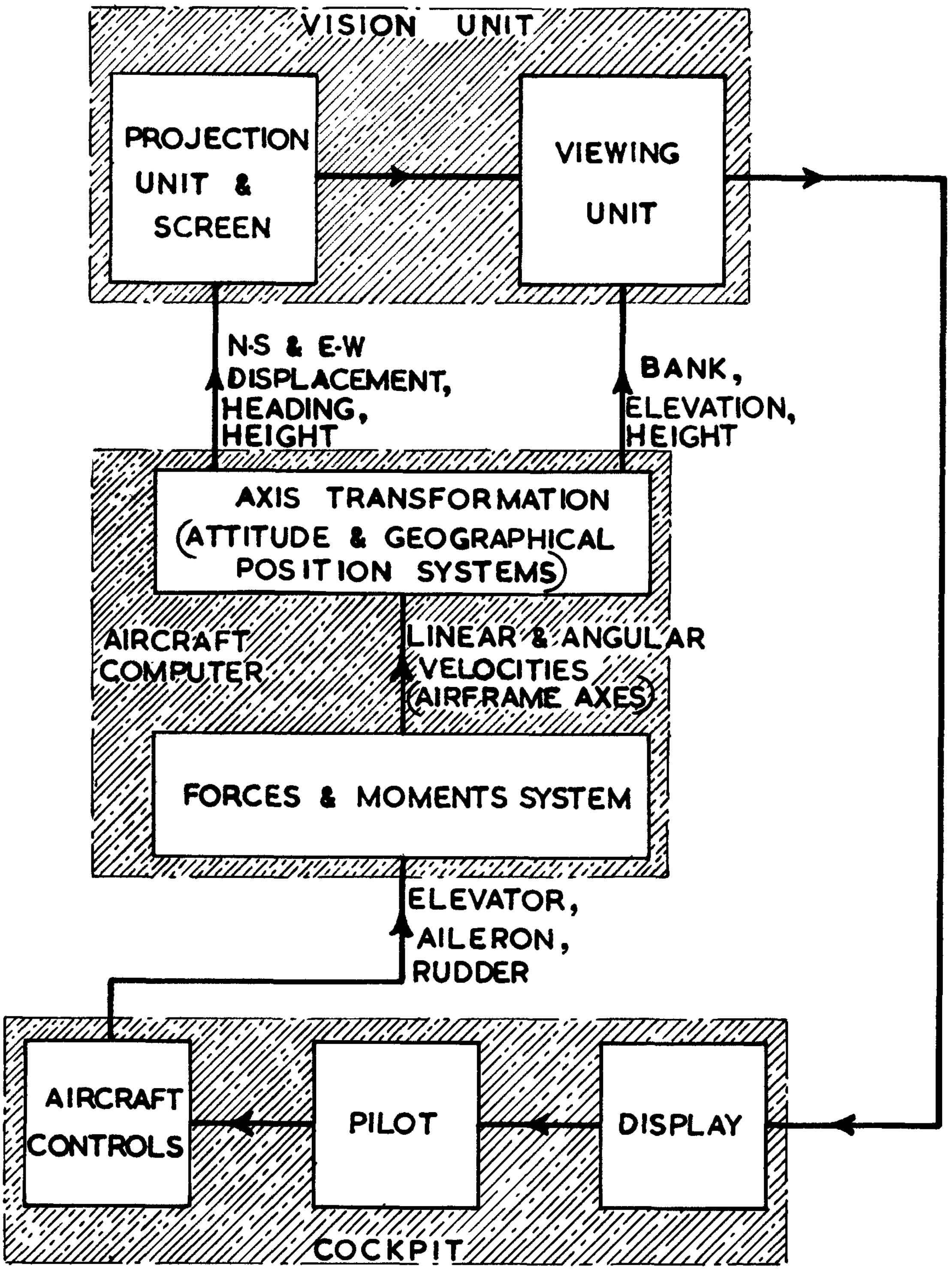

FIG. I BLOCK DIAGRAM OF VISUAL FLIGHT SIMULATION

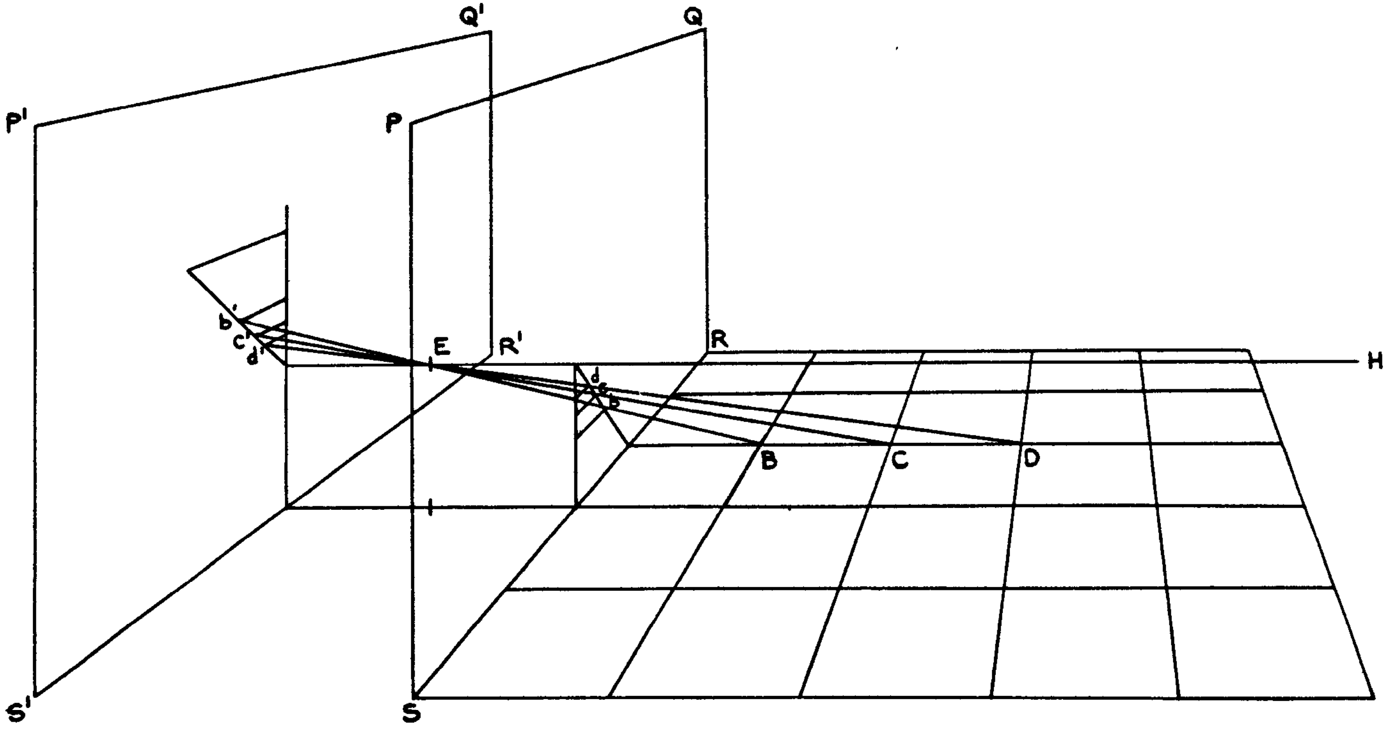

FIG. 2. REPETITION OF PERSPECTIVE ON AUXILIARY PICTURE PLANE.

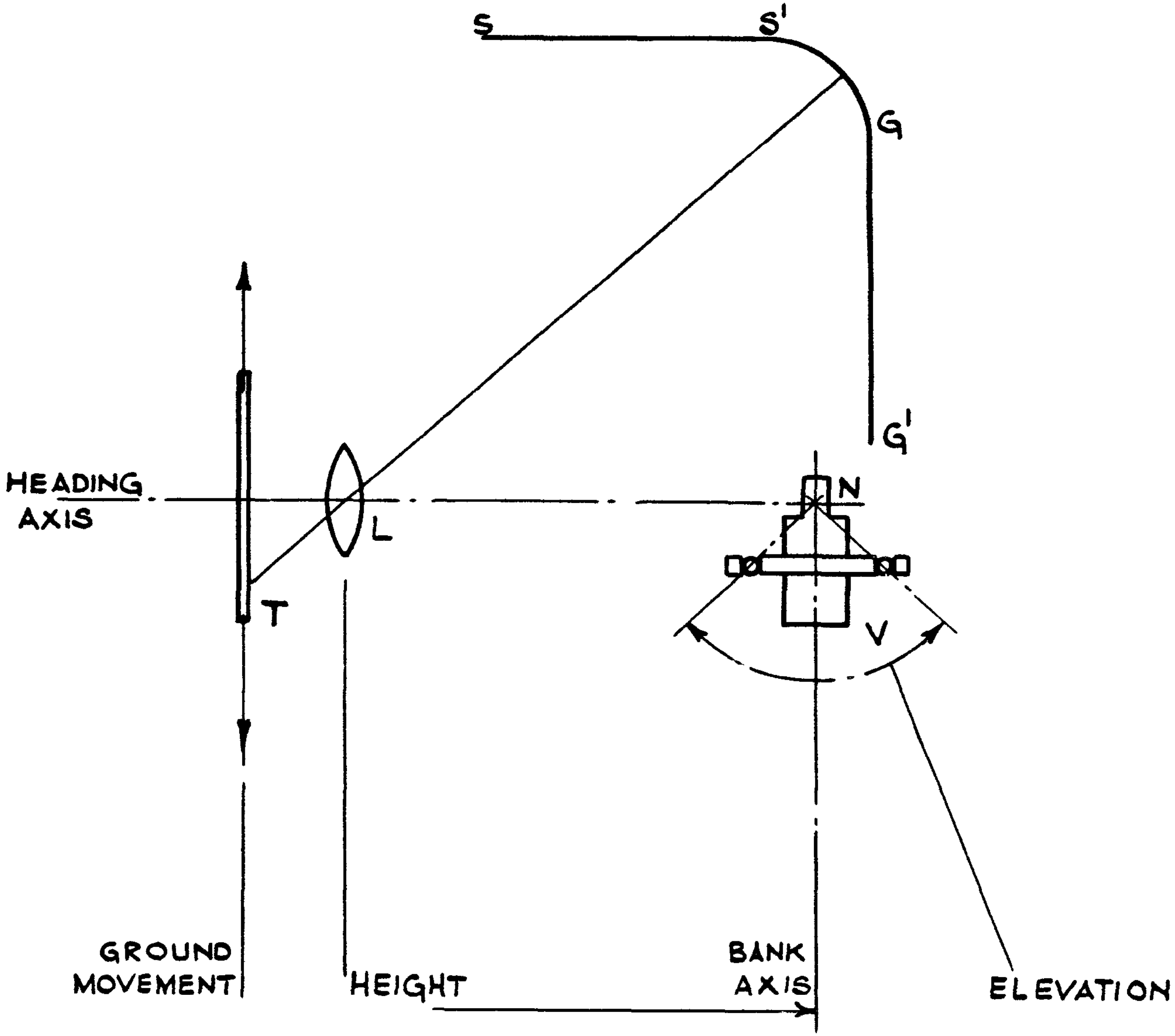

FIG. 3 WORKING PRINCIPLE OF VISUAL FLIGHT SIMULATOR

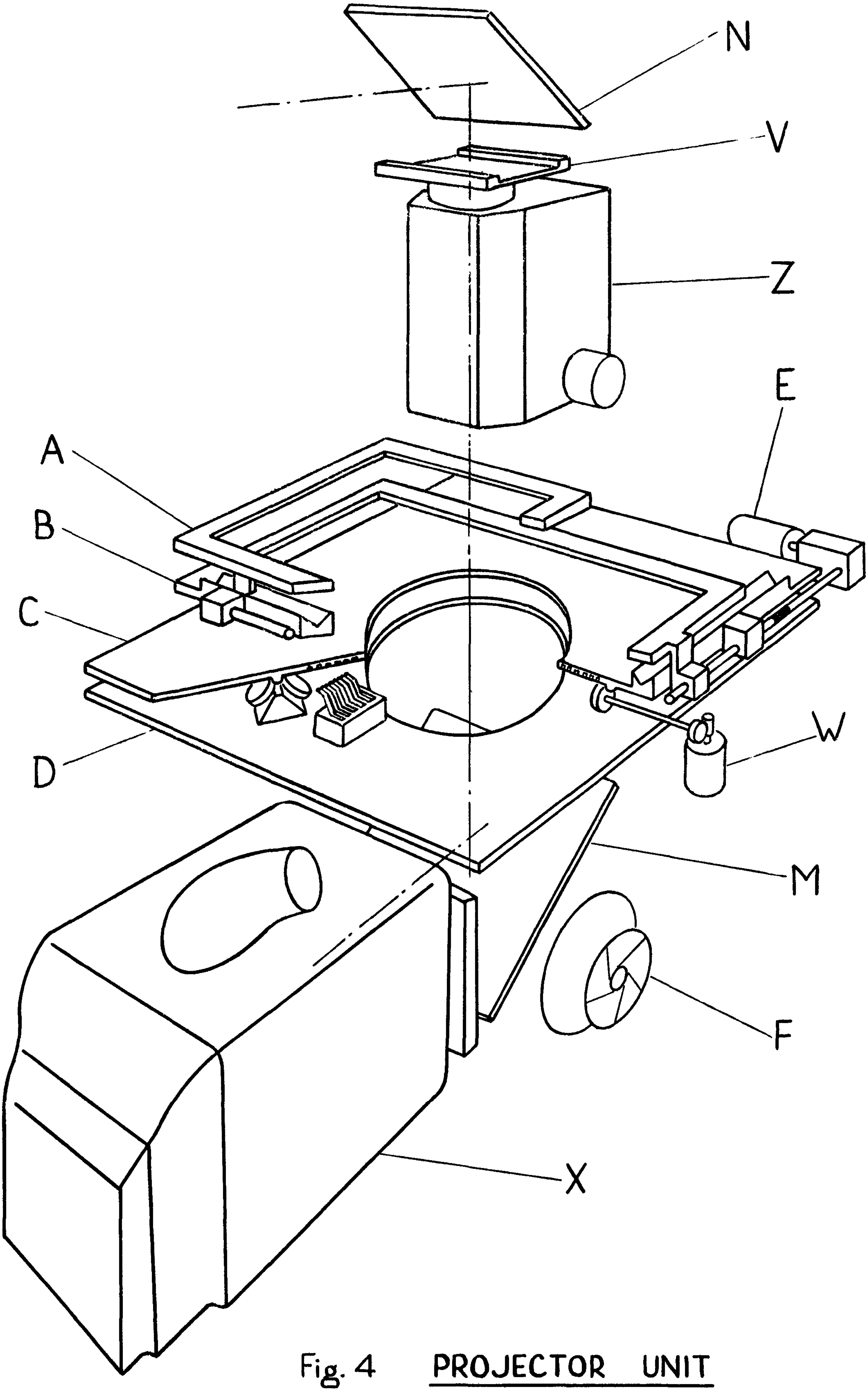

Fig. 4 PROJECTOR UNIT

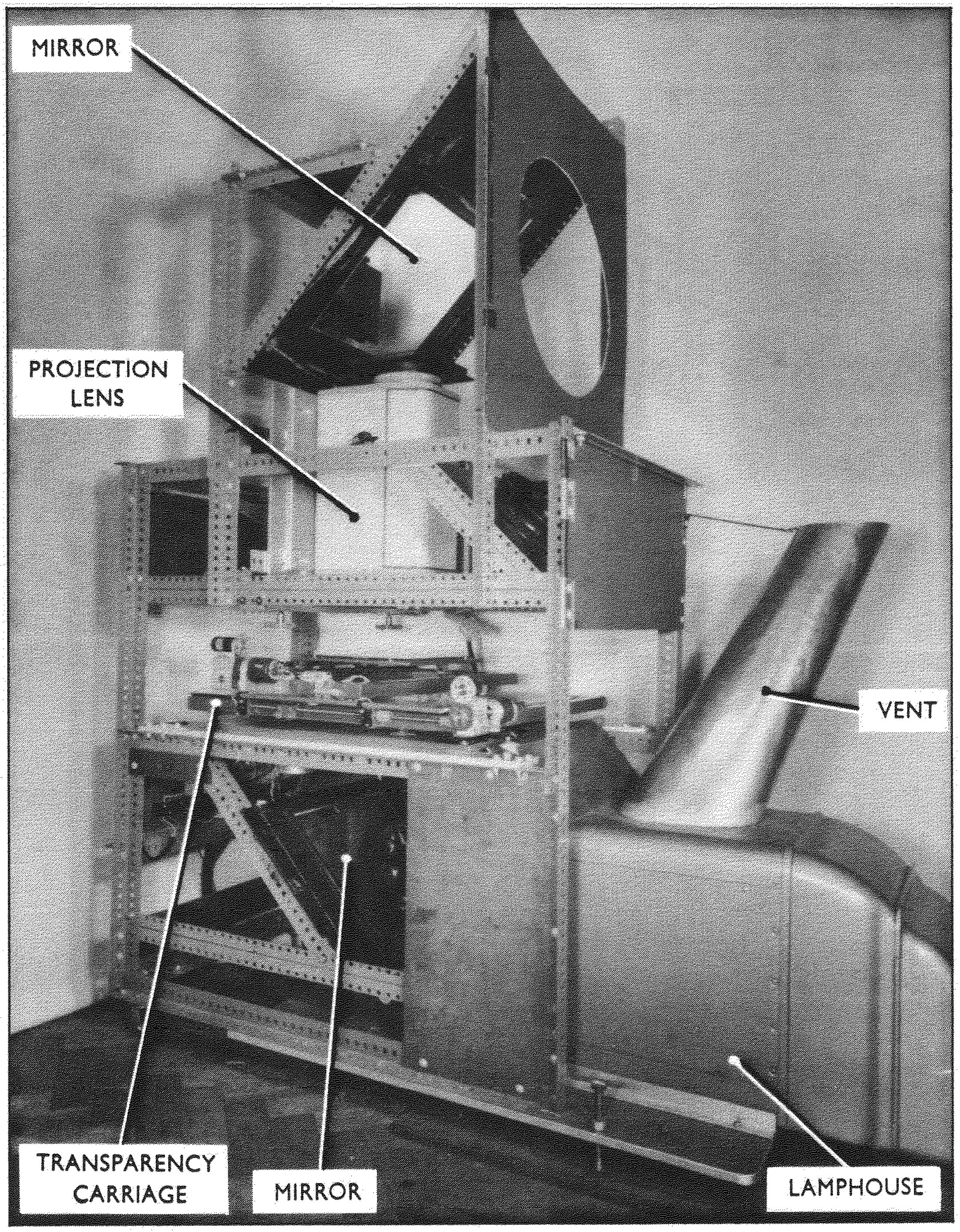

FIG.5. SIDE VIEW OF PROJECTOR UNIT

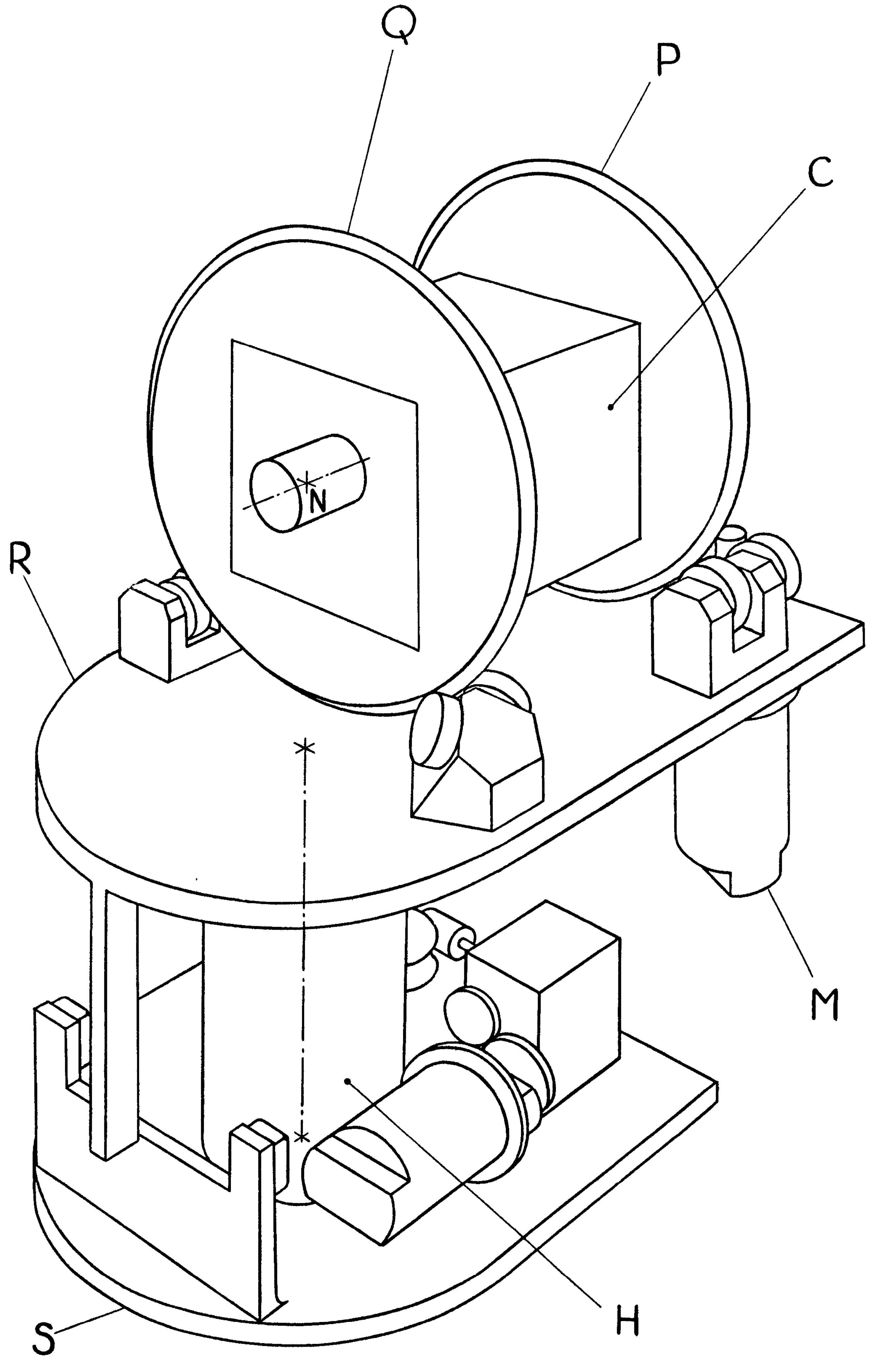

Fig. 6 VIEWING UNIT

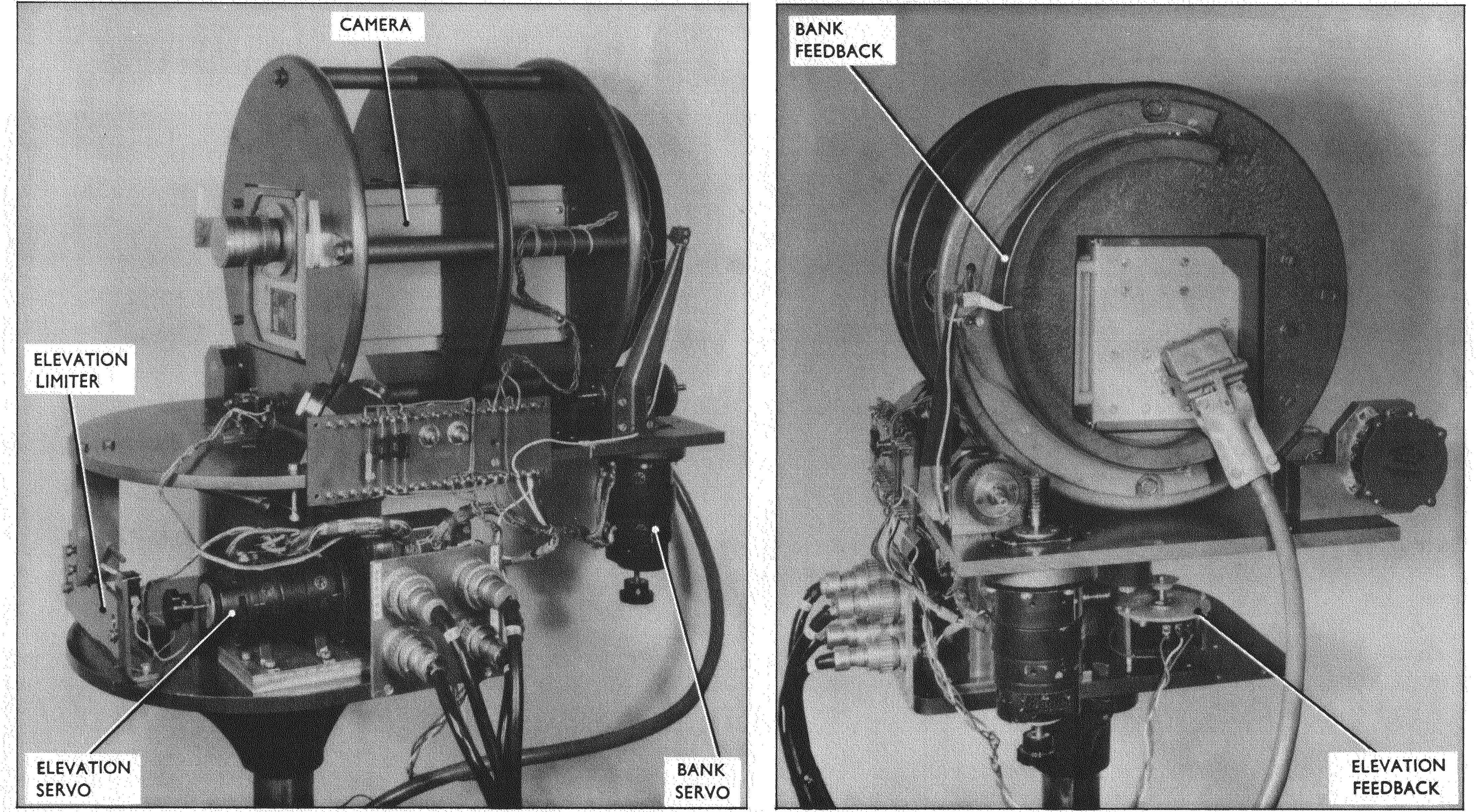

FIG.7. FROM SIDE

FIG.8. FROM REAR

FIG.7 & 8. VIEWING UNIT

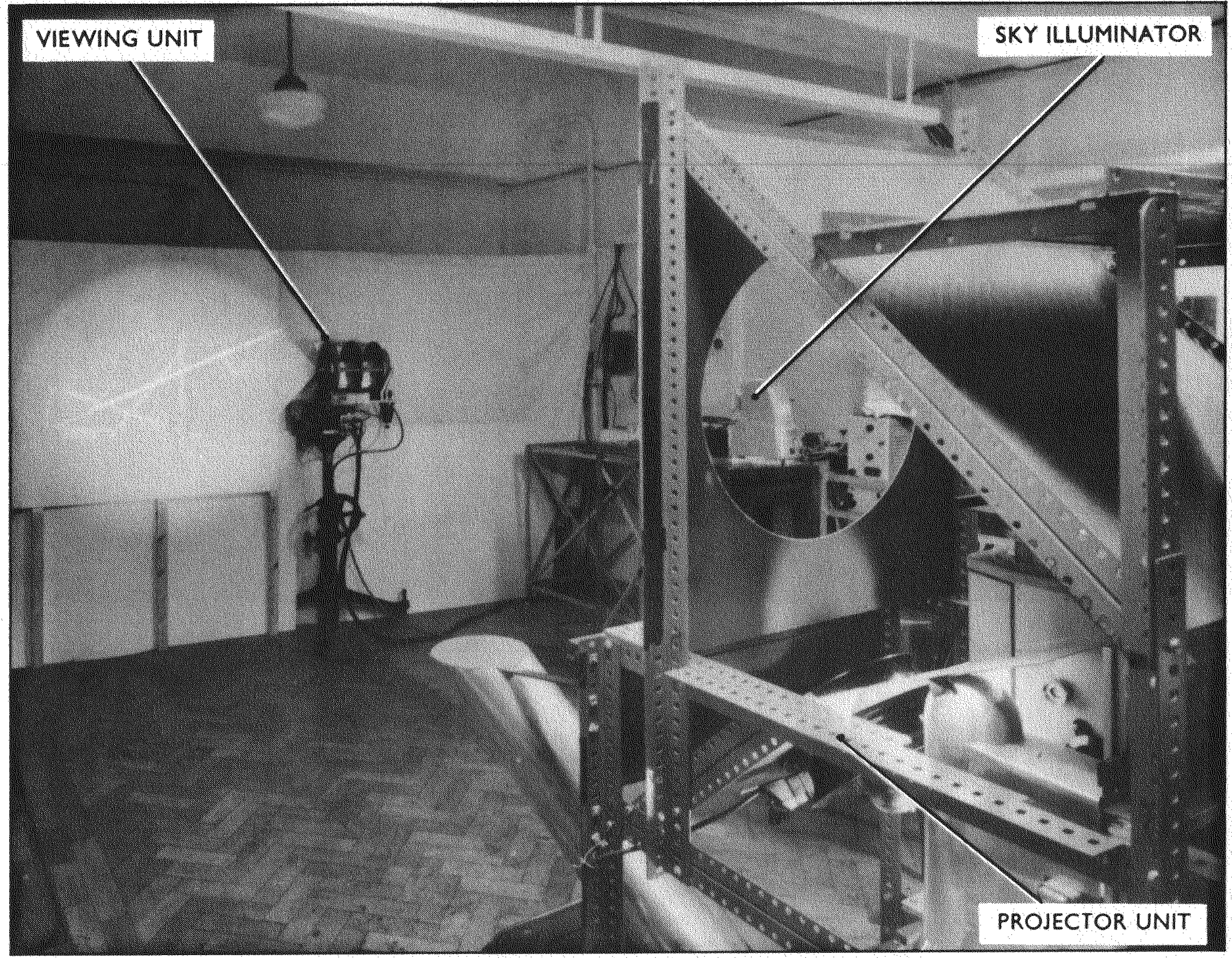

FIG.9. GENERAL VIEW OF VISUAL FLIGHT SIMULATOR

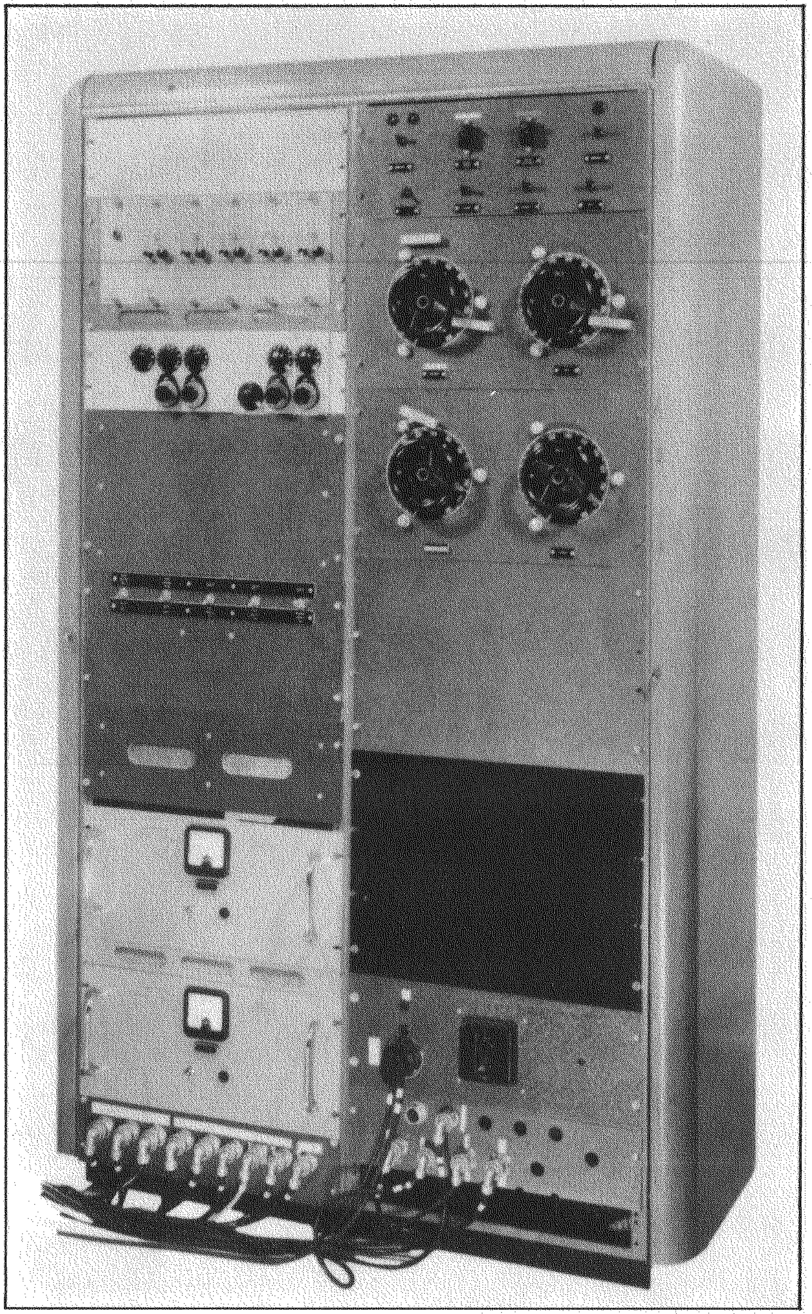

FIG.10. CONTROL UNIT

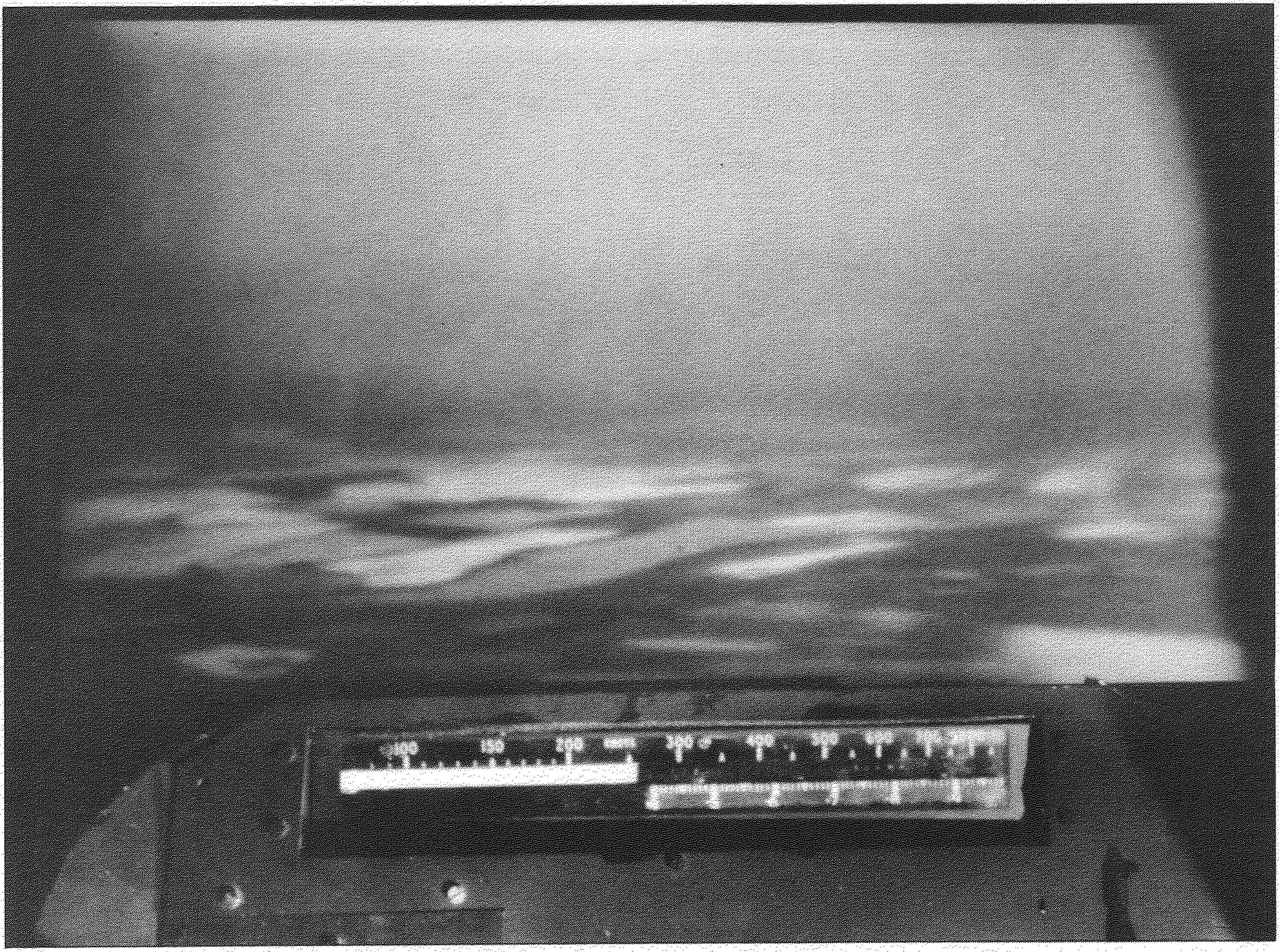

FIG. 11. SIMULATED FORWARD VIEW IN CROSS-COUNTRY FLIGHT

FIG. 12. TRANSPARENCY FOR CROSS-COUNTRY FLIGHT

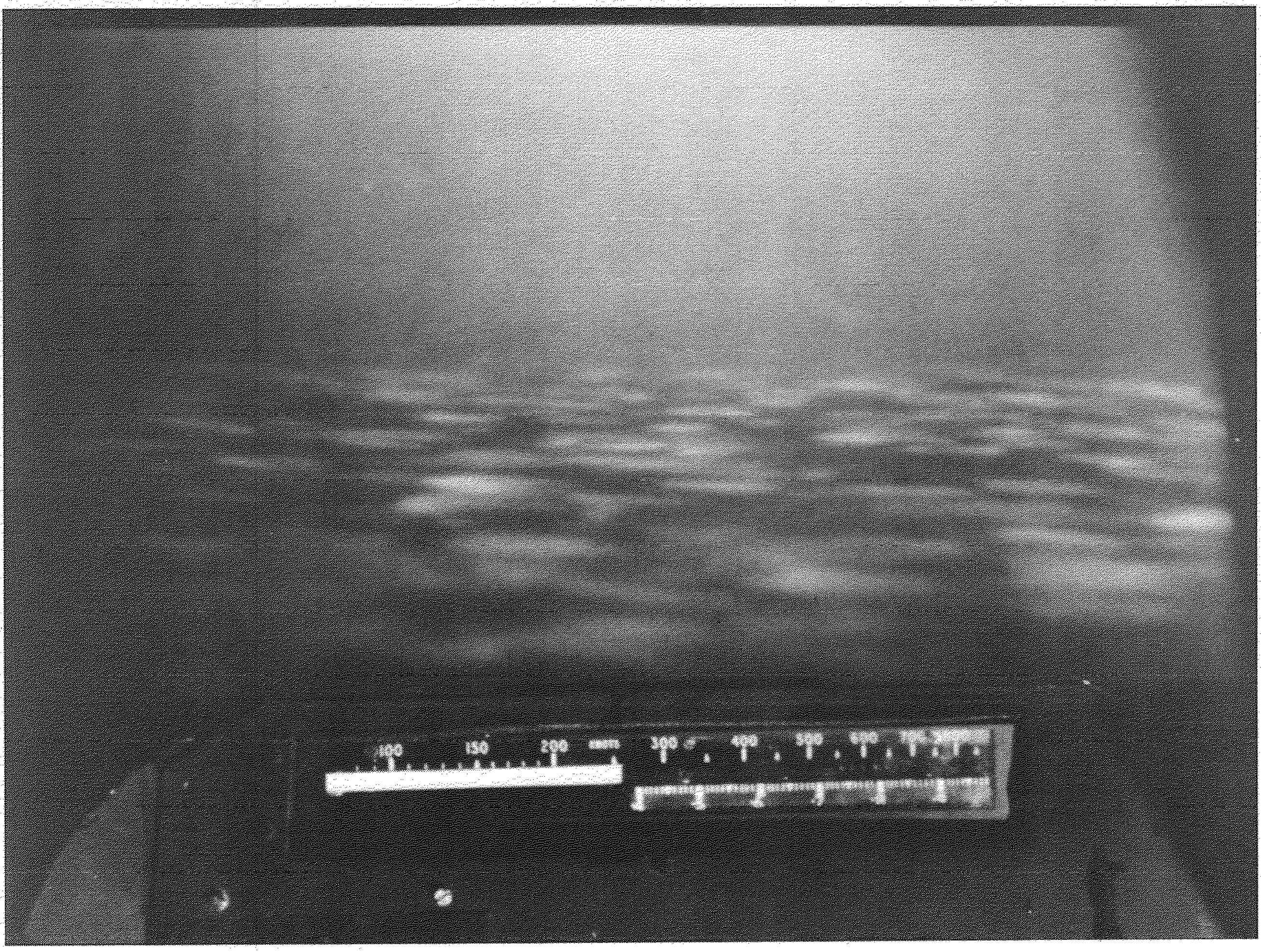

FIG.13. SIMULATED VIEW USING RANDOM INTENSITY DISTRIBUTION

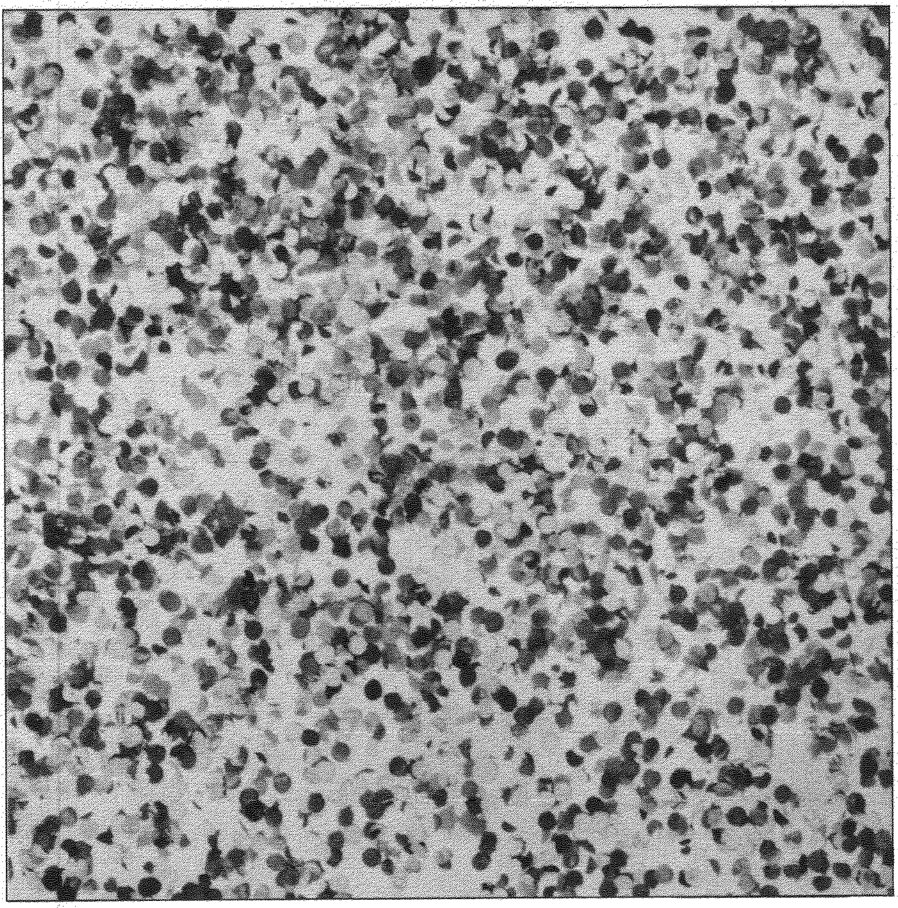

FIG.14. TRANSPARENCY WITH RANDOM DISTRIBUTION

FIG. 15. SIMULATED VIEW OF RUNWAY

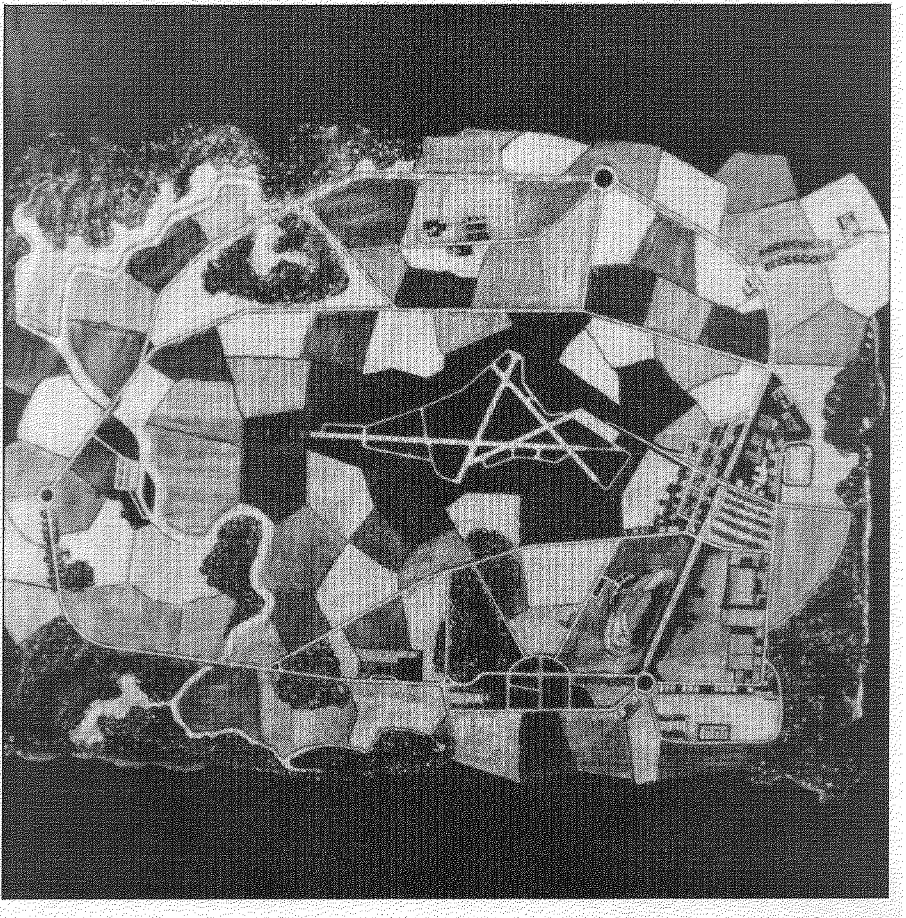

FIG. 16. TRANSPARENCY FOR RUNWAY

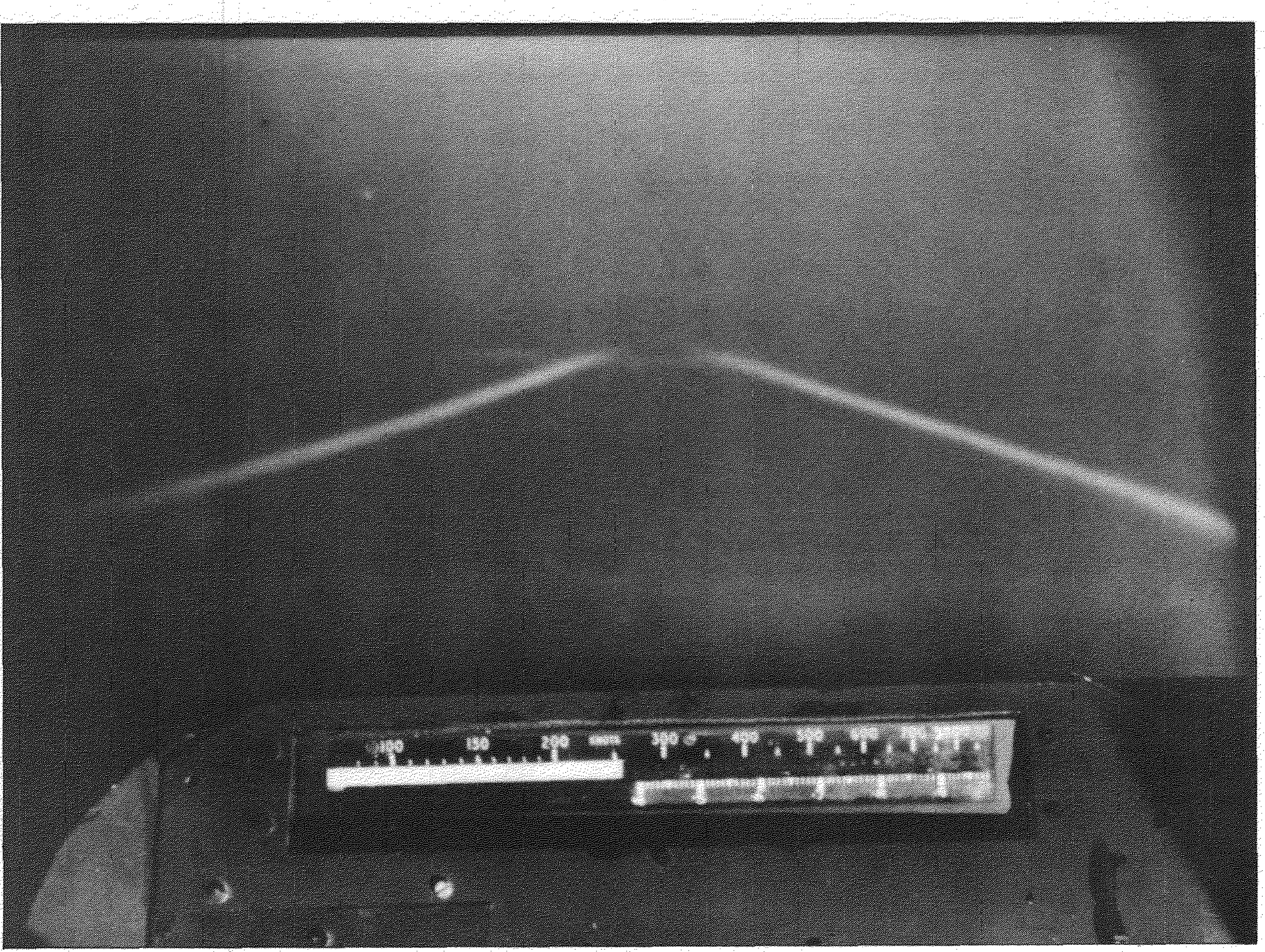

FIG.17. VIEW FORMED BY TWO INTERSECTING LINES

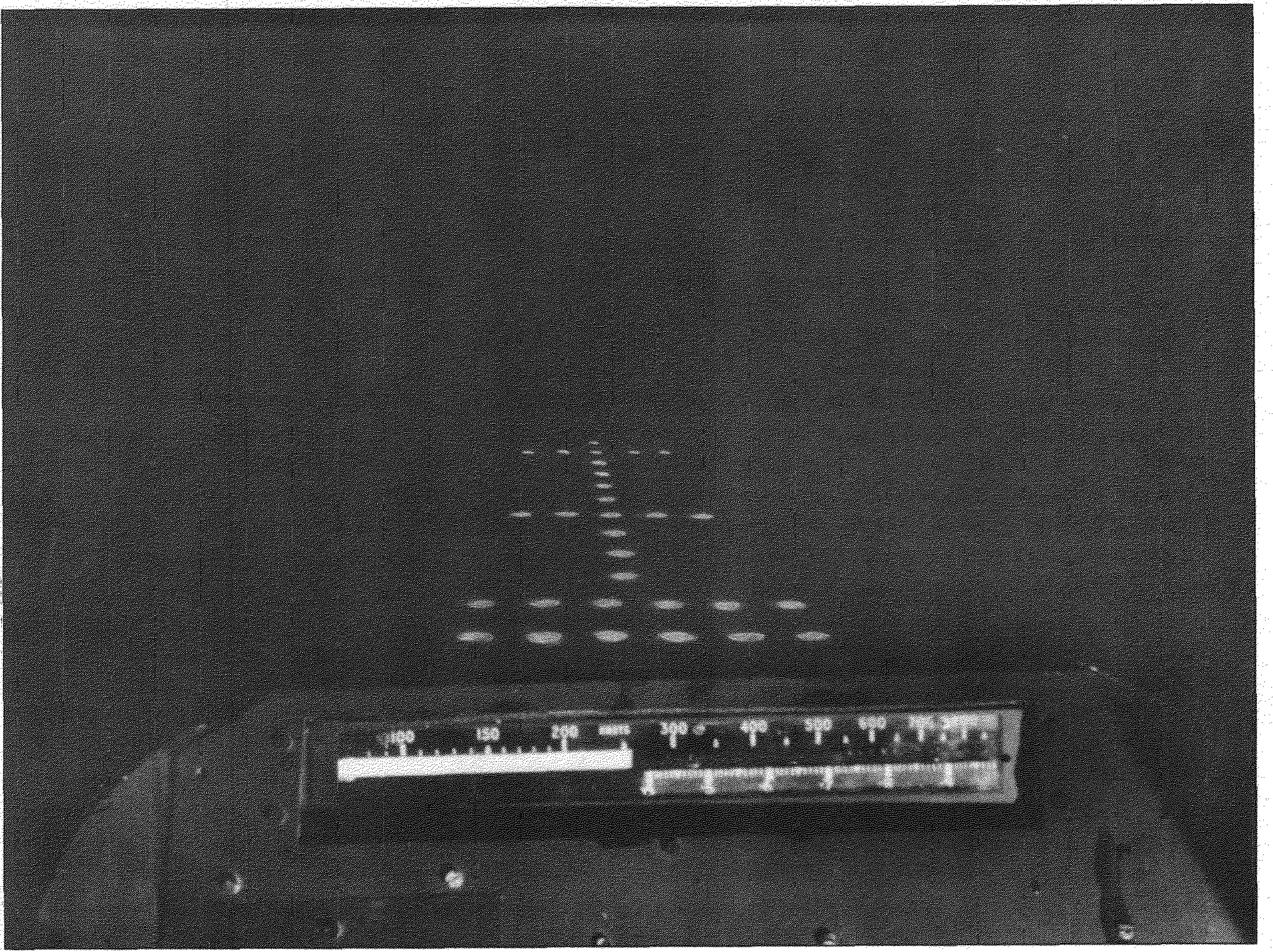

FIG.18. SIMULATED VIEW OF RUNWAY LIGHTING

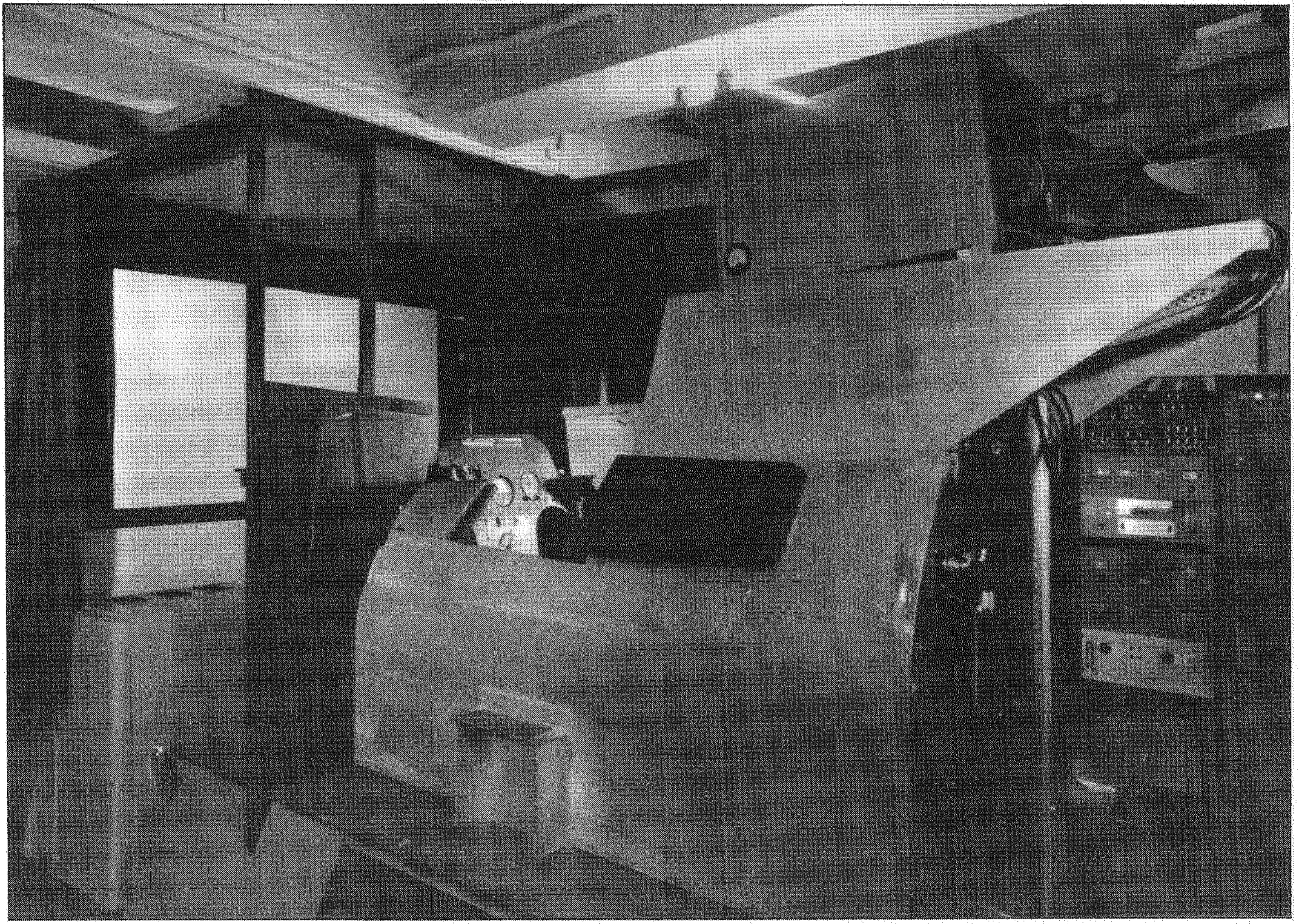

FIG.19. COCKPIT PRESENTATION OF PILOT'S SIMULATED FORWARD VIEW

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