WHITE PAPER

On Aspects of Glasses-free 3D Cinema ~70 Years Ago

Summary Discussion

Dr Barry G Blundell FBCS

Auckland University of Technology

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www.barrygblundell.com
barry.blundell@physics.org

OVERVIEW

This document is an abridged extract from a book that I am currently researching and writing: '3D Displays and Spatial Interaction', Volume II.

Dr Barry G. Blundell

In the following pages attention focuses on four exemplar strands of pioneering research carried out in the first half of the twentieth century in designing and implementing glasses-free (autostereoscopic) 3D cinema.

For nearly 100 years, it has been understood that stereoscopic techniques fundamentally based on conventional parallax barrier and lenticular methodologies are able to support multi-viewer glasses-free 3D – provided that all viewers are positioned at approximately the same distance from the screen. However, any approach that is to be successfully applied to cinema must clearly accommodate 3D viewing across the *length and breadth* of an auditorium. Central to the research efforts outlined in this document are innovative techniques which were intended to support this requirement.

The most rapid advances in early glasses-free 3D cinema and 3D cinematography in general occurred in Russia, and by 1941 Moscow cinema-goers were able to experience 3D on a screen measuring ~5m by 3m - without recourse to viewing glasses. Despite there being fewer than 400 seats, in a four month period (i.e. up until Russia's entry into WWII), approximately 500,000 people took the opportunity to view 3D – glasses-free.

Three of the exemplar strands of research outlined here focus on work undertaken by Professor Edmond Noaillon in Belgium, Semyon Ivanov *et al* in Russia and François Savoye in France. In each case their glasses-free 3D cinema solutions utilised some form of 'radial raster' (in barrier and/or lenticular forms). Whilst Noaillon (the largely unrecognized inventor of this barrier geometry) focused on turning theory into practice via increasingly complex electromechanical techniques, Ivanov and co-workers adopted more pragmatic solutions. Further, shortly after the end of WWII they made the significant advance of replacing the radial barrier with a radial lenticular arrangement. As a result, autostereoscopic cinema soon flourished in a number of Russian cities. In parallel, following Savoye's invention of the Cyclostereoscope, French audiences were quick to sample glasses-free 3D.

Although Dennis Gabor is widely recognized for his work in the late 1940's concerning the invention of holography, his extensive and innovative efforts in developing viable forms of glasses-free 3D cinema have received little attention. This work forms the fourth strand of pioneering activity selected for inclusion here. Discussion is limited to aspects of two patents filed by Gabor in 1940 in which images recorded on lenticular film are projected onto multi-layer optical structures. Related patents filed by Gabor in the 1960's will be discussed in greater depth in other sections of the second volume of '3D Displays and Spatial Interaction'.

There are many excellent publications devoted to the history of cinema. Early work undertaken in developing and deploying glasses-free 3D solutions has however received relatively little in-depth attention.

This document is intended to provide a technology-centric insight into several indicative approaches – these are considered in an accessible trans-disciplinary framework. Given the cyclic nature of 3D research coupled with the emergence of new materials, processes and technologies, an appreciation of past work can help in the identification of techniques which may be applied to the development of the diverse forms of 3D tableau needed to satisfy today's increasingly complex visualization requirements. However in parallel and from the perspective of planning future investment, it is important to recognize that in the case of some applications (particularly those involving the visualization of complex data sets and/or high levels of interaction), support for binocular parallax based 3D is in itself only a partial solution - natural support for motion parallax may be of at least equal importance.

CONTENTS

Background: This Discussion Paper is an abridged draft extract from the second volume of the book '3D Displays and Spatial Interaction'[1] on which I am currently working. This extract focuses on aspects of work carried out in Russia, Belgium, France and the UK in developing early forms of glasses-free 3D cinema. Related technologies will be reviewed in other sections of the book. As with the first volume, a key objective is to present content in such a way as to make it accessible to a broad interdisciplinary audience. Consequently, some simplifications are made and these are addressed in subsequent sections of the book.

I would very much like to hear from anybody who may be able to provide further additional references, background information on the researchers involved in the activities outline here, more detailed technical/performance information, photographic images, descriptions of audience reaction etc. Reviews and feedback are most appreciated.

barry.blundell@physics.org

Technical Note: Early approaches to the implementation of glasses-free cinema in Russia, Belgium and France were fundamentally based on image reflection techniques in which the stereo projection system is located behind the audience (i.e. at the rear of the auditorium). In the following discussion we primarily focus on this configuration. However it will be appreciated that alternative configurations are possible – specifically, the use of radial barrier and lenticular geometries in conjunction with active (opto-electronic) display screens, and arrangements in which the projection system is located behind a transmissive form of screen. In this latter case, two barriers or lenticular panels are needed –these being located on either side of the screen.

[1] The first volume may be freely downloaded from www.barrygblundell.com or may be purchased in both hard and softback forms from www.walker-and-wood.com.

1. INTRODUCTION

Glasses-free 3D (autostereoscopic) cinema opened in Moscow on the 4th February 1941. On offer was a 40 minute 3D film '*Konsert*'[2] and by all accounts, the Moskva cinema (Figures 1(a) and (c)) did a brisk trade. Over the next four months and with ten screenings each day, some 500,000 people were able to enjoy the 3D experience without needing to don viewing glasses. The techniques employed were pioneered by Semyon Pavlovich Ivanov[3] and co-workers (including B.T.Ivanov (principle engineer), E.F.Savchenko and N.A.Valyus). Writing in the 'American Cinematographer' magazine, Ivanov briefly outlined aspects of the system. He opens on a somewhat dramatic note reminiscent of 19th century accounts of the Phantasmagoria:

> '*The auditorium is plunged in darkness, except for a little lamp suspended from the ceiling by a long cord. But wait – an actor suddenly reaches out from the screen and draws the lamp towards him. How did he do it? As a matter of fact, there was no lamp left burning in the auditorium. It was simply an effect produced by the stereocinema… A juggler flings a ball straight at the audience, and those who happen to come within his line of vision blink and duck involuntarily…*' Ivanov [1941]

Some years later scientist and 3D pioneer Nikolai Valyus observed:

> '*Judged by acclamation, this mass experiment of direct-viewing stereoscopic cine-production was a resounding success.*'[4] Valyus [1966]

Unfortunately, this debut of autostereoscopic 3D cinema could not have been more ill-timed and came to an abrupt halt in June as, with the onset of Operation Barbarossa, Germany and Russia became embroiled in the devastation of total warfare.

As will be discussed shortly, the method initially adopted by Ivanov was underpinned by a large radial raster barrier able to provide viewing zones across the *length and breadth* of an auditorium. In Russia the first prototype systems were trialled in 1935 [Valyus 1966]. However some years earlier (1927) Belgian Professor Edmond Noaillon filed a key patent in which the use of the radial barrier to support glasses-free cinema is described in some detail. In addition, the patent discloses techniques that offer to improve image quality – specifically in relation to enhancing image brightness, reducing image loss (segmentation) and reducing barrier visibility. Despite the difficulties inherent in implementing the form of mechanical motion which is central to Noaillon's system, it is evident that the inventor had a sound understanding of the strengths and weaknesses of the radial barrier and that he carried out significant experimental work prior to the filing of his first patent. Unfortunately, Noaillon's invention of the radial barrier and his adoption oscillatory barrier motion is often overlooked in literature.[5] In parallel, the work carried out in Russia in developing the first pragmatic approach to glasses-free 3D

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2 During production this film was titled 'Land of Youth' (Sammons [1992]). It comprises seven parts. For example, Vera Dulova playing the harp accompanied by views of the fountains at Peterhof, an aviary accompanied by music from Mikhail Glinka's opera *A Life for the Tsar*, and a carnival of youth (Mayorov [2012]). The film was directed by A.N.Andrievskii with D.Surenskii as stereoscopic specialist.

3 Not to be mistaken for General S.P.Ivanov (1907-1993).

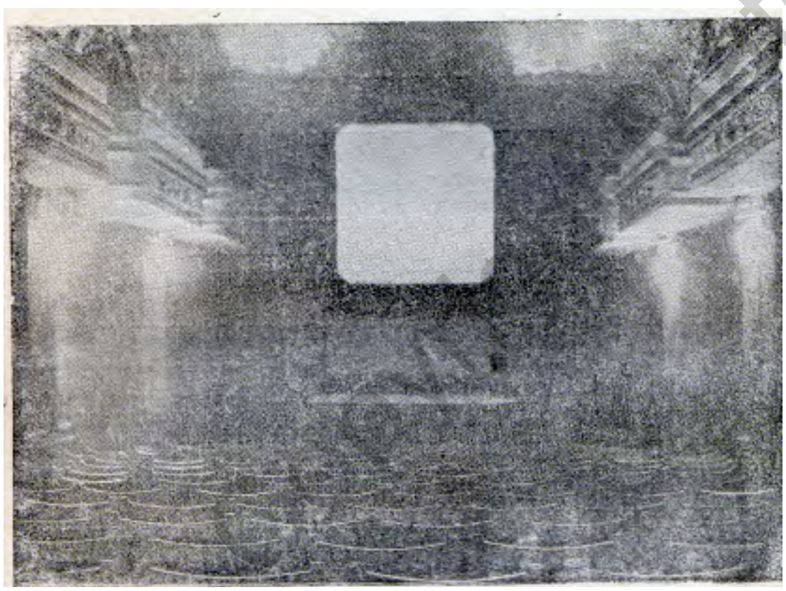
4 A brief article appearing in 'Cinema' relating to the post WWII re-opening of glasses–free 3D cinema in Moscow indicates: '…*Pravda reports that people lined up early in the morning waiting for the doors to open and that* [the] *film* [Robinson Crusoe] *has been playing to capacity audiences'*. Cinema [1947].

5 For example Kaplan [1952] incorrectly writes: '*A radial nonparallel-type barrier system was invented by B. T. Ivanov…*' and '*One such arrangement of interest is the radial plane* [barrier] *arrangement invented by Ivanov…*'.

cinema, in subsequently pioneering innovative lenticular-based techniques and in the field of 3D cinematography in general is frequently under-represented.

(a)

(b)



(c)

Figure 1: In (a) the Moskva *circa* 1941 – home of the world's first glasses-free 3D cinema. Image (b) shows stereo frames from '*Konsert*'. This was filmed in black and white with the occasional insertion of colour. It is '… *a screen concert in which the best Soviet musicians and singers take part.*' (Ivanov [1941]). In (c) the interior of the Moskva cinema – unfortunately, the passage of time has impacted on image clarity. (Images (a) and (c) respectively reproduced from Ivanov [1945] and Ivanov [1951].)

On 20^{th} February 1947 glasses-free 3D cinema reopened in Moscow with Ivanov *et al.* replacing the radial barrier with a radial lenticular optical arrangement. This paved the way for glasses-free cinemas in other Russian cities including Leningrad, Kiev and Odessa and enabled audiences to enjoy 3D films such as Robinson Crusoe, Machine 22-12, Crystals, May Night, Aleko, A Precious Gift, and the like.

Writing in the Monthly Film Bulletin, Joseph Macleod provides a first hand account of post WWII glasses-free cinema in Moscow – with specific reference to a second, and apparently improved, version of Robinson Crusoe.[6] He opens:

[6] Also see Segaller [1949].

> '*As in all Soviet cinemas, performances are not continuous. All seats are booked in advance, and you wait in the foyer till the previous house has come out. There is a big run on seats, although the film is showing all day long; and the only man who wangled his way in when the house was full, it is said, was a young film enthusiast who had travelled from Siberia for the purpose.*' (Macleod [1947])

He goes on to mention that as the lights dimmed, the audience was given brief instruction on maintaining the correct viewing position. Naturally, this immediately catalysed human curiosity:

> '*As a result of this advice, everybody begins peering sideways and inclining their heads to see what happens.*'

In relation to the Crusoe film, Macleod makes numerous positive comments:

> '*…It was only when Crusoe in his shipwreck throws a rope to a drowning sailor that you get the first shock. The rope comes hurtling and curling right out of the screen into the darkness…. You duck. We all did. After that we were ready for anything…*
>
> *As Crusoe advances down a corridor of undergrowth, the camera tracks backwards in front of him. Out in the auditorium, about three rows in front of you, leaves and lianas materialise in the air, dangle and dance, and float away into Crusoe's face…*
>
> *Personally I am allergic to spiders. I was nauseated by an immense brute as real as life and half as large as the screen within what appeared to be a hands grasp of my nose.*'

Clearly, the makers of the film were willing to incorporate high impact 3D dynamics and this may have significantly contributed to the visual discomfort which is briefly mentioned by Macleod. However, it is evident that the 3D tableau was also exploited in more subtle ways – particularly in enhancing the profundity of audience immersion:

> '*…this luminous effect resembles the unearthly atmosphere of the Insect or Tropical Bird Houses in London Zoo. As if light were liquid. As if the heat were tangible…*
>
> *The depth is used cleverly to increase our sense of Crusoe's loneliness…When he* [Crusoe] *goes down with fever, therefore, though little dialogue has been possible, he is a real person to us. Sensation in place of speech has placed us inside his head. We fight every inch of the way with him towards survival and recovery…*
>
> *A strikingly beautiful shot of a ship in full sail close inshore (and the effect of stereoscopic photography on the canvas, rope and wood of a sailing ship cannot be described except in terms of goldsmith's work) unexpectedly brings the wide world curving round.*'

Russian accomplishments were sometimes treated with a certain degree of scepticism by Western writers. On inspection of several articles it is evident that the more sceptical authors invariably lacked first-hand experience of the cinema and clearly there was considerable misunderstanding of the underlying techniques. Additionally, the political climate of that era may have influenced attitudes. For example, and without any indication of first-hand experience, one author writes:

> '*This integral or lenticular screen, as it is called, imposes a disciplinarian rigidity in the viewing position which would discontent the free-and-easy audiences of the West much more than the wearing of a comfortable pair of glasses…*' (Spottiswoode [1953])

By way of a further example, Norling [1955] cites an article published in the New York Times [1944] and quotes James Aldridge[7] as stating that the images produced by the Russian system were '*coarse and blurred*'. However, on inspection of the original newspaper article it is evident that this observation related to a pre-WWII system (where difficulty was often experienced in establishing the optimal viewing positions). In fact Aldridge's mainstream newspaper comments relate to his experience of a lenticular-based prototype then under development. For example:

> *'Mr Aldrich who witnessed the new development in Sgvintorgkino studio reported having seen newsreels and film of a concert which had "depth on the screen as well as width and height". The glass screen is engraved with more than 2,000 converging lines, and it is in these markings that the secret of the new screen lies, stated Mr Aldrich… The screen used for the demonstration was six feet wide and three feet high and was made in one day, according to information given Mr Aldrich by Alexander Andreyevsky, Chief of the Sgvintorgkino studio. He added that a screen fifteen feet square will shortly be installed in a Moscow movie house…'*

Norling goes on to quote from a New York Herald Tribune [1948] article which casts a shadow over S.P.Ivanov's abilities to deliver effective glasses-free 3D cinema:

> '*Moscow April 28 (AP) – The Communist newspaper 'Pravda' disclosed today that Semyon P. Ivanov, described as the inventor of three-dimensional motion pictures, had been removed from the job of scientific chief of the special studio in which he perfected the invention. The newspaper (Pravda) said that I. Bolshakov, Motion Picture Minister, did not take Mr. Ivanov's work seriously, tried to picture him as a faker and publicity seeker and finally pulled him off with the excuse that he was freeing him from his administrative duties.*
> *Pravda went on to state:*
> *'That's how the cinema industry freed itself of the worrisome individual whose name will go down in the history of the Soviet and world cinema.*"

A New York Times [1946] article by A.H. Weiler quotes positive observations made by Nicholas Napoli[8] following a tour of Russian studios in Moscow, Leningrad and Erevan:

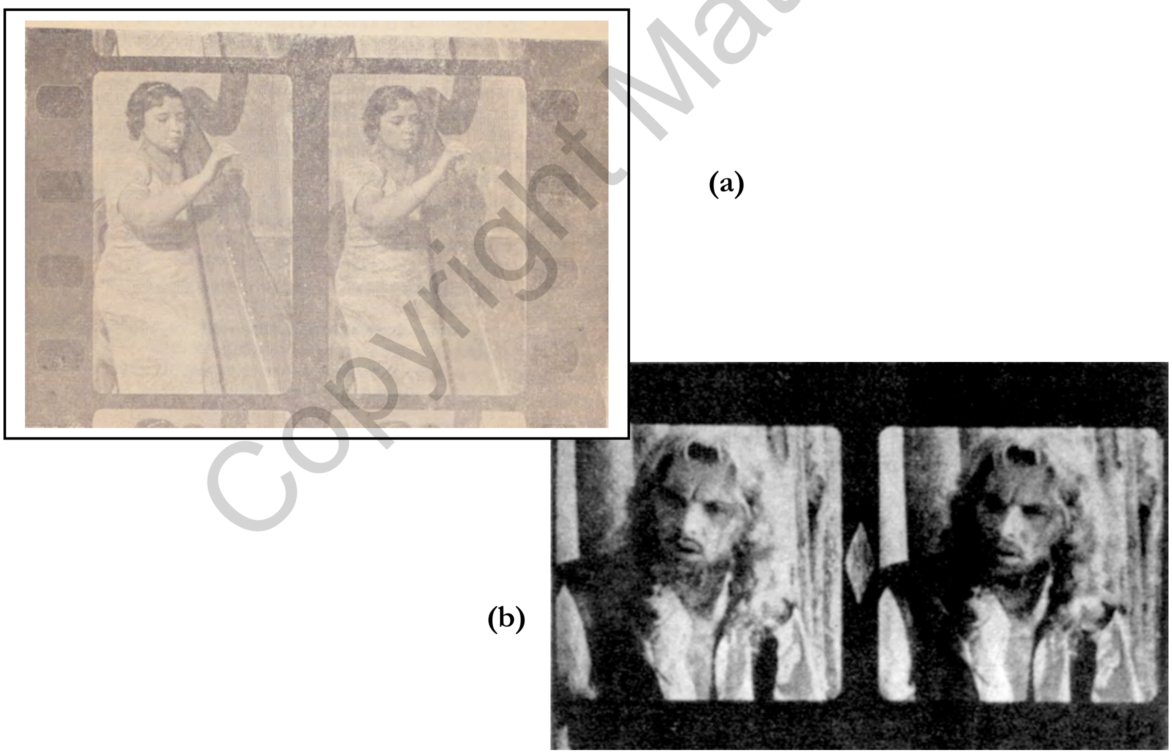
> '*…the Stereocinema studio in Moscow has already shot much of the adaptation of "Robinson Crusoe." Portions of the film which Mr Napoli saw were "simply wonderful, but it will be at least another year before the screen is perfected." There was "no distortion or strain on the eyes" and the whole secret of the new screen "seems to be in the chemical composition and the manufacture of the glass used for it."*'

[7] Correspondent for the North America Newspaper Alliance.
[8] Then President of Artkino Pictures.

It is evident that the extensive and sustained work carried out in Russia in 3D cinematography coupled with the development and application of glasses-free 3D technologies was driven by strong governmental support. In this context, Mayorov [2012] writes:

> *'In one of his lectures the film historian Nikolai Kriuchechnikov spoke of a legend: '…some days after the first demonstration* [of Ivanov's early system] *rumours about a miracle-cinema reached Stalin. After a viewing in his personal cinema in the Kremlin, where Ivanov's first raster screen was urgently installed, 'the best friend of Soviet cinematographers' was fully satisfied and ordered that the invention be shown to the broad masses. The leader's desire is the law. 'Stereoscopic cinema without glasses received the green light…'*

In the next section we summarise characteristics of the conventional parallax barrier. Subsequently we turn our attention to technical aspects of the planar radial raster (in both barrier and lenticular forms) and discuss its role in the implementation of early glasses-free cinema.[9] In Section 7 we briefly consider the Cyclostereoscope with its novel form of non-planar radial barrier. It is likely that the pioneering work of both Edmond Noaillon and the pre-WWII successes of Ivanov *et al.* laid important foundations for Francois Savoye's research. In contrast in the patents filed by Dennis Gabor in 1940 (see Section 8) we are presented with a quite different and independent solution to glasses-free cinema.



(a)

(b)

Figure 2: In (a) a stereopair of Vera Dulova in the 1941 3D film '*Konsert.*' (11x16mm format). In (b) a stereopair from Robinson Crusoe - released on the 20th February 1947 (16x16mm format). The stereopairs shown here may be easily fused by slightly crossing the eyes. (Image (a) reproduced from Ivanov [1945] and (b) from Sammons [1992].)

[9] For a wide-ranging overview of the history of autostereoscopic cinema see, for example, Funk [2012].

2. THE CONVENTIONAL BARRIER

Current autostereoscopic display systems based on the parallax barrier employ a panel comprising a set of fine vertical transparent parallel slits separated by opaque regions. Such a barrier[10] constitutes a re-imaging subsystem (Blundell [2011a]) and may be defined as follows:

> *'A masking device which when interposed between an object space and an image space prevents any given part of the image space from being sighted from any but a given set of predetermined directions.'* Kaplan [1952]

Consider the simple scenario illustrated in Figure 3 in which a point source casts light onto a barrier and in turn five vertical lines are illuminated on a screen. The five light planes shown in the diagram respectively denote a region of visibility of each of these lines. If for convenience we assume monocular vision, then when the location of the eye coincides with the position of the light source and attention is turned towards the screen, all five lines will be simultaneously visible. Indeed the intersection of the light planes implicitly denotes the region in which all lines cast onto the screen by the point light source will be simultaneously visible. In the illustration, this region is indicated in red and corresponds to a vertical line passing through the point source.

In practice, the lines generated on the screen are visible from other locations. In Figure 4, a point source is located at *O* and the diagram illustrates that the set of lines cast onto the screen are also visible from all points along line segments which are normal to the page and which pass through exemplar locations S_1 and S_1'. In more general terms the set of lines cast onto the screen by the point source located at *O* are visible from a plurality of equally spaced locations – all being at approximately the same distance from the barrier. Figure 5 illustrates the projection of light from two point sources located at O_L and O_R and so indicates the general behaviour of the projection system in the case that it is used for the depiction of stereoscopic images.

Consider the two similar triangles shown in Figure 4 and which are depicted using dashed red lines. On the basis of these triangles it is evident that:

$$\frac{y}{S} = \frac{b}{p},$$

where *p* denotes the barrier pitch, *b* the separation of the barrier and screen, *S* the separation of the locations from which all lines cast onto the screen by a single point source located at *O* are visible, and *y* the distance between the screen and the line AB. Hence:

$$S = \frac{yp}{b}. \tag{1}$$

[10] For discussion on parallax barrier based approaches see, for example, Kaplan [1952], Valyus [1966], Okoshi [1976]. For related discussion, also see Timby [2001].

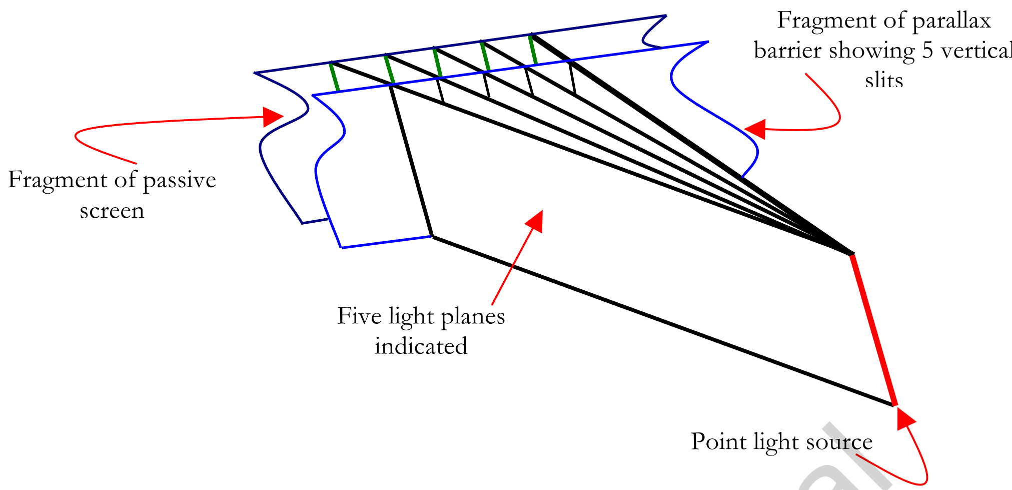


Figure 3: A simplified representation of the standard parallax barrier used in conjunction with an external point source located at *O*. Light emanating from this source passes through five barrier slits (we neglect the finite width of these slits and for clarity greatly exaggerate their separation) and illuminates five indicative vertical lines on the screen (partially visible and depicted in green). The light planes indicate the path of light returning through the barrier slits. These intersect in a vertical line that passes through the point light source. Thus all five vertical lines cast onto the screen are simultaneously visible from positions along the line segment depicted in red.

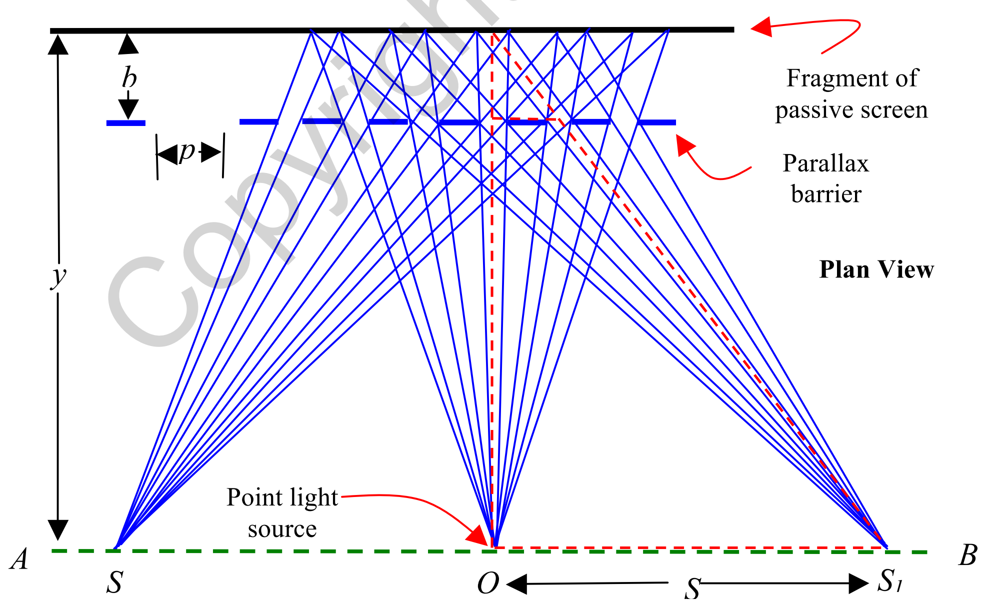


Figure 4: A fragment of the screen and barrier in plan view. A point light source is located at *O*. All lines cast onto the screen are visible from the locus of points which form line segments that are normal to the page and that pass through the points *O*, S_1 and S_1'. An extension of this diagram to the left and right would illustrate that the lines cast onto the screen are in fact visible from a plurality of equidistant positions along the line AB. We refer to these as 'side lobe' locations.

3. THE STATIC BARRIER IN RADIAL RASTER FORM

The approach outlined above supports a set of discrete viewing locations that lie at an approximately fixed distance from the display screen. Consequently, as indicated in Figure 6, several proposals for glasses-free 3D cinema involved the use of screen and seating arrangements which conformed to this somewhat impractical constraint. Other researchers focused on identifying alternative display solutions able to support audience viewing locations across two spatial dimensions – that is over both the length and breadth of the auditorium. This objective led to Noaillon's invention of the linear radial raster form of barrier. Here, the interleaved transparent slits and opaque regions are implemented in a fan-like structure and as illustrated in Figure 7, if extended, both sets of elements meet at a common centre of convergence (COC).

The radial raster is also referred to as the perspective raster for, as illustrated in Figure 8, the raster geometry can be generated by the central projection of a conventional parallel slit raster onto an inclined plane. Indeed the conventional parallel raster barrier can be considered to be a specific instance of the more general radial raster. In this context the former is considered to be a radial raster with the COC located at infinity.

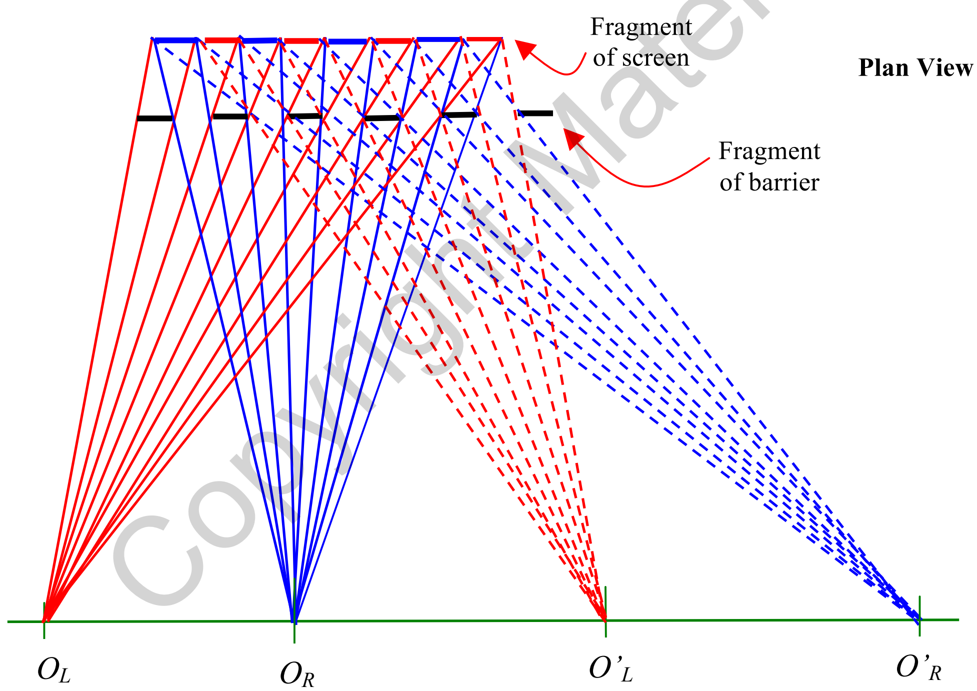


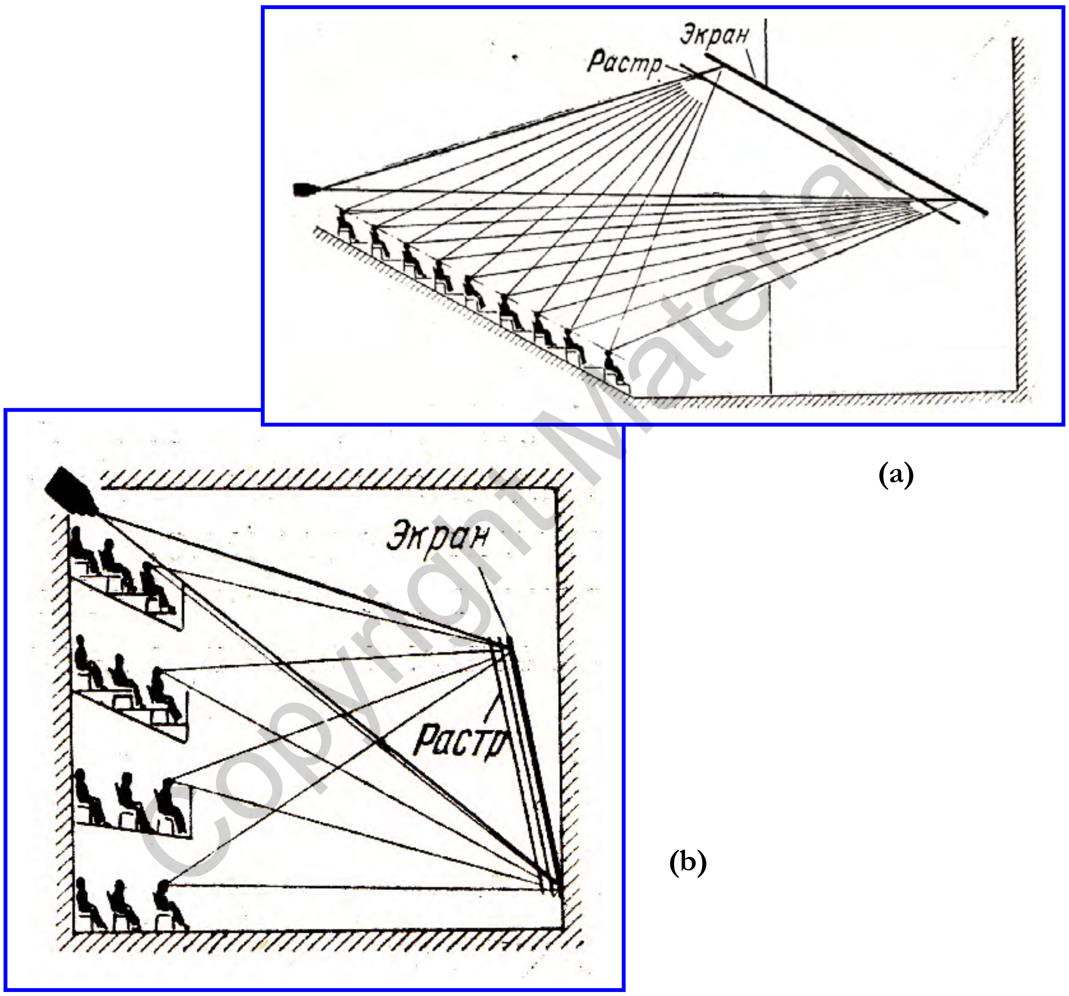
Figure 5: Light from two point sources O_L and O_R passes through the indicative barrier slits and illuminates a set of adjacent strips on the screen. For clarity, light emanating from the left source is indicated in red and that from the right source in blue. The strips formed on the screen are shown in cross-section. The dashed lines indicate (by way of example) the first right-hand 'side lobe' viewing locations.

It is important to note that a key feature of the radial raster barrier is that in cross-section (that is in the direction that lies perpendicular to the raster's axis of symmetry) it should, in principle, exhibit constant pitch and hence uniform distance between adjacent slits.[11] The

[11] The introduction of cyclic barrier motion is likely to ameliorate issues arising from variations in barrier pitch.

construction presented in Figure 9(a) shows the formation of 3 adjacent slits. These have been positioned by drawing from *O* three radial lines – the angle (ϕ) between neighboring lines being constant. The horizontal line MN is perpendicular to the assumed axis of symmetry and so should intersect the radial lines (on which the slits are located) at uniform intervals. However, as is evident from the diagram, this is not the case – the use of a constant angular offset clearly results in non-uniform pitch.

In Figure 9(b) the radial lines are arranged so as to intersect the line MN at regular intervals and in this case the pitch of the raster is constant along any line that lies perpendicular to the raster's axis of symmetry. On the basis of this diagram:



(a)

(b)

Figure 6: Schemes summarised by Ivanov that are intended to place all members of an audience at an approximately equal distance from a parallax barrier (parallel raster) based cinema screen. Clearly these are non-optimal approaches. The radial raster forms of barrier employed by Noaillon, Ivanov *et al.* and Savoye provided a more practical solution by supporting viewing locations distributed across the length and breadth of a cinema auditorium. In relation to (b), also see discussion on François Savoye's early display system which is provided in the Appendix to this document. (Diagrams reproduced from Ivanov [1956].)

For n=1: $\tan\phi_1 = \dfrac{p}{\sigma}$. For n=2: $\tan(\phi_1 + \phi_2) = \dfrac{2p}{\sigma}$.

Hence for the n^{th} radial line:

$$\tan\theta = \frac{np}{\sigma},$$

where:

$$\theta = \sum_{i=1}^{n} \phi_i .$$

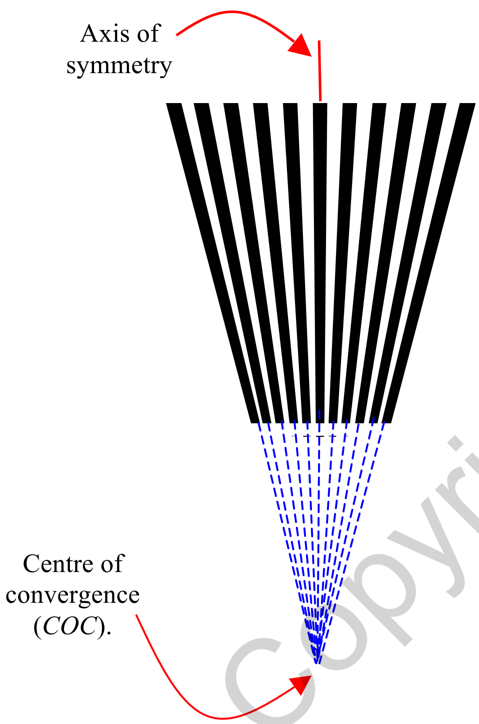


Figure 7: In the case of the radial raster form of barrier, the interleaved transparent and opaque bands form a fan-like structure and if extended meet at a common point – the centre of convergence (COC). Also note that the barrier exhibits symmetry about a vertical axis and that the width of the slits and opaque elements increases in proportion to distance from the COC. However along any line that is perpendicular to the axis of symmetry, the barrier should, in principle, exhibit constant pitch – see Figure 9(c).

Thus the angle of each radial line as measured from the vertical axis is given by:

$$\theta = \tan^{-1}\left(\frac{np}{\sigma}\right). \tag{2}$$

Figure 10 illustrates the basic configuration used by both Noaillon and Ivanov for cinematic projection. As may be seen, the passive screen (which lies in a vertical, or approximately vertical, plane) and barrier have a relative inclination such that if extended, the plane of the former passes through the COC of the radial raster.

Recall Figure 3 in which three exemplar slits are illuminated by a point light source and the path of light emerging from the barrier is indicated by three planar surfaces. In Figure 11(a) an equivalent diagram is presented for a radial raster barrier. Again we assume the use of a point light source, neglect effects arising from the finite width of each slit and assume that the screen returns a significant portion of the incident light along its original trajectory. Naturally, each light plane must pass through a corresponding slit and additionally all light planes must intersect at *O* – the location of the light source (recall that from the position of the light source the illuminated regions of the screen are entirely visible). Thus the orientation of each light plane is now defined. If these planes are extended downwards their mutual intersection will occur along a line segment drawn between the COC and *O* (indicated as a red line in Figure 11(a)). As a result, if an observer was to position one eye at any point along this line and look towards the barrier, the illuminated regions of the screen would be simultaneously visible.

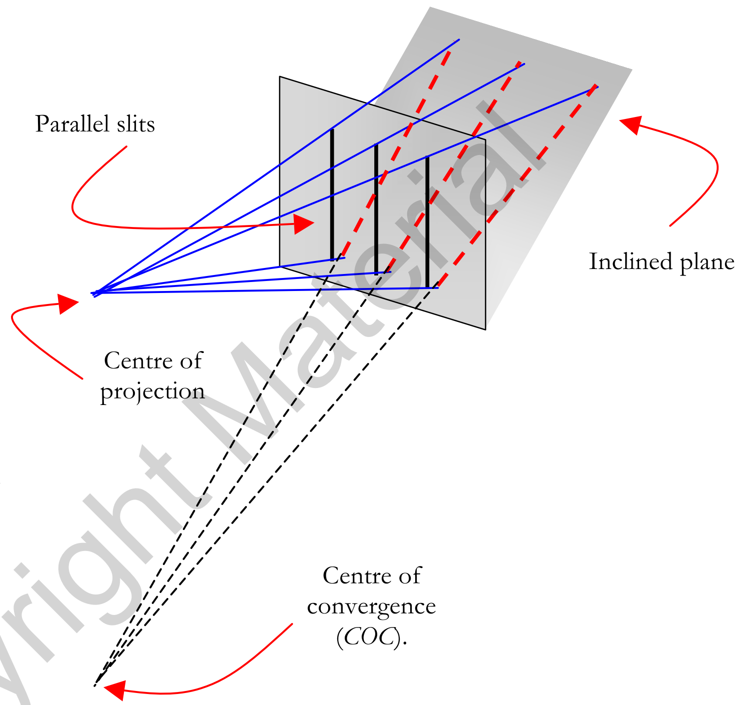


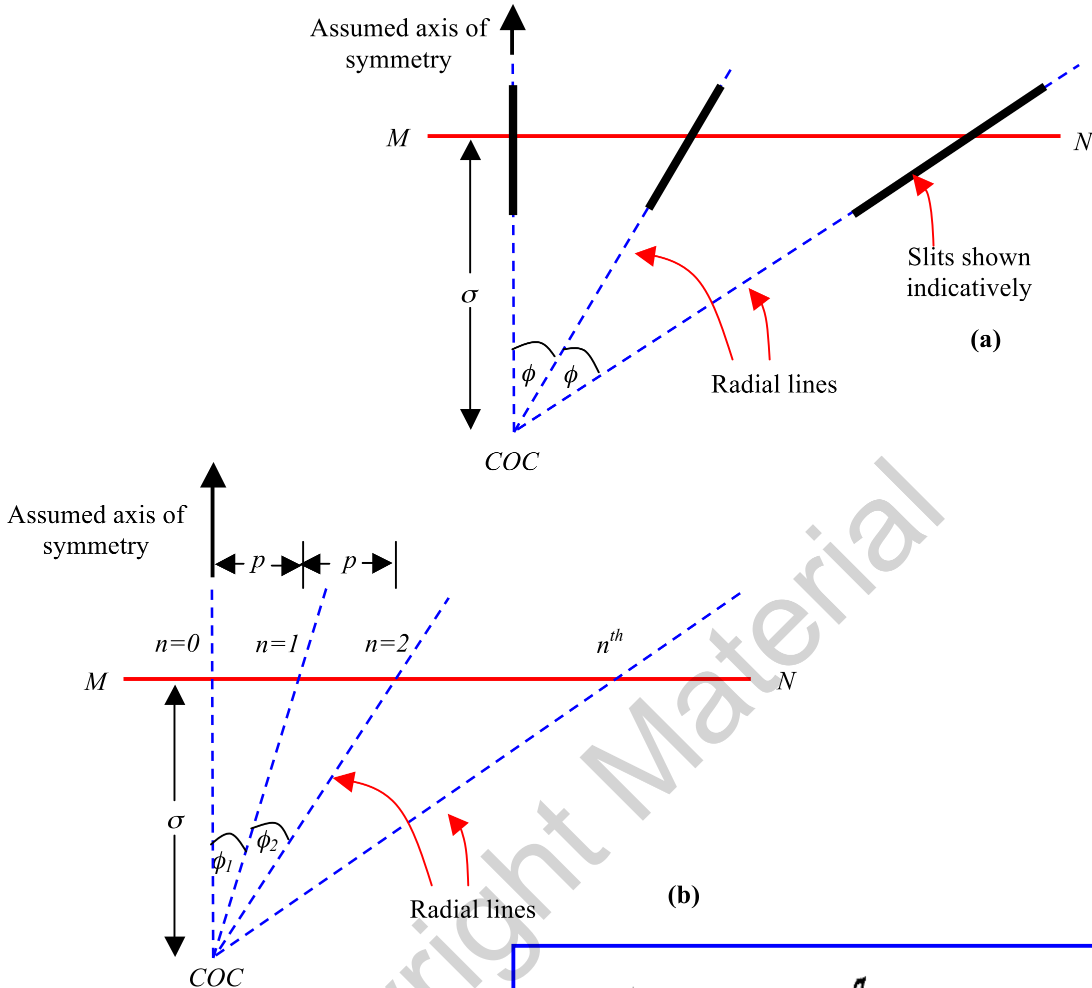
Figure 8: The geometry of the radial raster can be generated by the central projection of a conventional parallel raster onto an inclined plane.

Recall that in the case of the conventional parallel slit barrier employing the projection arrangement (Figure 3), all strips illuminated on the screen are simultaneously visible (in their entirety) at a particular distance.[12] In contrast the radial barrier operates in such a way as to eliminate this constraint and in principle is better able to support viewing locations distributed across two spatial dimensions – for example, across the length and breadth of a cinema auditorium.

3.1 MULTIPLE VIEWING ZONES

The strips illuminated on the screen by a point source located at *O* are not only visible from all points on the line segment connecting *O* with the COC, but also from other lateral locations. This is illustrated in Figure 12 where several indicative axial viewing lines (denoting possible vantage positions) radiate from the COC.

[12] As previously indicated, the conventional parallel slit raster may be considered to be a particular instance of the more general radial raster. In this context, since the slits of the former are parallel, we may consider that their COC is located at infinity. Thus a line drawn between the light source and the COC would lie parallel to the slits and be at a fixed distance from the barrier. Hence the location of the red line segment in Figure 3.



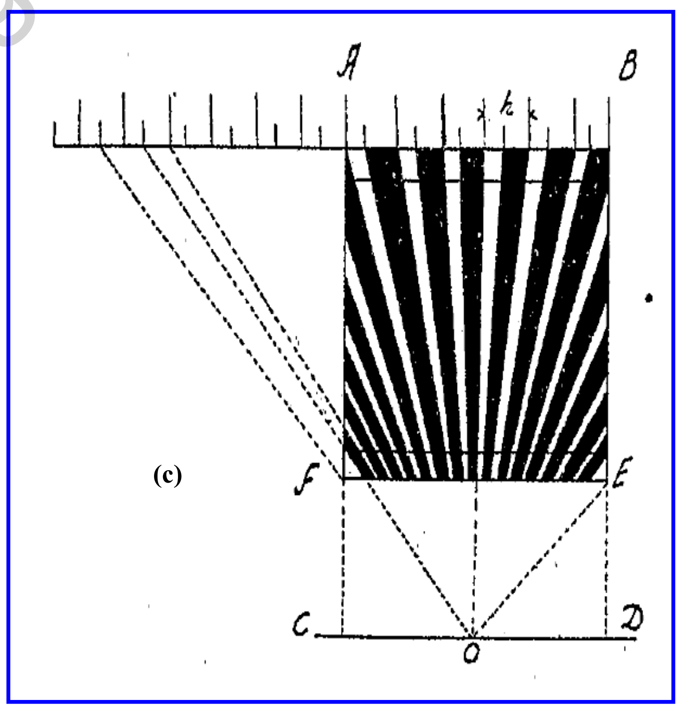
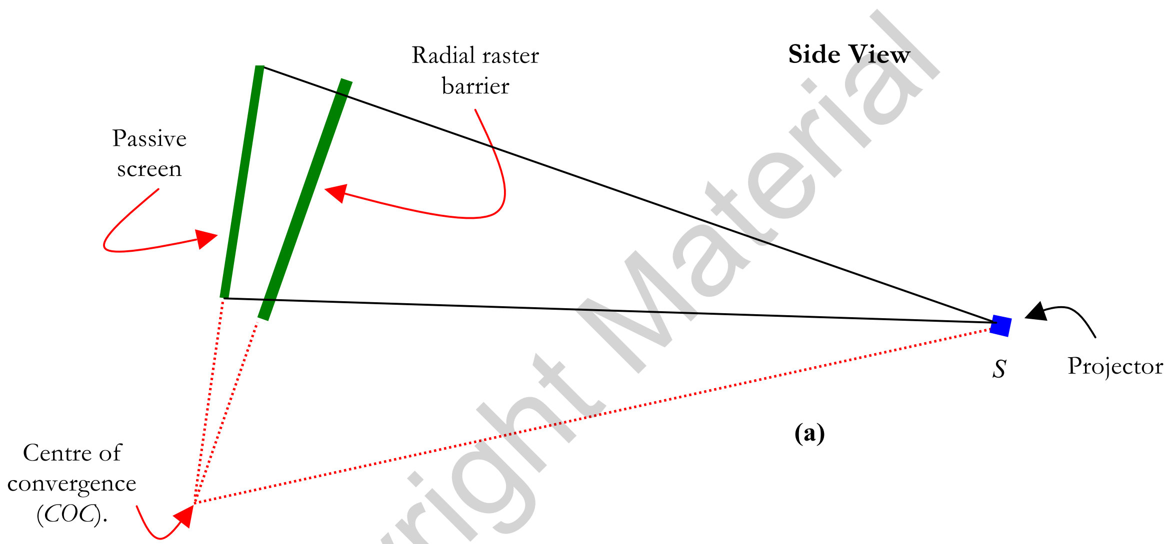


Figure 9: In (a) the three indicative lines (blue) radiate from the COC at constant angular intervals of ϕ. As a result the pitch of the raster is not constant along horizontal line MN. In contrast, in (b) the angular intervals are adjusted so that the radial lines intersect MN at regular intervals (denoted p) and so in this case the radial raster exhibits constant pitch along any line perpendicular to the barrier's axis of symmetry. Diagram (c) is reproduced from Ivanov's 1941 patent and here, the scale drawn above the radial raster confirms his adoption of constant pitch in the horizontal plane. The pitch of the raster shown in this diagram is of course greatly exaggerated. (Diagram (c) reproduced from British Patent 602,794.)

Consider the case of a monocular observer moving along the blue horizontal line AB which lies parallel to the surface of the screen and which cuts through the axial viewing lines. Figure 13 provides a simplified illustration of the variation of screen brightness with position. As an axial viewing line is approached there is an increase in brightness which attains a maximum value when the eye reaches the line. Further movement along AB results in a reduction in brightness until a position is reached at which none of the strips cast onto the screen are visible. This effect is repeated as the next axial viewing line is approached.

In practice and as a consequence of the use of a projection system with a finite aperture coupled with possible diffraction of light passing through narrow barrier slits and the reflection characteristics of the screen, the distribution of light in the vicinity of the axial viewing lines is more complex. This was recognized and discussed by Noaillon in his 1936 patent (British Patent Number 496,971). Also see Noaillon's US patent filed in 1937 (US Patent Number 2,198,678).



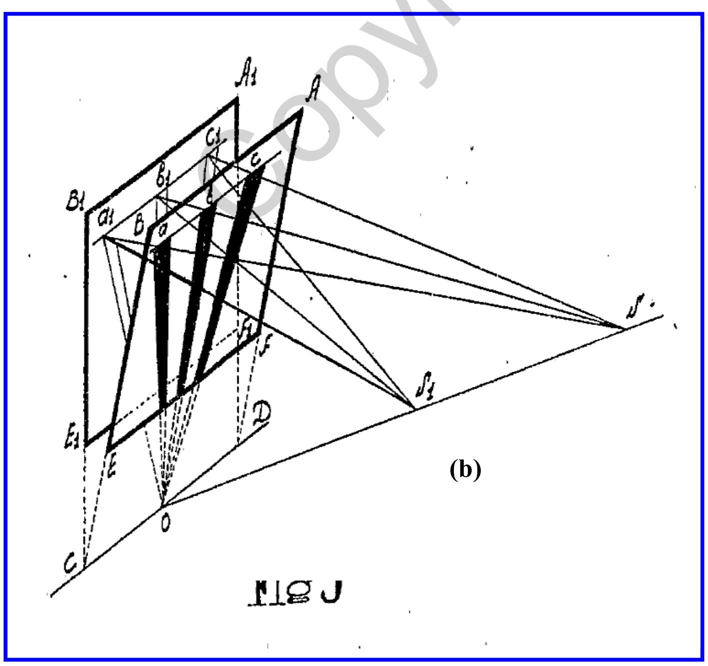


Figure 10: In (a) the basic configuration of screen, radial raster barrier and projector independently employed by both Noaillon and Ivanov. The plane of the screen is normal to the projector's optical axis and also if extended downwards, it passes through the COC. Diagram (b) provides a further insight into the overall geometrical arrangement and is reproduced from Ivanov's 1941 patent (see British Patent 602,794).

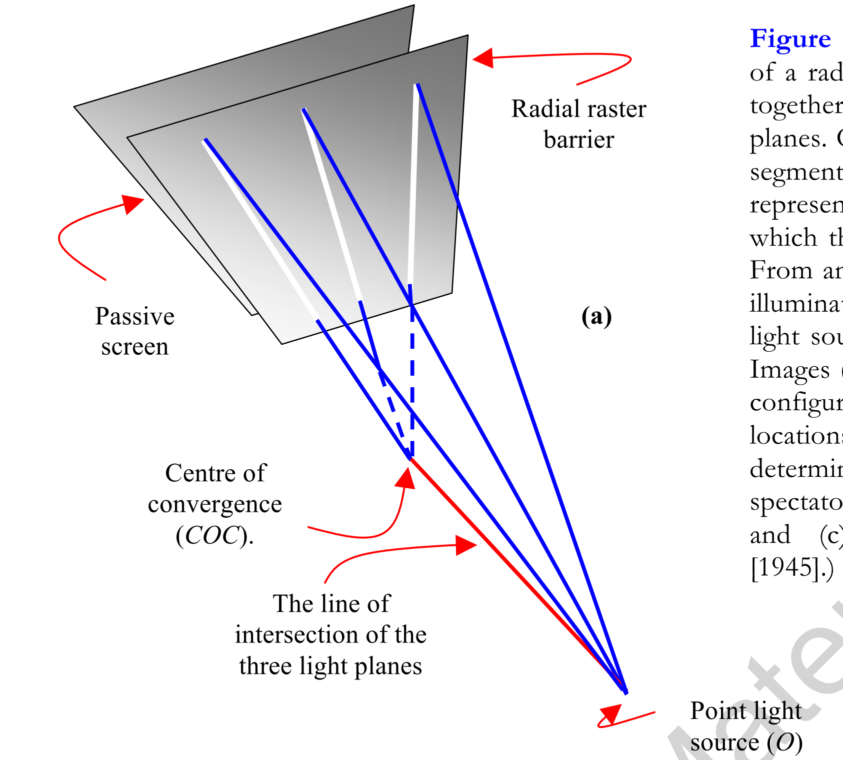


Figure 11: In (a) three indicative slits of a radial raster barrier are illustrated together with their associated light planes. Of particular interest is the line segment (depicted in red) which represents the locus of points along which the set of light planes intersect. From any point on this line all regions illuminated on the screen by the point light source are simultaneously visible. Images (b) and (c) show two projector configurations. In both cases the locations of the COC and projector(s) determine the height from which spectators view the screen. (Images (b) and (c) reproduced from Ivanov [1945].)

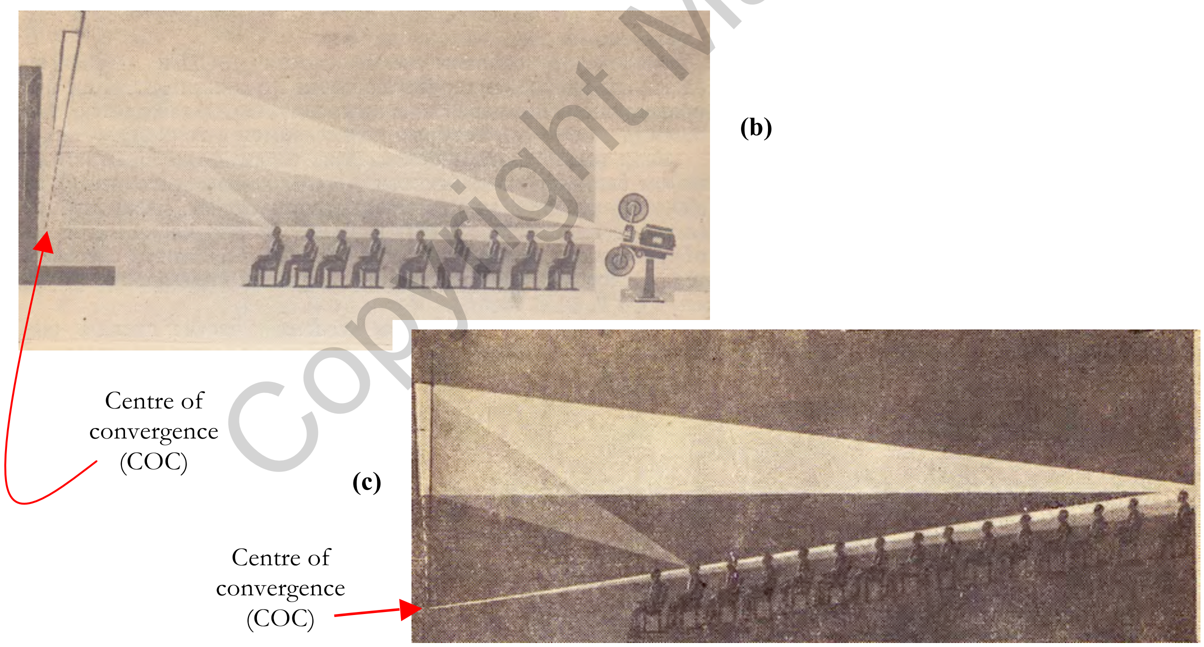


Figure 14 also indicates light output in the vicinity of three exemplar axial viewing lines. From this diagram and on the basis of similar triangles (depicted in blue), it is evident that:

$$\chi = \frac{2\xi y}{b}, \tag{3}$$

where χ denotes the width of each region over which the strips cast onto the screen are visible, ξ the barrier slit width, y the distance of the line AB from the screen and b the mean separation of screen and barrier. Hence, using Eq.1 it follows that:

$$\chi = \frac{2\xi S}{p}. \tag{4}$$

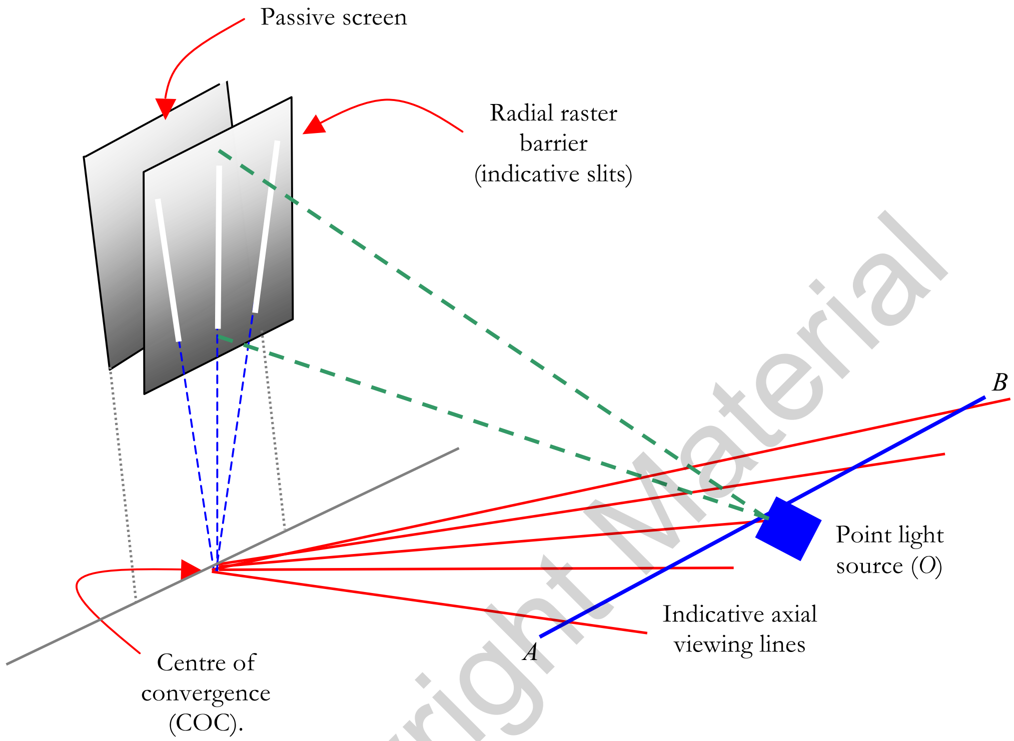


Figure 12: The illuminated strips that are cast onto the screen by a point source located at O are not only visible from locations along the line segment connecting O to the COC but also from other positions along a set of axial viewing lines (denoted in red).

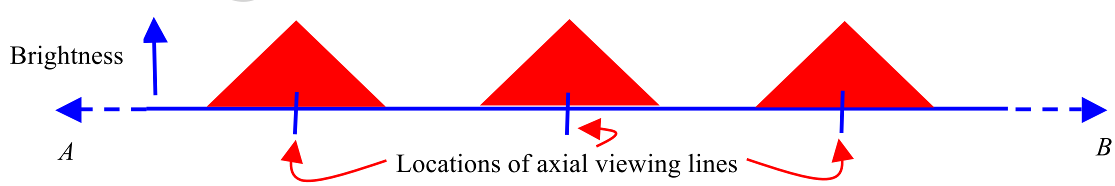


Figure 13: Traversing the line segment AB (Figure 12). In this simplified scenario, on approaching an axial viewing line there is an increase in brightness which reaches a maximum at the point at which the line AB intersects the axial viewing line. Subsequently brightness decreases until a point is reached at which the strips cast onto the screen by the light source cannot be seen. This effect then repeats as the next axial viewing line is approached. Note that in practical applications, these visibility profiles have a more complicated form. Also look ahead to Figure 33.

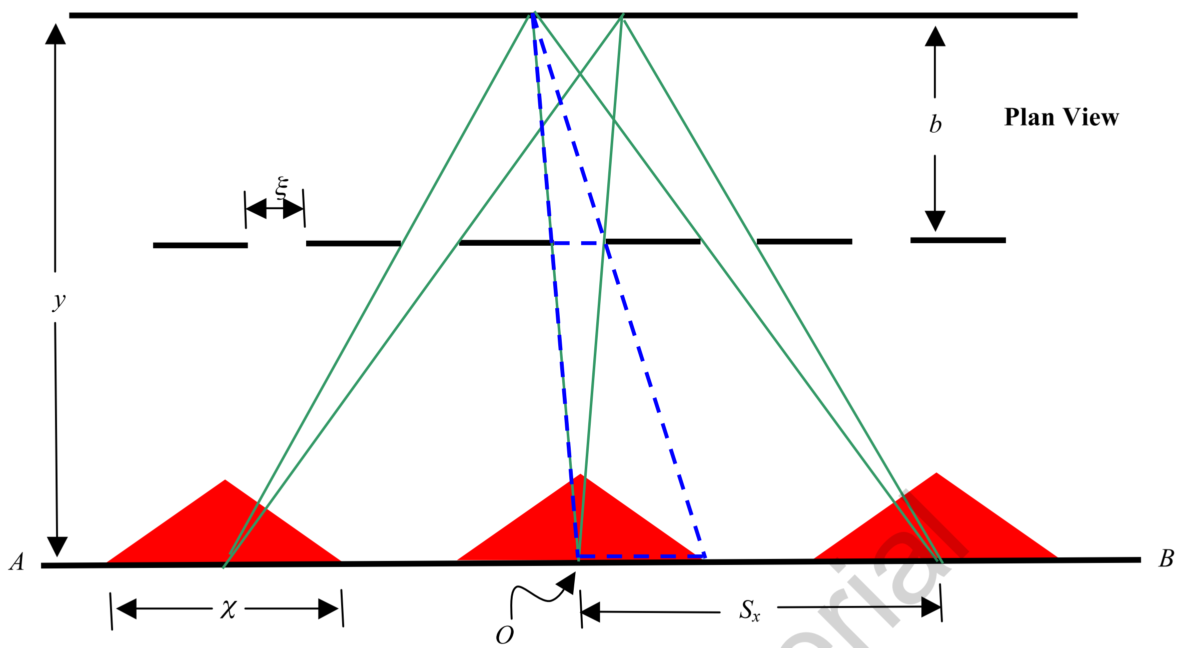


Figure 14: Illustrating the basic geometry giving rise to regions of visibility (depicted in red) for a point source located at *O*. In practical situations these visibility profiles have a more complex shape.

3.2 PROJECTING STEREO IMAGES

So far we have focused on the use of a single point source for the illumination of the barrier. In order to consider the formation of 3D images it is necessary to extend this discussion to accommodate the projection of the left and right images that comprise the stereopair. We begin by simply assuming the use of two point light sources (O_L and O_R) which are located upon a horizontal line AB lying parallel to the plane of the barrier and screen. This projector configuration is the same as that used for the parallel slit barrier (Figure 5).

The dual light source arrangement gives rise to two sets of axial viewing lines which in the case of 3D image formation respectively correspond to left and right hand stereo views – see Figure 15. In this illustration the separation of pairs of axial viewing lines is greater than the spacing of the lines that comprise each pair. This approach is helpful in suppressing audience exposure to the pseudoscopic image which occurs when the left hand stereoview is presented to the right eye and the right hand view to the left eye.[13]

Clearly, in an ideal situation the axial viewing lines comprising each pair would be separated by the interpupillary distance (~65mm). However, the lines radiate from the COC and so fixed separation cannot be achieved over the length of an auditorium. This difficulty is ameliorated by the region of visibility surrounding each axial viewing line (recall Figure 13) and consequently it is *possible* to perceive a satisfactory 3D experience at locations in the vicinity of each line.

---

[13] However, the presentation of the pseudoscopic image to the visual system does not *necessarily* give rise to the perception of overall depth inversion – other cues often override the reversed binocular information stream. See, for example, Blundell [2011a]. However, as with other forms of depth cue conflict, exposure to pseudoscopic content can cause visual fatigue/discomfort.

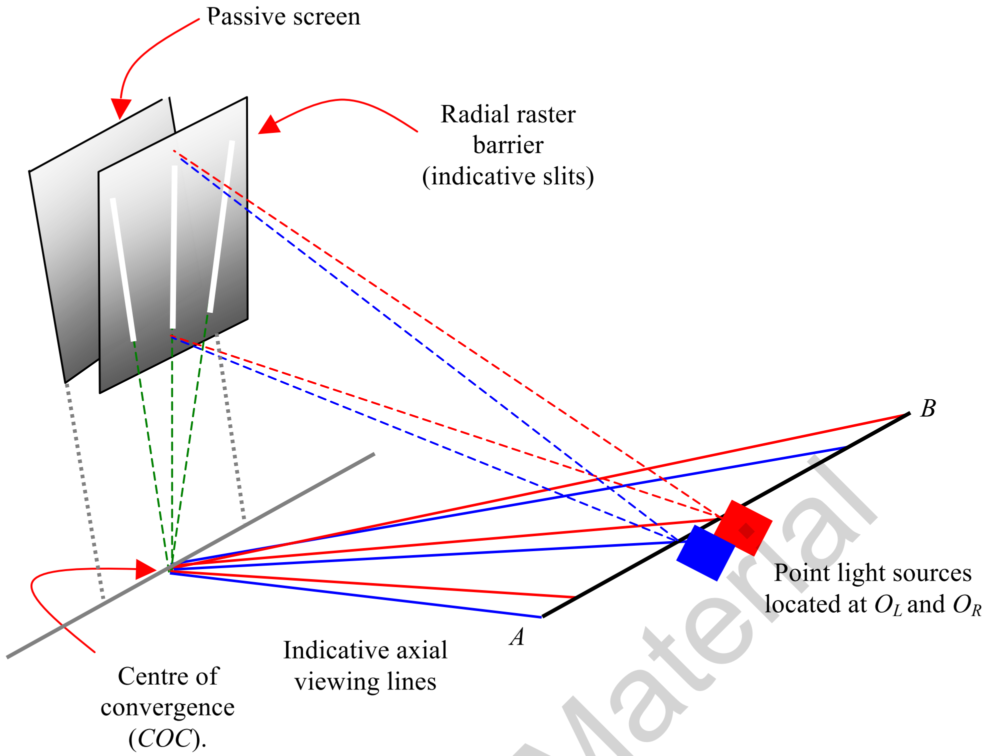


Figure 15: The use of two point light sources gives rise to two sets of axial viewing lines. For the formation of 3D images, the point sources are replaced by two image projectors (or a single dual projector system – look ahead to Figure 21) such that from O_L the left hand view of the stereopair is cast onto the screen whereas the right-hand view emanates from O_R. To experience glasses-free 3D, an observer must be located so that the left eye is in the region close to an axial viewing line generated by the projector at O_L and the right eye is in the region of an axial line generated by the projector located at O_R.

3.3 ESTIMATION OF VIEWING BOUNDARIES

In this subsection we loosely follow Valyus [1966] and consider the range of viewing distances over which a satisfactory 3D view may be experienced. This discussion makes several significant simplifications and should therefore be assumed to represent an indicative 'back of the envelope' estimation. We begin by assuming the use of two point light sources, consider all regions of visibility to be triangular in profile, and assume that they are have equal areas. From Figure 16 it is evident that:

$$\delta = S - \chi .$$

Using Eq.4 to eliminate χ, we obtain:

$$\delta = S\left(1 - \frac{2\xi}{p}\right). \tag{5}$$

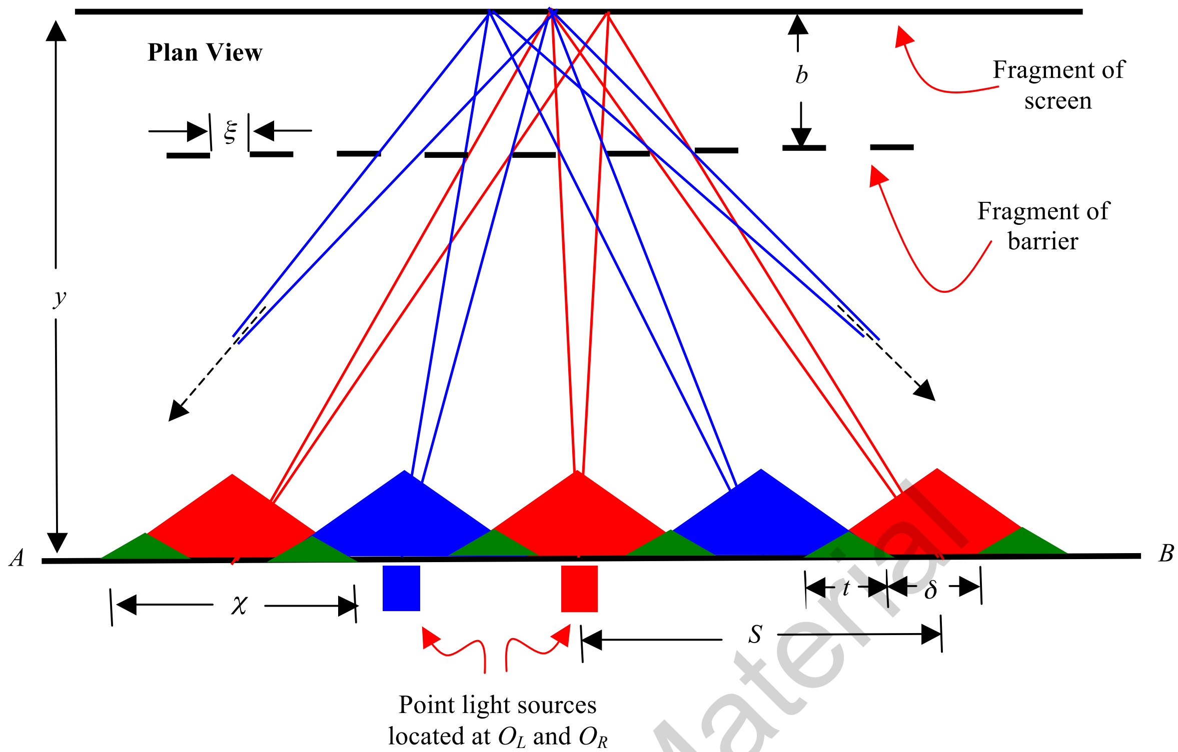


Figure 16: Here, the barrier is illuminated by two point light sources in such a way that that the spacing of the axial viewing lines (when measured parallel to the screen) is constant. The larger triangles denote regions of visibility and for clarity these are depicted in red and blue. The smaller triangles (green) represent the regions in which the left and right hand regions of visibility overlap. Thus if an observer were to place an eye in one of these regions then the strips illuminated on the screen by *both* point light sources would be simultaneously visible.

From Figure 16 it is also apparent that:

$$S = 2\chi - 2t.$$

Hence:

$$t = \chi - \frac{S}{2}.$$

Again using Eq.4 to eliminate χ, we can write:

$$t = S\left(\frac{2\xi}{p} - \frac{1}{2}\right). \tag{6}$$

In Figure 17 L_{max} and L_{min} respectively denote the maximum and minimum distances (as measured from a horizontal line *PQ* passing through the COC and lying parallel to the plane of the screen) over which the 3D view may *in principle* be experienced. The line *AB* also lies parallel to the plane of the screen and passes through the axial viewing lines. We assume it is located at a distance *x* from *PQ*. Hence, on the basis of similar triangles:

$$S_1 = \frac{Sx}{y}. \tag{7}$$

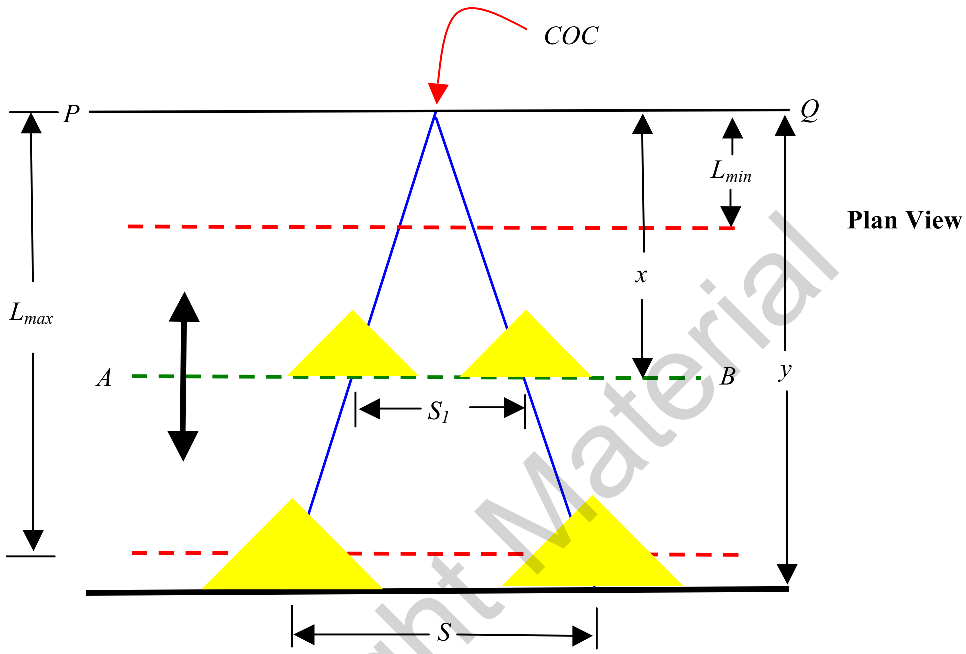


Figure 17: Indicating the maximum and minimum viewing distances (L_{max} and L_{min}) together with other symbols referred to in the text.

Similarly,

$$t_1 = \frac{tx}{y}, \qquad \delta_1 = \frac{\delta x}{y},$$

where t_1 and δ_1 denote the size of the t and δ parameters (Figure 16) on the line *AB*. Indicative values for distances L_{min} and L_{max} can be determined on the basis of the following inequalities:

$$L_{min}\text{: } t_1 + 2\delta_1 > I \text{ and } L_{max}\text{: } t_1 < I,$$

where I denotes the interpupillary distance. Clarification of these inequalities is provided in Figure 18. Turning now to the estimation of the closest satisfactory viewing distance (but bearing in mind that this is based on a single criterion). Substituting Eq's 5 and 6 into the first of the above inequalities, we obtain:

$$S_1\left(\frac{2\xi}{p} - \frac{1}{2}\right) + 2S_1\left(1 - \frac{2\xi}{p}\right) > I$$

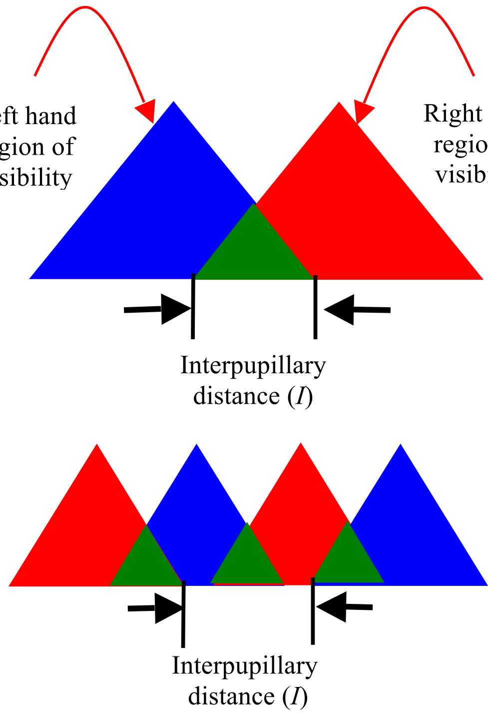


Figure 18: Simplified diagrams indicating the relationship between indicative viewing zones and interpupillary distance for furthest viewing distance (top) and smallest viewing distance (bottom). The green triangles indicate regions in which the left and right stereo views are simultaneously visible.

Using Eq.7 to eliminate S_1, and simplifying, we can write:

$$L_{\min} > \frac{Iy}{S\left(\frac{3}{2} - \frac{2\xi}{p}\right)}, \tag{8}$$

Turning to the maximum viewing distance and substituting Eq.6 into the above inequality for L_{max}, we obtain:

$$I > S_1\left(\frac{2\xi}{p} - \frac{1}{2}\right).$$

Using Eq's 1 and 7 we obtain:

$$L_{\max} < \frac{Ib}{2\xi - \frac{p}{2}} \tag{9}$$

Given an interpupillary distance of 65mm, consider the case that the average period of the barrier slits (p) is ~2.25mm and that the mean separation of the screen and barrier (b) is ~325mm. Further we assume that ξ/p~1/3 (thus ξ~ 0.75mm). From Eq.1 we obtain a value for y/S of ~144.

By means of Eq.9 we obtain L_{max}<56m – thereby indicating that the criteria introduced above does not *in itself* impose any unworkable practical restriction on maximum viewing distance.

Now turning attention to L_{min}. For convenience we assume that distances y and L_{max} coincide. From above, y/S~144 and hence S~39cm (approximately 6*I*). From Eq.8, we obtain L_{min}>11.2m.

In considering these numerical results, it is important to recognize that we have focused exclusively on support for binocular parallax – and even here we have simplified the form of the regions of visibility.

3.4 GLASSES-FREE CINEMA IN MOSCOW: 1941

As noted in the Section 1, on 4th February 1941 glasses-free 3D cinema opened to public audiences in Moscow and rapidly grew in popularity. Table 1 summarises key physical parameters of the system and also provides limited information about an earlier demonstration system constructed *circa* 1937.

The radial raster barrier used for the Moscow cinema was built *in situ* and was undoubtedly of sturdy construction – see Figures 19 and 20. It comprised a rectangular steel frame that was used to support and tension some 30,000 black-enamelled copper wires. These were arranged in bundles – each of which formed an opaque barrier region (Figure 19(b)). To prevent the passage of light, the individual wires overlapped – and naturally, the degree of overlap would have increased towards the base of the barrier. The screen comprised a frame over which aluminized cloth was stretched. Screws located at the four corners of the barrier enabled the relative distance and inclination of the screen/barrier assembly to be adjusted. This unit was then attached to two reinforced concrete columns via bolts which could be adjusted so as to set the assembly's vertical alignment.

The optical systems used for filming and for the projection of the stereopair onto the barrier/screen assembly are summarised in Figure 21 (see, for example, Mayorov [2012] for further details).

It is instructive to briefly consider the issue of barrier visibility. Referring to Table 1, the maximum barrier pitch is 3.45mm – with the slit width accounting for 1/3 of this value. Thus the maximum opaque portion of the barrier spans 2.3mm. If we assume a minimum viewing distance of 10m, then the maximum angle subtended at the eye is ~48″ (yielding a retinal image of ~0.005mm). Thus from the perspective of both detection and grating (resolution) acuities (see, for example, Blundell and Schwarz [2006] or Boff *et al.* [1986]) it is, in principle, possible that the upper part of the radial raster may have been visible to members of the audience seated towards the front of the auditorium (for brief related discussion, see Cornwell-Clyne [1954]). On the other hand, it is almost certain that the illumination provided by the projection system would have been insufficient to support this level of visual acuity, in which case the barrier would not have been directly visible.

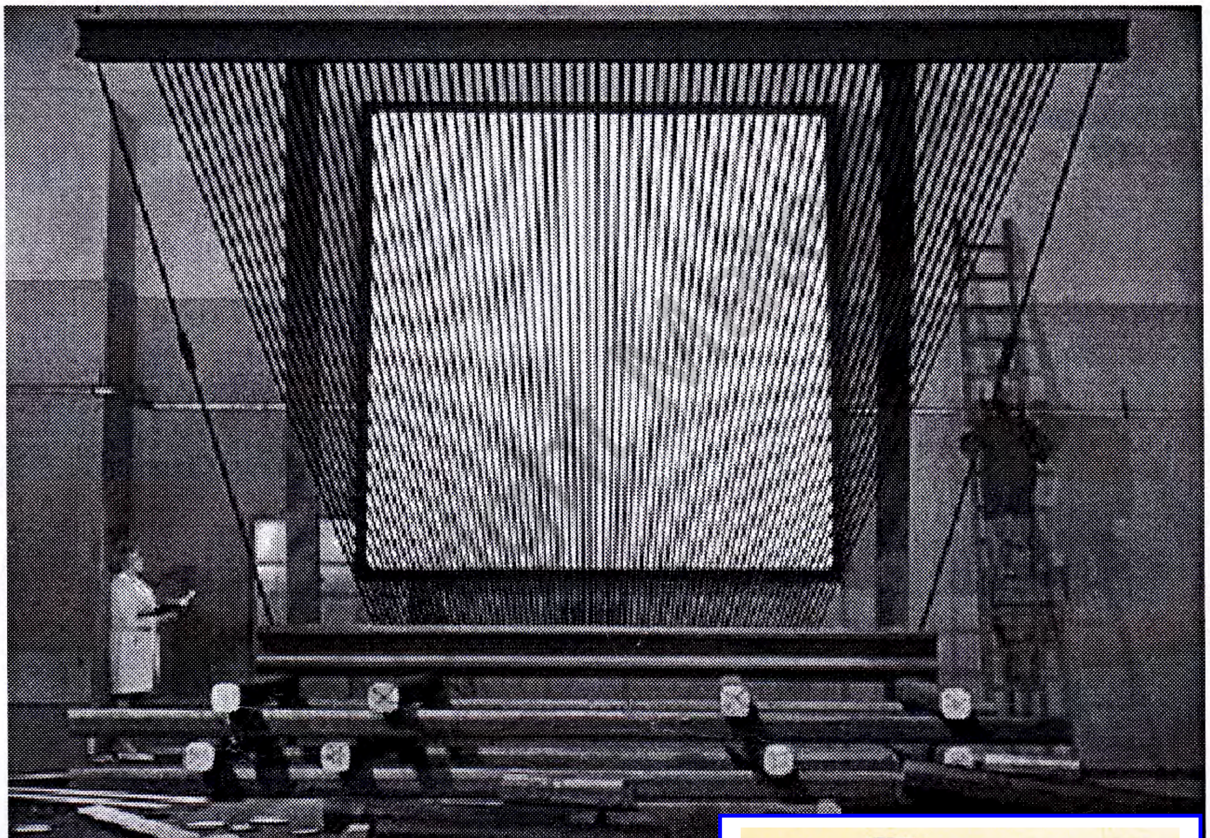
4. THE PIONEERING WORK OF EDMOND NOAILLON

In this section we briefly review aspects of Noaillon's 1928 US patent (US Patent Number 1,772,782 (an equivalent patent was filed in Belgium towards the end of 1927)). In addition to discussing the use of a radial raster barrier to support 3D viewing across the length and breadth of a cinema, the patent discloses several other interesting inventive steps. Two of these are outlined below.

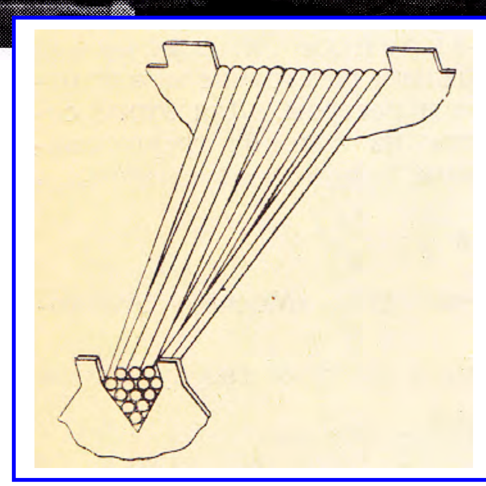
4.1 THE OSCILLATORY RASTER BARRIER

As the widths of the opaque portions of a raster barrier are increased, there is a corresponding increase in the barrier's visibility. In addition a greater percentage of the projected image will fall on these opaque regions and so will not contribute to image formation. At some point perceptible image segmentation will occur. These issues were recognized by Noaillon (although not explicitly described) and his solution was to subject the barrier to oscillatory motion about the COC. Recall from Figure 11(a) that each axial viewing line corresponds to the locus of points that denote the intersection of a set of light planes. Further recall (Figure 15) that all axial viewing lines emanate from the COC and intersect the horizontal line AB (which lies parallel to the plane of the screen) at regular locations.

When the barrier is subjected to an oscillatory motion about the COC, there is no shift in the location of the axial viewing lines (*as the position of the COC remains unchanged*) and so it is unnecessary for an observer to change vantage point. Figure 22 illustrates the basic principle underpinning small amplitude barrier motion.



(a)



(b)

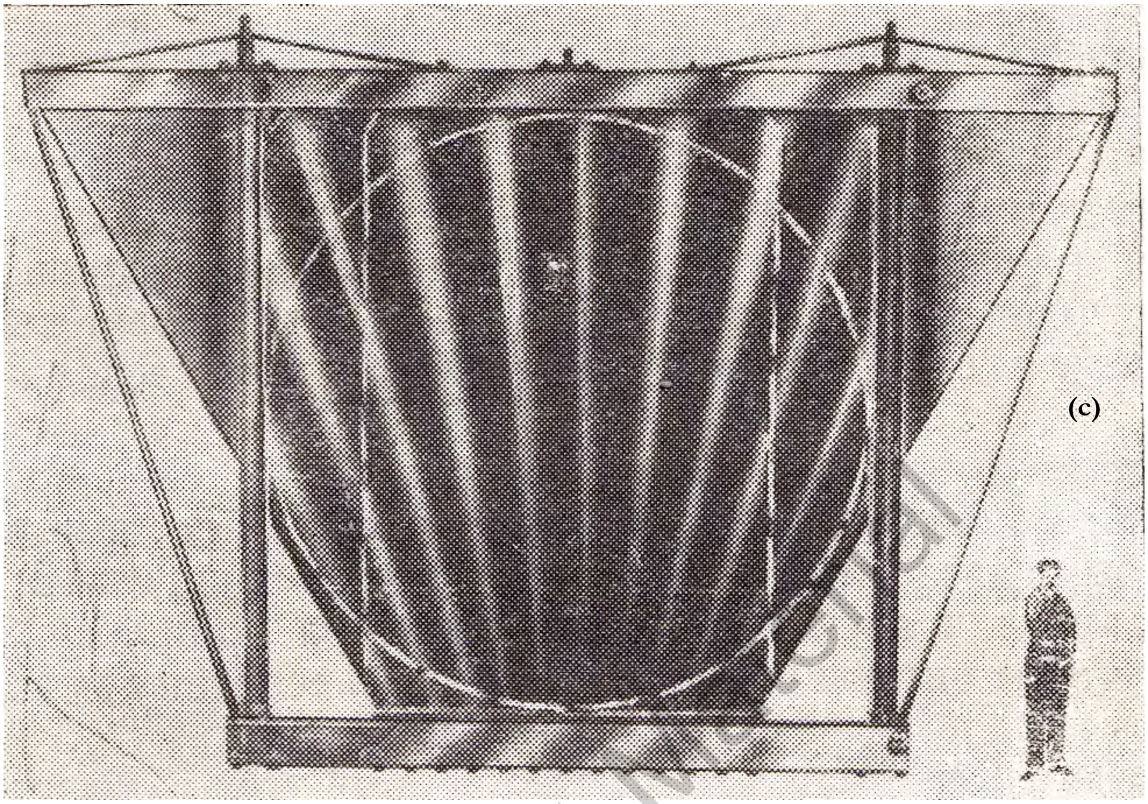


Figure 19: Images (a) and (c) show the radial raster barrier and screen. In the case of the latter image, the screen size is ~5x3m. Image (b) illustrates the use of a group of wires to form an opaque barrier strip. (Image (b) reproduced from Ivanov [1945] and (c) from Ivanov [1956].)

In principle, in order to satisfy the visual requirements of an audience the minimum amplitude of barrier motion corresponds to the pitch of the raster. However this assumes that each cycle of motion occurs at a frequency that is no less than the flicker fusion frequency. This level of movement ensures that over each cycle of barrier motion, the image returned from the screen via the barrier is non-quantized and because of the persistence of vision, an audience will, in principle, be able to experience glasses-free 3D without experiencing image segmentation.

Alternatively, the frequency of motion may be reduced by making a corresponding increase in the amplitude of motion. Thus, for example if the amplitude of motion is doubled (twice the barrier pitch) then in principle it may be possible to halve the drive frequency.

Ideally, the drive system for such an arrangement should maximise the extent to which the barrier moves with constant speed – necessitating maximization of the acceleration occurring at each extremity of barrier movement. Despite the innovative suspension arrangement adopted by Noaillon, it is probable that the significant barrier mass (and in turn not inconsiderable barrier inertia) would have forced him to adopt a sinusoidal velocity profile. As a consequence it is likely that the amplitude of motion employed would have been significantly greater than the minimum referred to above.

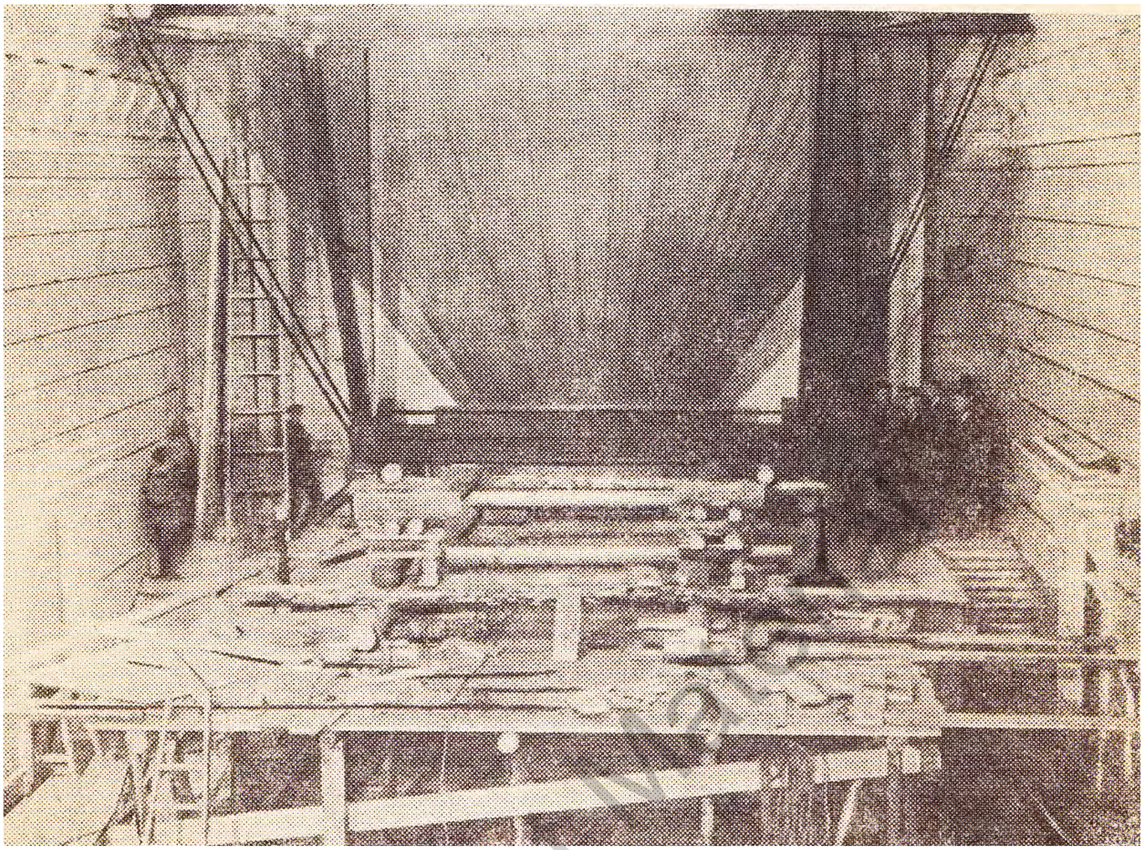


Figure 20: Construction of the radial raster barrier at the Moskva cinema (Moscow) *circa* 1940. The completed barrier weighed ~6 Tons. The opaque regions were formed from groups of copper wire and in total ~150 km of wire was used (Ivanov [1941]). Give the required accuracy and the lack of today's lightweight plastics the development of this barrier represents a remarkable technical achievement. (Image reproduced from Ivanov [1941].)

However, even when the amplitude of movement is increased, during each cycle the barrier must still slow down and instantaneously stop before reversing direction. During this time raster visibility is an issue. Furthermore unless appropriate precautions are taken, the image projection system may interact with the moving raster in such a way as to heighten barrier visibility due to stroboscopic effects.

Noaillon initially sought to minimize barrier visibility by applying to it a matt black coating. Subsequently, in a US Patent filed in 1937 (US Patent Number 2,198,678) he indicates that this approach is unsatisfactory and goes on to outline the use of a 'glossy black lacquer'. His purpose was to cause specular rather than diffuse reflection from the barrier and ensure that this reflected light was directed to the floor at the front of the auditorium so that it was not perceived by the audience.[14] However, in the earlier 1928 patent filed by Noaillon (US Patent Number 1,772,782) the inventor discloses a novel approach intended to significantly

[14] In Section 8 we briefly review a patent filed by Dennis Gabor in 1940 in which he discloses techniques for the implementation of glasses-free cinema. Gabor employed a set of horizontal prismatic ledges that were fabricated into the front face of an optical assembly (within which the 'screen' was integrated). These reflected light along a path lying outside the audience's visual field.

reduce the amount of light falling onto the opaque portions of the barrier – thereby reducing both light loss and barrier visibility. This is outlined in the next subsection.

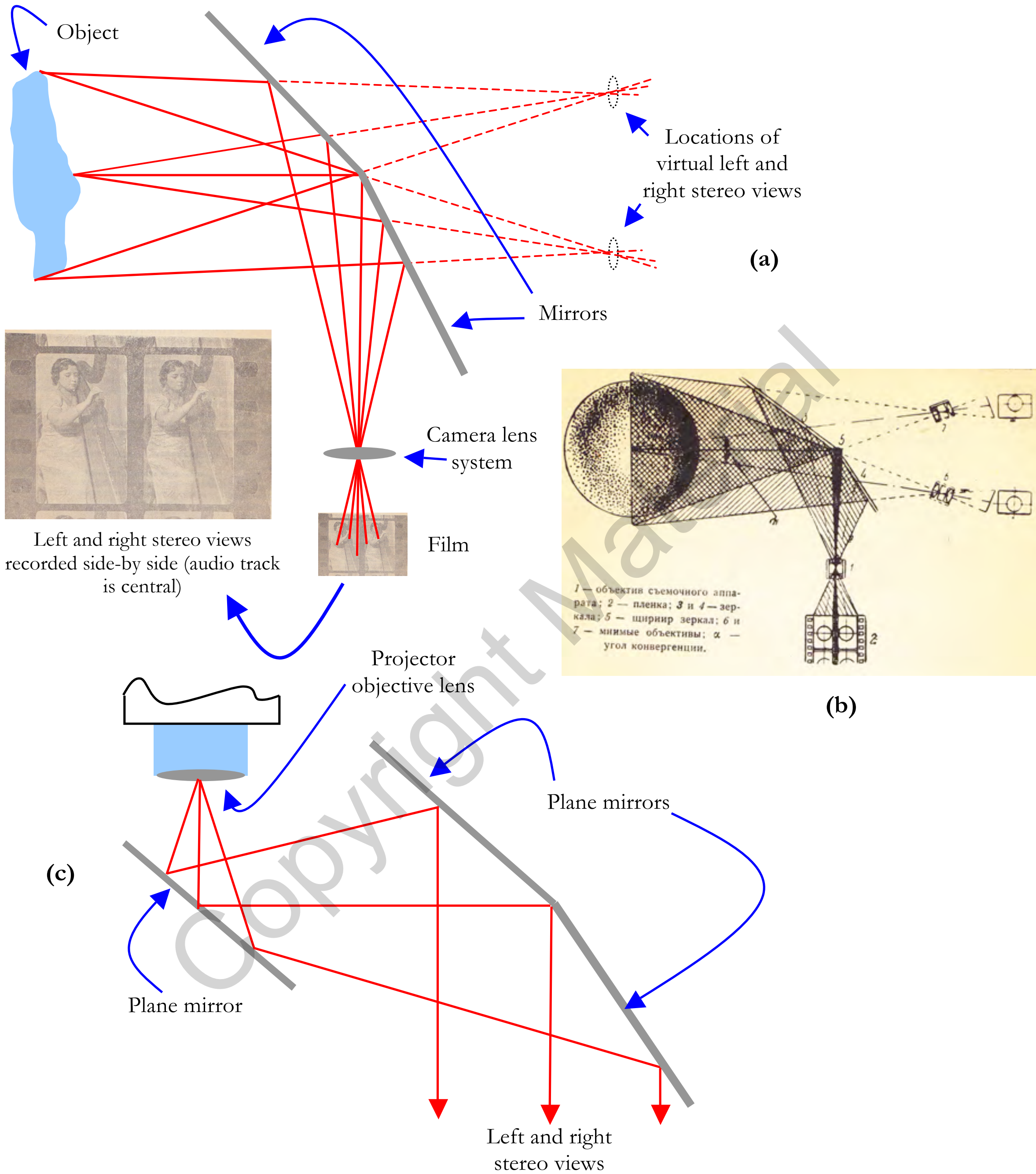


Figure 21: Diagrams (a) and (b) summarise the capture of the left and right stereo views. Here two plane mirrors are slightly inclined relative to each other thereby casting the two views onto adjacent regions of the film. The insert in (a) depicts Vera Dulova in the 1941 3D film '*Konsert*'. In (c) the projection system in which two inclined mirrors are employed so enabling a single projector to generate the stereo images. (The insert in (a) and diagram (b) are reproduced from Ivanov [1945].)

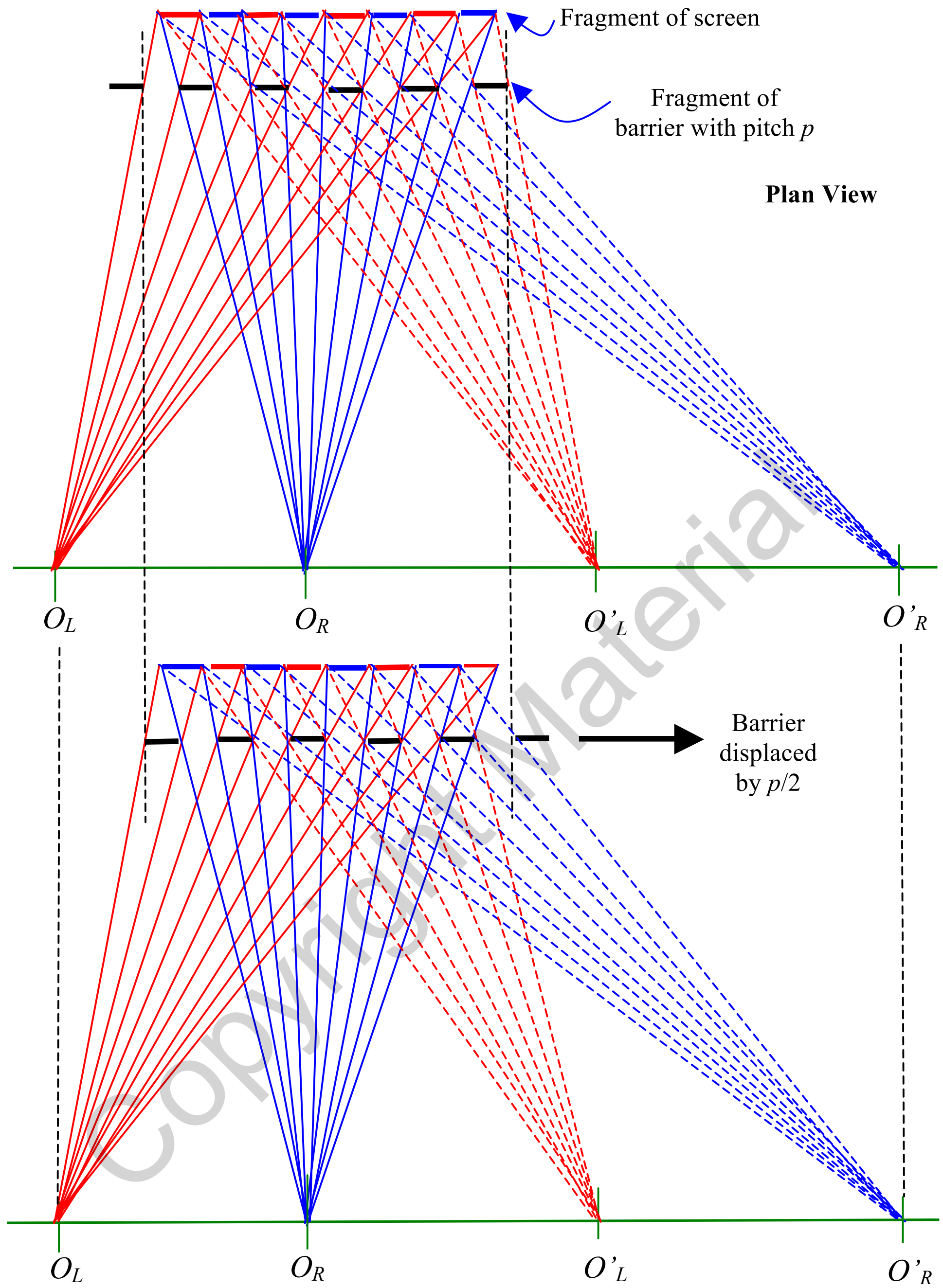


Figure 22: The principle of cyclic barrier oscillation. The upper diagram shows the projection of the left and right stereo views (from locations O_L and O_R respectively) together with the first right-hand side lobes (O'_L and O'_R). In the lower diagram the barrier has been displaced by a distance $p/2$ (where p denotes the barrier pitch) such that the locations of the opaque and transparent slits are swapped. As can be seen, this results in an exchange in the positions of the left and right view strips on the screen in such a way that image content which, in the upper diagram was unable to reach the screen, is now able to do so. Given the new barrier location, there is no shift in the positions of O'_L and O'_R. Assuming that the barrier is subjected to a cyclic oscillation with a frequency in excess of the critical flicker frequency, this process can eliminate image segmentation resulting from the finite width of the opaque regions of the barrier.

	Demonstration System: 1937	Moscow Cinema: 1941
Screen Dimensions	2.25x3m	5x3m[15]
Barrier Construction		~30,000 copper wires (black)
Barrier to Screen Spacing		Top: 480mm, Bottom: 170mm
Barrier Pitch	Top: 3mm, Bottom: 1.5mm	Top: 3.45mm, Bottom: 1.2mm
Slit Width	Top: 1mm, Bottom: 0.5mm	~1/3 barrier pitch
COC		2.8m (below screen)
Front Row Seats: Distance from Screen		10m
Back Row Seats: Distance from Screen		29m
Height of axial viewing lines		1150mm (above the floor)
Viewing Zone Width		Front Row: 80mm Back Row:165mm
Number of stereo viewing positions per seat		Front Row: 4-5, Back Row: ~2
Number of Seats		24 rows of 16 seats
Projector System		KZS-22
Pseudoscopic Image Visibility		Suppression by uneven spacing of axial viewing lines

Table 1: Physical parameters relating to a demonstration system trialled in 1937 and also to the glasses-free cinema which opened in Moscow on 4th February 1941. After WWII the radial raster barrier was superseded by the radial lenticular configuration which enhanced image brightness and offered to provide limited support for motion parallax. (Data from Valyus [1966].)

4.2 THE FORMATION OF LIGHT BANDS

A key issue associated with the use of a barrier for the implementation of the re-imaging subsystem centres on its inefficiency in the throughput of light. Only light which is directed at the transparent slits is able to pass through the barrier and if, for example, $\xi/p=1/3$ then on traversing the barrier ~2/3 of the light is lost. In the case that a projection system (either directed from the front or rear of the screen) is used, this problem is exacerbated as the light must traverse a barrier twice and so only ~1/9 of the light incident on the barrier will contribute to the visible image.

In the case of glasses-free 3D cinema in Russia, this shortcoming was recognized and as outlined in Section 5, by 1947 the barrier approach had been superseded by a radial lenticular configuration.

In contrast, in his 1927/28 patents Edmond Noaillon disclosed a means of increasing the transmission efficiency of the radial raster barrier and in parallel of reducing barrier visibility. To gain an insight into the approach adopted by Noaillon, it is necessary to examine aspects of the stereo projection system described in his patent – see Figure 23. This employs a single light source (21) from which two beams are formed and after passing through several optical components the light emerging from the projector (at 5 and 6) is directed towards the radial raster barrier. Element 33 in the illustration represents the stereo film comprising the left and right views.

[15] Mayorov [2012] reports screen dimensions of 5 by 3.25m whereas Coe [1981] indicates screen dimensions of 4.25 by 5.8m. Coe indicates a seating capacity of only 200.

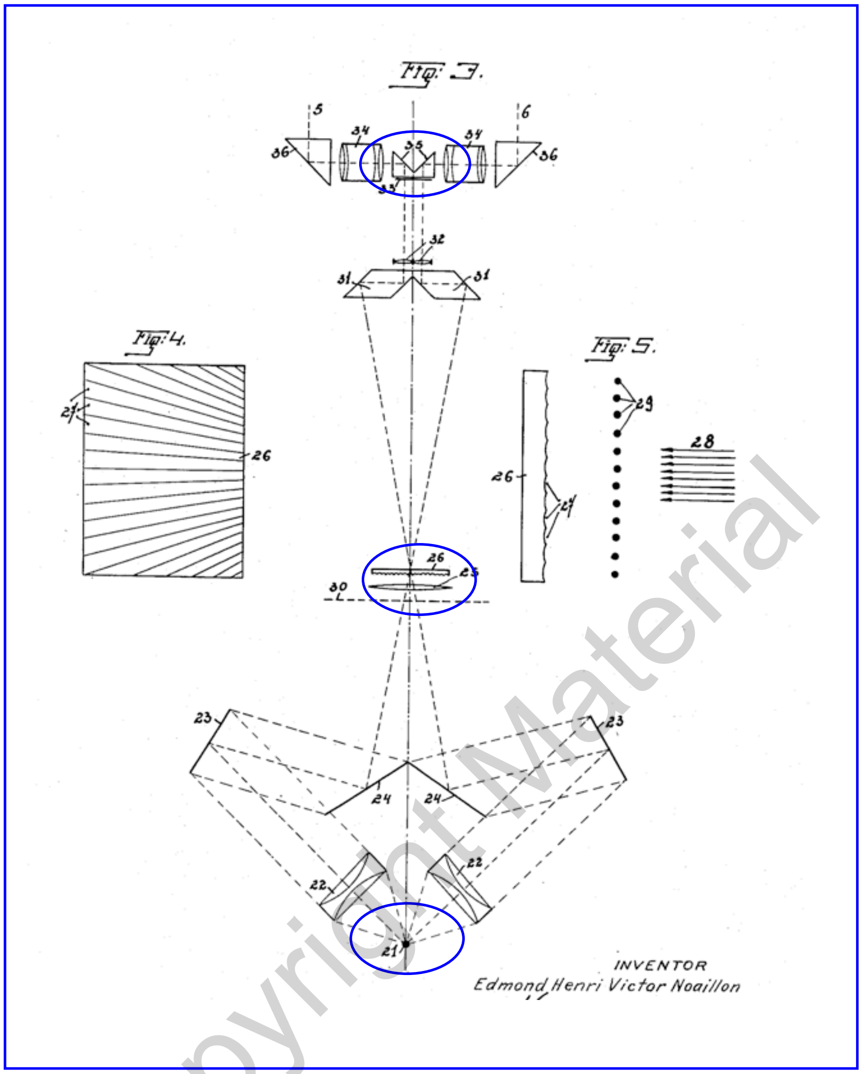


Figure 23: The stereo projection system described by Noaillon in his 1927/28 patents. Element 21 represents the light source from which two beams are derived. Element 33 is the stereo film with adjacent left and right hand views. Of particular interest is element 26 which takes the form of a micro-filter (see insert diagrams labelled Figs 4 and 5 above). This comprises a set of concave lenticules (gofferings) which are arranged so as to form a radial raster. The micro-filter oscillates about its COC in synchronism with the main radial raster barrier – see text for discussion. (Diagram reproduced from US Patent 1,772,782.)

From the perspective of our current discussion, element 26 is of particular consequence. Noaillon refers to this as a 'micro-filter' and its form is illustrated in the two smaller diagrams reproduced in Figure 21 (labelled Figs 4 and 5 in Noaillon's patent). The micro-filter comprises a glass plate equipped on one side with a set of *concave* grooves arranged so as to match the geometrical configuration of the slits in the radial raster barrier. Thus as with the slits in the barrier, if extended, the grooves converge to a COC. The projection of the two beams of light through the micro-filter results in the formation of two sets of virtual lines of light (which also converge to the COC). These light lines are modulated by their passage through the film and are cast onto the barrier in such a way that there is a direct mapping between light lines and barrier slits.

One final ingredient is needed to better appreciate the overall thrust of Noaillon's scheme. As outlined in Section 4.1, Noaillon subjected the barrier to an oscillatory motion about its COC. Consequently to ensure that the two sets of light lines generated by his projection system (corresponding to the left and right stereo views) were accurately cast onto the barrier slits, it was necessary to arrange for the micro-filter to also undergo oscillatory motion about its COC. Naturally, this scheme relies on the accurate synchronization of the motion of both barrier and micro-filter. As a consequence of the limited technologies that were readily available in the 1920's, Noaillon was unfortunately forced to use mechanical linkages such that the motion of the barrier directly provided the impetus for the movement of the micro-filter. This must surely have caused inaccuracies in synchronization which could have been easily resolved had the inventor had access to simple electromechanical components that we now take for granted.

In principle, this general approach (in which Noaillon took the interesting step of making simultaneous use of barrier and lenticular techniques) offers to significantly increase the efficiency of the radial barrier by ensuring that practically all light cast onto it passes through the slits and so reaches the screen. Unfortunately, it does not improve efficiency in respect of the return of light emanating from the screen. Finally, by reducing the amount of light falling on the barrier's opaque regions the technique offers to ameliorate barrier visibility issues.[16]

4.3 THE IMPLEMENTATION OF THE RADIAL RASTER BARRIER

A mechanical system used by Noaillon to effect barrier motion is illustrated in Figure 24. Unfortunately, the inventor's patents do not provide quantitative design information and so it is necessary to infer barrier characteristics. For example, in a US patent filed in 1938 (US Patent 2,198,678 – see Section 6) Noaillon describes the formation of opaque regions in a multi-layer radial barrier. Here, he indicates the use of metallic strips which are bolted to a surrounding rectangular frame at their upper ends and tensioned by means of individual helical springs at their lower ends (look ahead to Figure 31). This approach suggests the use of quite a coarse raster pitch. Certainly, in terms of the effort involved in constructing the barrier, Noaillon's use of spring loaded strips would have been simpler than the method used by Ivanov. On the other hand, Ivanov was able to produce barriers exhibiting a smaller pitch (which is advantageous from the perspective of the spacing of the axial viewing lines and in alleviating the need to resort to oscillatory barrier motion in order to deal with image segmentation and barrier visibility issues). However, Ivanov's approach was not entirely straightforward for, as Valyus [1966] indicates, difficulties were experienced in uniformly tensioning the 30,000 wires used in the formation of the opaque regions.

4.4 CINEMA LAYOUT

The 1941 Moscow cinema was able to deliver glasses-free 3D content to ~384 people in a viewing hall measuring ~10 by 30m. In contrast, in his 1928 patent Noaillon suggests the adoption of a two tier approach (Figure 25). Here, members of the audience located in the upper tier view the screen indirectly via its reflection in the wall mounted mirror (7). However,

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[16] In US Patent 2,351,032 (filed in 1940), Dennis Gabor also considers ensuring that light emanating from the source is used to maximum efficiency in his lenticular-based projector system.

this approach is flawed and it is most unlikely that it would have produced a satisfactory glasses-free 3D experience.

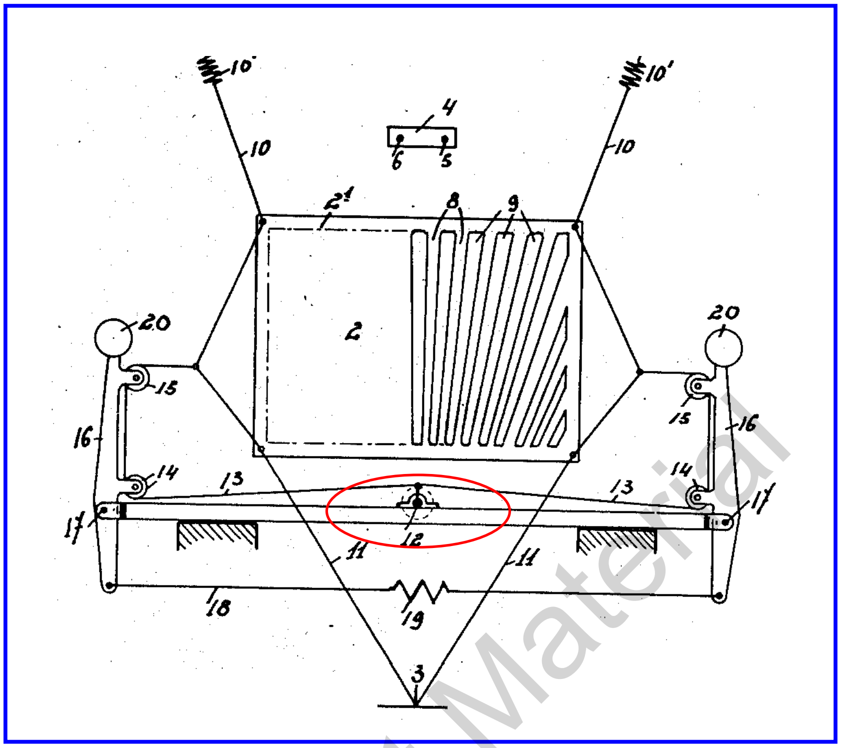


Figure 24: A mechanical system described by Noaillon in his 1927/28 patent in relation to the application of oscillatory motion to the radial barrier. Element 12 is a motor driven crank and causes the barrier to move with a sinusoidal velocity profile. (Reproduced from US Patent 1,772,782.)

5. GLASSES-FREE 3D IN RUSSIA: GENERATION II SYSTEMS (35/19)

On 20th February 1947 autostereoscopic 3D cinema re-opened in Moscow. The radial barrier was superseded by a more efficient radial lenticular configuration enabling audiences to enjoy brighter and more vibrant films. Initially, the screen size (measuring 3x3m) was significantly smaller than that used in 1941 but this was soon increased to 3x4m.[17] Exemplar cinema layout diagrams are presented in Figure 26 (also look ahead to Figure 42).

The overall techniques used in the implementation of radial barrier and radial lenticular based cinema are quite similar. Firstly, if extended, the imaging elements (slits or gofferings) meet at a common COC. Secondly, both forms of re-imaging subsystem employ a screen which is inclined relative to the barrier or lenticular panel in such a way that if extended, the two planes intersect on a horizontal line that passes through the centre of convergence (COC) – recall Figure 12. Both approaches give rise to a set of axial viewing lines which radiate from the COC.

[17] Valyus [1966] indicates that two prototype systems were implemented in 1943. One of these is reported to have employed a radial lenticular raster measuring 110x70cm comprising 2,000 - 3,000 gofferings.

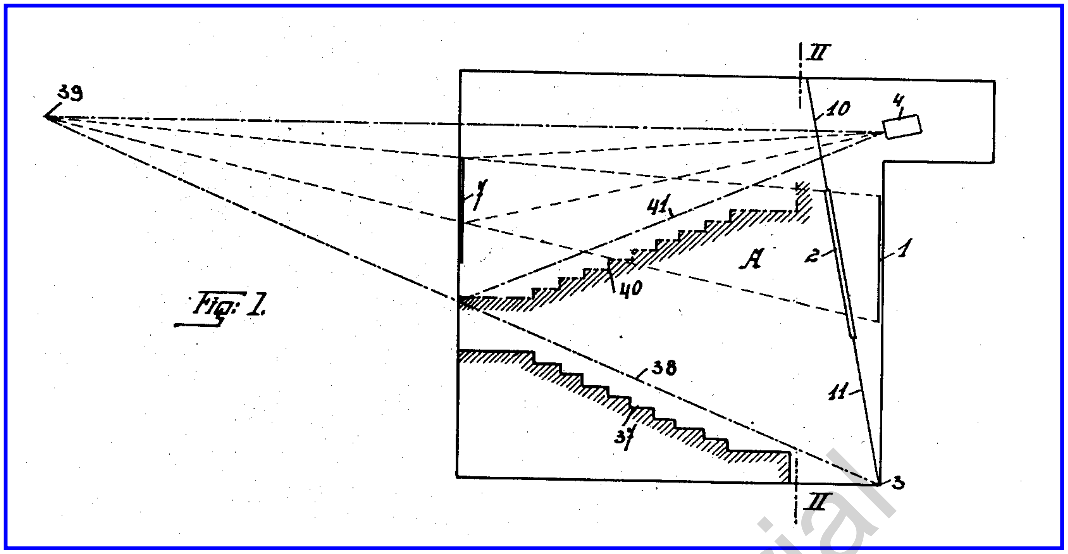


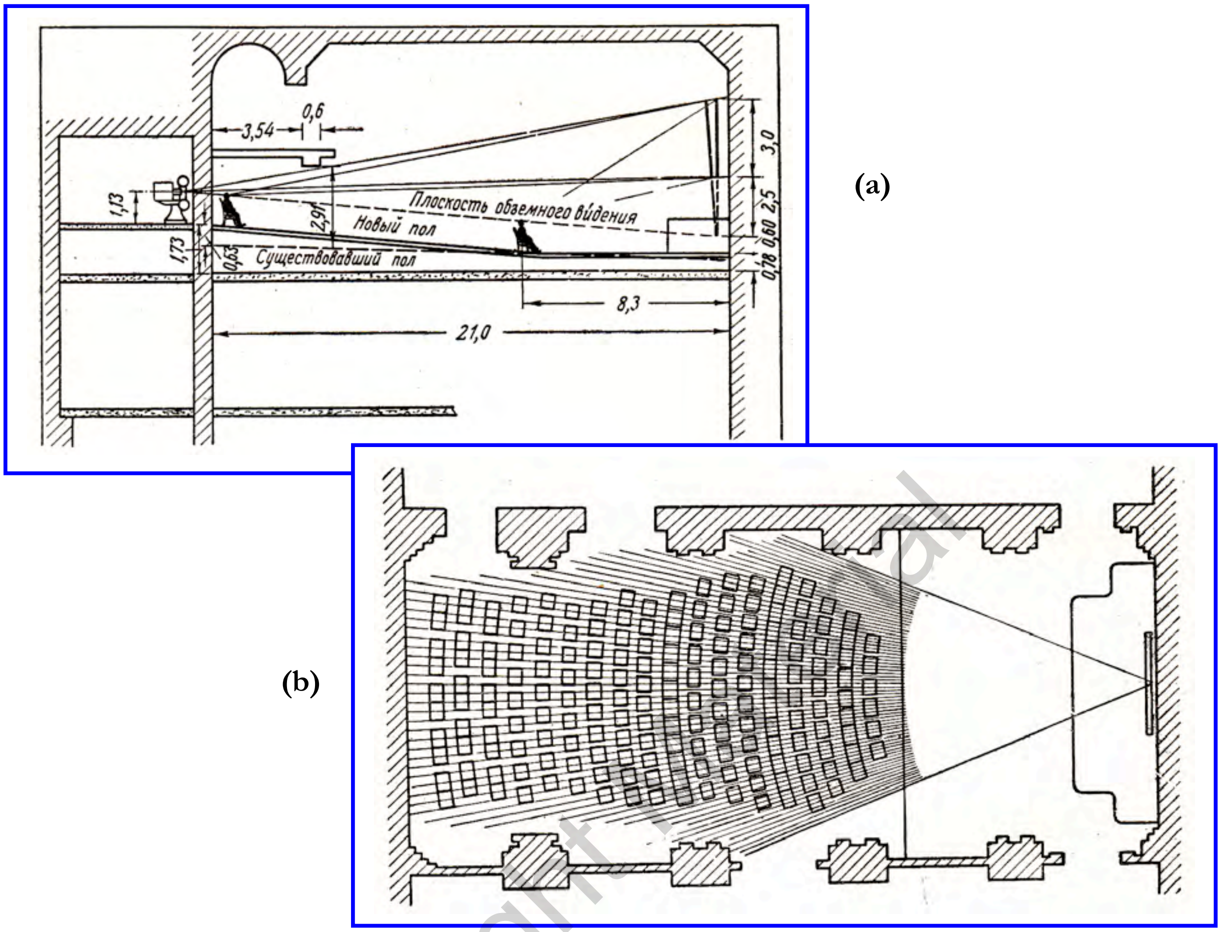
Figure 25: A side view of the general cinema layout described by Edmond Noaillon in his 1927/28 patent. The COC of the radial raster barrier (2) is located at (3). Light from the stereo projector system (4) is cast onto the barrier via a wall mounted mirror (7). The audience is seated on two levels (37 and 40). Those on the upper level view the screen via its reflection in the mirror. However, it is most unlikely that this indirect viewing approach could have provided a satisfactory visual experience. Lines (38) and (41) indicate the vertical locations of the axial viewing lines. (Reproduced from US Patent 1,772,782.)

The radial lenticular panel used in the re-opening of autostereoscopic cinema in 1947 was reported as being formed from a glass plate covered with a thin layer of corrugated gelatine. Since the screen and lenticule surfaces were inclined, it was necessary to construct each lenticule element so that its radius of curvature (and hence focal length) continuously varied along its length (see Figure 27). This approach ensures accurate focusing of the incident light onto the screen. Nikolai Valyus writes:

> '*Each lenticular element took the form of a thin slice cut from a transparent cone about 6m long and of base diameter 20 to 30cm. At the widest part the width was 2 to 3mm and the thickness about 8μ(m).*' Valyus (1966)

Exemplar discussion concerning the fabrication of a variety of micro-lens arrays is provided by Victor C.Ernst in a patent filed late in 1926 (see US Patent 1,849,036). This includes the formation of plano-concave and plano-convex gofferings (see Figure 28). The inventor focuses exclusively on fabrication details and makes no reference to the application of the various micro-lens structures described in his patent.[18]

[18] Also see Ives [1931] and [1932].



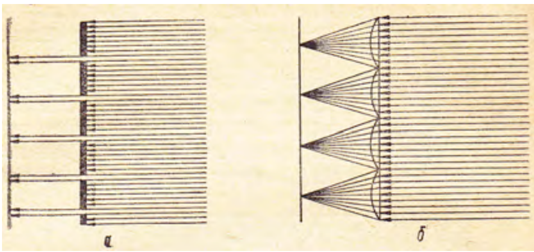
(a)

(b)

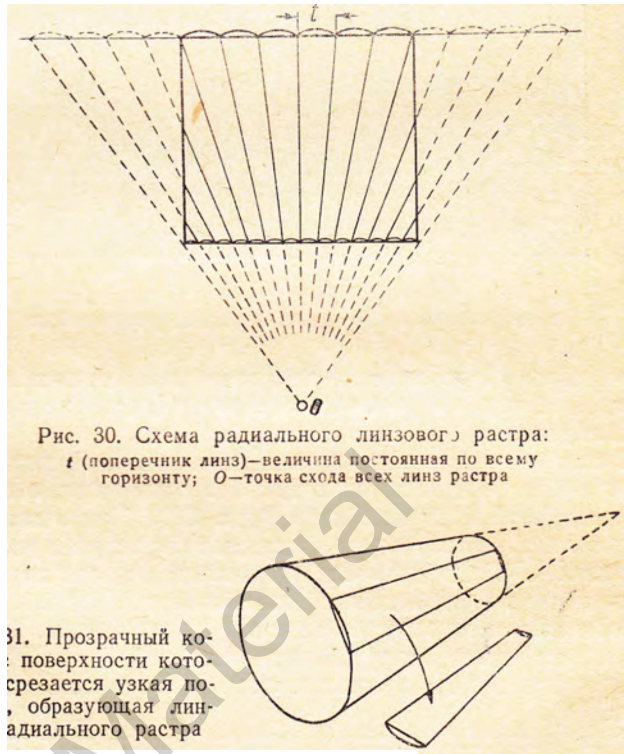
Figure 26: Russian cinema layout diagrams in side elevation (a) and plan (b) views. Also look ahead to Figure 42. (Diagrams reproduced from Ivanaov [1956].)

The general approach described by Ernst for the formation of the lenticular type optical structure depicted in Figure 28(b) is underpinned by the fabrication of a metallic mould of the form shown in Figure 28(a). A transparent malleable material such as celluloid is pressed into the mould thereby enabling the formation of convex lenticules. Concavities in the mould are formed by etching with a suitable acid. Naturally, it is necessary to limit contact between acid and metal to those regions requiring etching. Here Ernst describes in some detail the use of photographic techniques to create a mask on the surface of the metal. Central to this method is the use of a photosensitive emulsion which hardens in the presence of light. This enables the photosensitive material to be washed away from the areas in which etching is to take place and ensures that other areas of the metal are protected from the acid – see, for example, Figure 29. Unfortunately, this early approach provides little control over the cross-section of the micro-lenses.

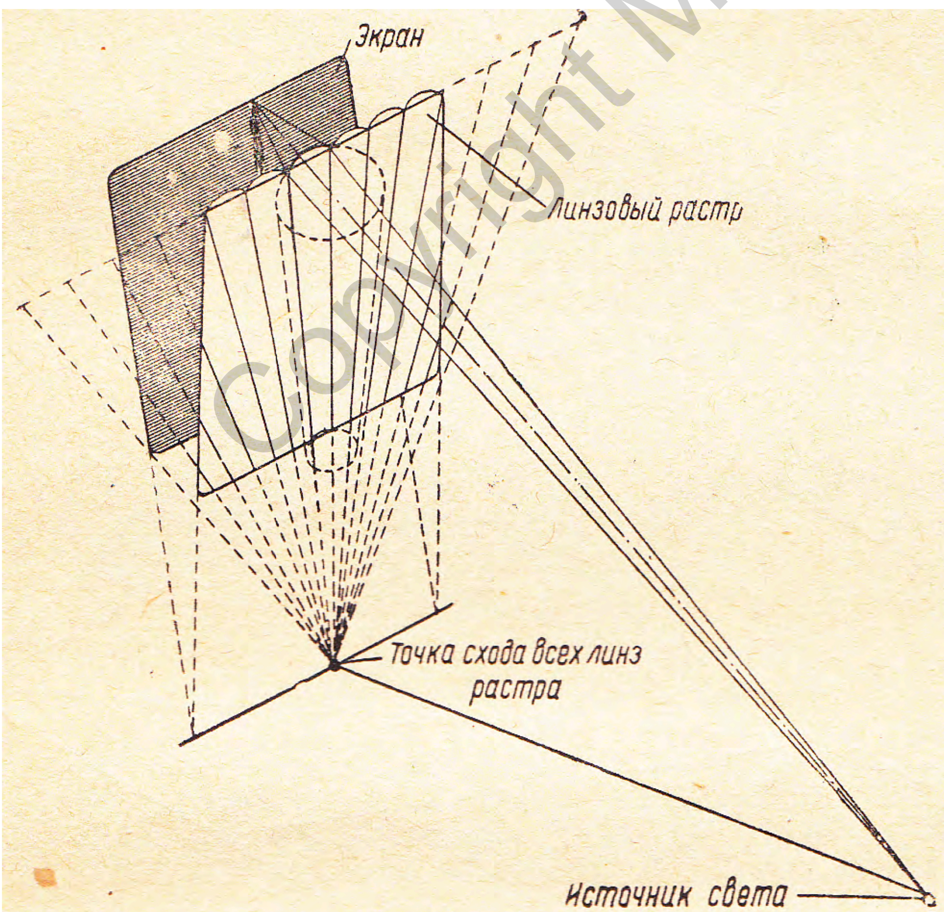
In 1965 S.P.Ivanov filed a US Patent describing techniques intended to support the formation of micro-lenses of predetermined cross-section. His method also supports the creation of non-transparent interspace regions (between the micro-lenses) - so ensuring that when in use only light incident on the micro-lenses can pass through the panel. In the patent the inventor includes brief discussion on the fabrication of the radial raster form of lenticular structure. (See US Patent 3,582,329).



(a)

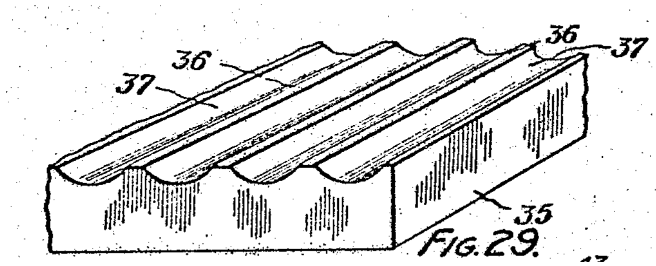


(b)



(c)

Figure 27: In (a) the light transmission capabilities of barrier and lenticular approaches are compared. Diagrams (b) and (c) summarise aspects of the radial lenticular geometry. The shape of each lenticule corresponds to a section from a cone and so the radius of curvature continuously varies over a lenticule's length. (Diagrams reproduced from Ivanov [1951].)



(a)

(b)

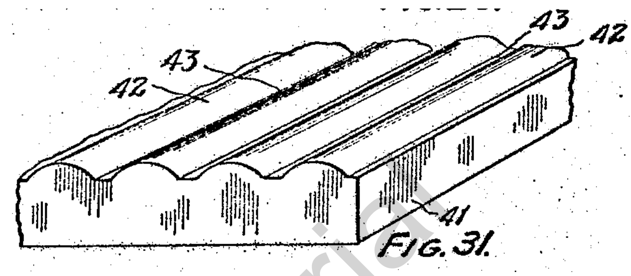


Figure 28: Greatly enlarged drawings of fragments of (a) plano-concave and (b) plano-convex lenticular panels. The fabrication of a range of micro-lens structures is described by Victor C. Ernst in a patent filed in 1926. (Reproduced from US Patent 1,849,036.)

As discussed previously, a key difficulty associated with the barrier approach is that it exhibits low transmission efficiency. When a projection technique is employed, the light must traverse a barrier twice and so in the case that $\xi/p{\sim}1/3$, in excess of 80% of the incident light may be lost. Noaillon's use of lightbands (Section 4.2) can in principle halve this loss – but at a cost of increased system complexity. However, when the radial barrier is replaced by the equivalent lenticular panel, transmission losses are much lower and hence for a given level of illumination brighter images can be obtained.

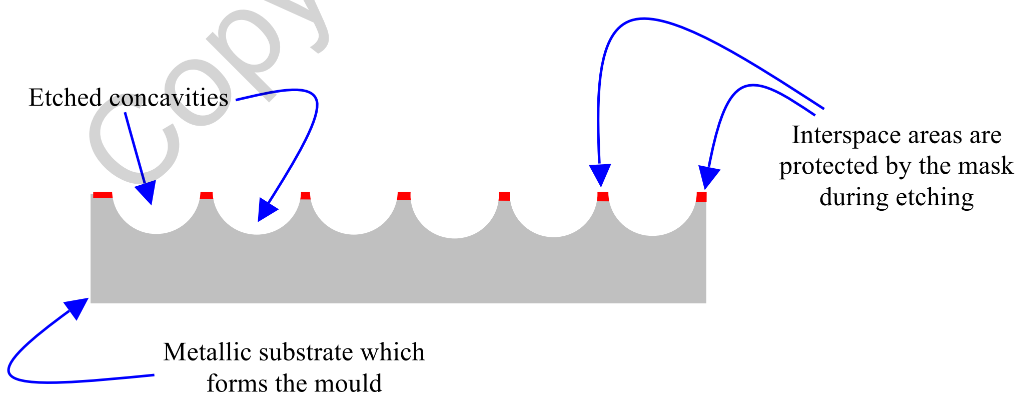


Figure 29: In his 1926 patent, Ernst describes the use of an acid resistant mask to support the formation of a metallic mould. Once the mask has been deposited, a suitable acid is used to etch the concavities. Subsequently, a set of lenticules may be created by, for example, pressing an appropriate malleable transparent material into the mould.

In comparison to the radial raster barrier, the lenticular arrangement is able to support the formation of more sharply focused and narrower image strips on the screen. Consequently it is quite feasible to employ a plurality of image projectors such that each projector pair depicts the 3D image scene from a slightly different vantage point (in the horizontal plane). In this scenario, the image focused onto the screen by each goffering no longer simply comprises a strip through the left hand stereo view together with one through the right hand view but rather a set of image strips, each element of which maps to a specific projector. Thus the transition from radial barrier to the radial lenticular configuration made it possible for Russian researchers (at least in principle) to provide limited support for the motion parallax cue – enabling cinema audiences to shift lateral position and observe a 3D scene from different vantage points.[19]

6. NOAILLON'S MECHANICALLY COMPLEX BARRIERS

Throughout the 1930's Edmond Noaillon continued to refine the radial raster barrier method and filed several patents in the area. Of particular interest is a patent filed in October 1933 (British Patent 432,185) in which he focuses on the variations in barrier pitch which occur when a barrier is subjected to rotational motion about the COC. Figure 30 extends Figure 9(b) and shows three indicative radial lines before and after barrier rotation. The radial lines (blue) define indicative slit locations prior to barrier rotation. We assume that before displacement the radial raster exhibits constant pitch over any horizontal cross-section and so the blue lines intersect the line MN at equal intervals denoted p. The broken red lines indicate the respective positions of the blue radial lines after their rotation through an angle ψ about the COC.

Applying the Cosine Rule, in relation to the n^{th} radial line, we can write:

$$p_n^2 = R_{n-1}^2 + R_n^2 - 2R_{n-1}R_n \cos\phi_n,$$

where R_n and R_{n-1} denote the lengths of the n^{th} and previous (n-1) radial line segments as measured from the COC through to the point at which they each intersect the line MN. These lengths may be expressed as:

$$R_n = \frac{\sigma}{\cos(\psi + \theta)}, \qquad \text{where } \theta = \sum_{i=1}^{n} \phi_i.$$

Similarly:

$$R_{n-1} = \frac{\sigma}{\cos(\psi + \theta)}, \qquad \text{where } \theta = \sum_{i=1}^{n-1} \phi_i.$$

Thus the barrier pitch p_n (as measured along the horizontal line MN) varies with the rotation angle ψ and so is no longer constant. In the case that the radial raster undergoes oscillatory motion over small angles then this effect may be neglected but, as mentioned in Section 4.1, it is likely that in practice Noaillon would have been forced to adopt a significant angular displacement of the barrier in which case the effect of pitch variations may have had a

[19] Support is restricted to motion in the horizontal plane. This is frequently referred to as HPO (horizontal parallax only). In Blundell [2011b] it is termed H,POD (horizontal parallax for observer dynamics).

noticeable visual impact. With inventive spirit Noaillon endeavoured to resolve this matter using a more mechanically complex form of barrier (see Figure 31).

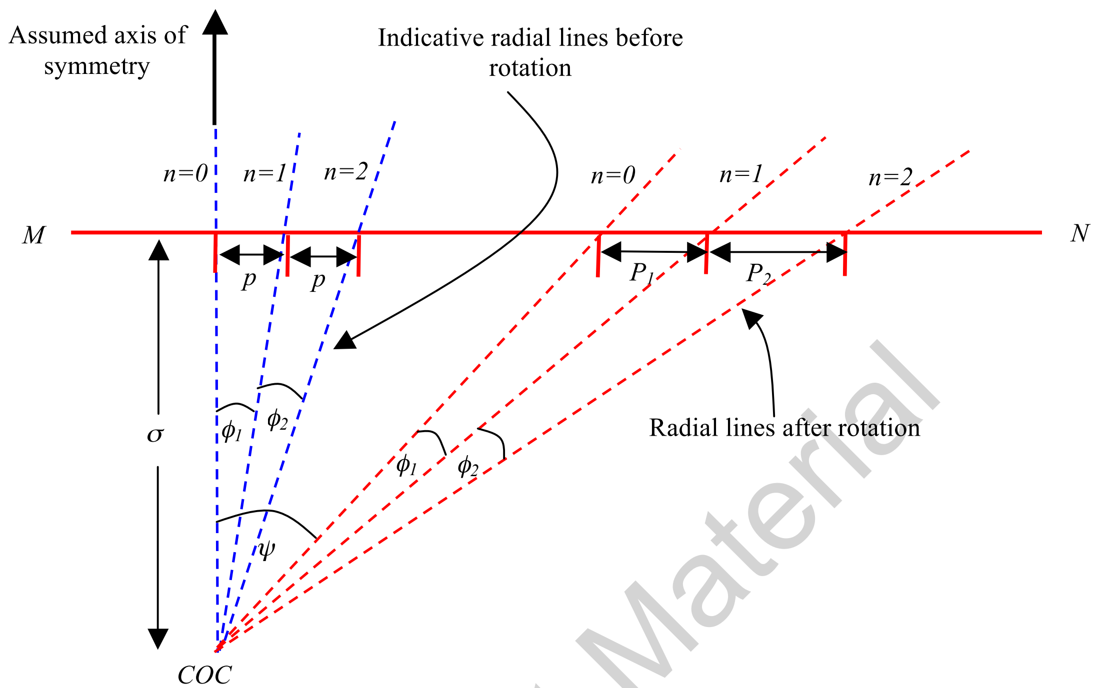


Figure 30: Here we adapt Figure 9(b) so as to consider the rotation of the radial raster. Prior to rotation the indicative radial lines (blue) intersect MN at constant intervals (p). We use the integer n as an index to the radial lines and as a subscript when referring to both their relative angles and the pitch values generated as a result of the rotation of the barrier. The broken red lines indicate the positions of the radial lines after rotation through an angle ψ about the COC. The separation of the points at which adjacent radial lines now intersect *MN* is denoted p_n where $p \neq p_n$. Extending this to other radial lines it is apparent that the constant pitch of the radial raster becomes non-uniform when the raster is rotated about the COC. This was recognized by Noaillon in his 1933 patent application where he describes a mechanically complicated radial barrier (Figure 31) intended to ensure that the impact of barrier rotation on pitch (as measured in horizontal cross-section) is reduced.

Unperturbed by the increasing complexity of his barrier designs, in June 1937 Noaillon filed a further patent (see British Patent 496,971 and also US Patent 2,198,678) detailing an oscillating mutli-layer radial barrier. Figure 32 identifies the three layers that form the barrier assembly (denoted 2, 1 and ½) together with the location of the screen (4). The COC is at *O* and the two projectors (9 and 10) which generate the two views comprising the stereopair are located at the rear of the auditorium. Labels A-A-3-3 identify the plane passing through the set of axial viewing lines.

Figure 33 illustrates the underlying principle on which Noaillon's patent is based. This plan view depicts a fragment of the screen and multi-layer barrier together with the horizontal line (3) which passes through the locations of the projectors and lies parallel to the plane of the screen (equivalent to line *AB* in Figure 16). The right hand projector (9) is identified with an asterisk and the left hand projector (10) by a circle. This same form of identification is used on the screen to indicate the respective regions that are illuminated by each projector and also to indicate the extent to which these regions are visible from two positions along the horizontal line (3).

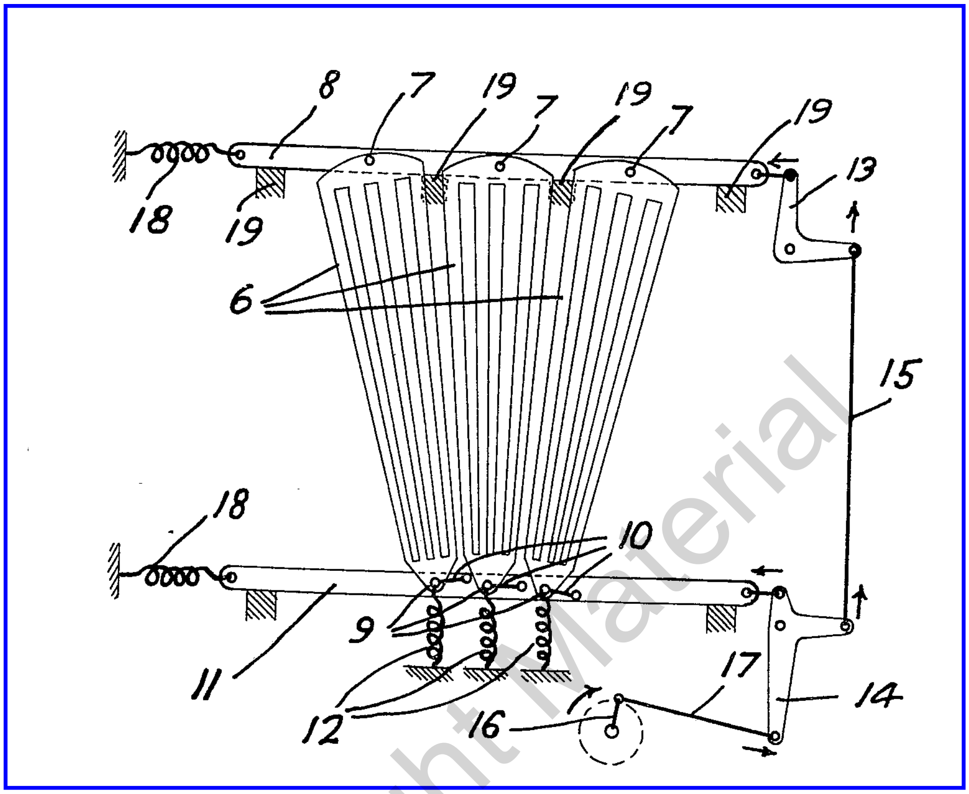


Figure 31: A fragment of the radial raster barrier disclosed by Edmond Noaillon in his 1933 patent application. The radial slits are formed in groups of three by means of thin metallic frames (6). These are attached to two horizontal bars (8 and 11). A crank (16) is driven by a motor and the mechanical linkages cause the upper bar (8) to rapidly undergo translational motion. The lower bar (11) moves with a smaller displacement such that the ratio of the amplitudes of their motion equates to the ratio of their relative distances from the COC. The implementation of the frames (6) so as to group slits was most probably intended to facilitate assembly. Note that the frames (6) are pivoted to the top bar whilst, most importantly, at the lower end they are attached to the bar (11) indirectly via spring loaded linkages (10). Unfortunately, this approach appears to represent only a partial solution. (Reproduced from British Patent 432,185.)

Noaillon manually estimated the profiles of these visibility regions by summing the widths of the set of illuminated strips which are visible from different locations in the area of two exemplar axial viewing lines. As may be seen, in both cases the dominant left and right hand views overlap and peripherally there are two minor regions from which the left and right views are visible. In this latter case, the positioning of the two views is reversed relative to that of the dominant regions of visibility. Areas of overlap signify regions in which the left and right views are simultaneously visible and so the extent of these regions should be minimized. Indeed correct stereo viewing is achieved by positioning one eye within the region whose extent is denoted g (or g') and the other eye in that labelled d (or d'). In order to maximise viewing freedom around each of the axial viewing lines Noaillon sought to develop a barrier system which would maximise d (and d' etc.) and minimize t (and t' etc.).

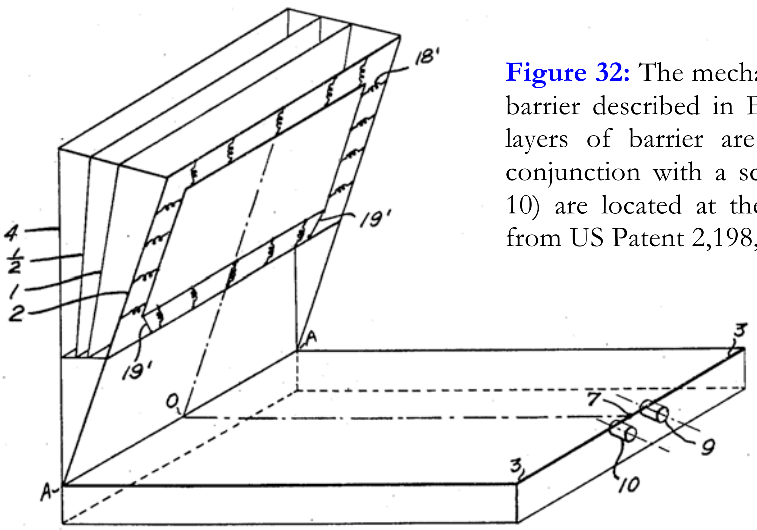


Figure 32: The mechanically complex multi-layer radial raster barrier described in Edmond Noaillon's 1937 patent. Three layers of barrier are employed (labelled 2, 1 and ½) in conjunction with a screen (4). The stereo projectors (9 and 10) are located at the rear of the auditorium. (Reproduced from US Patent 2,198,678.)

In terms of its implementation, the multi-layer barrier comprises three sets of radial rasters. In the case of the front most raster (2), the barrier strips are of constant width – as measured along any horizontal cross-section. This also applies to the middle radial raster (1). However, the radial raster (1/2) located closest to the screen (4) is of an unusual design in that it is formed from strips that alternate between two widths. The adoption of this form of raster was intended to meet the objectives of maximising d (and d' etc.) and minimising t (and t' etc.). In addition Noaillon sought to create barrier layers which would enhance the sharpness of the strips illuminated on the screen by minimizing the extent of surrounding penumbra.

In parallel, so as to reduce the visibility of the barrier, Noaillon again resorted to the use of oscillatory motion – a technique that would surely have been more difficult to successfully implement given the increased mass of the multi-layer barrier assembly. Figure 34(a) illustrates the suspension of one barrier layer. From this diagram it would appear that Noaillon's aim was to suspend the barrier in a way that would allow him to capitalize on the system's natural frequency of vibration.

Noaillon's recourse to barrier motion should certainly not be dismissed for as briefly outlined in the next section (and elsewhere in this book) other more recent systems have capitalized on this technique.

7. THE CYCLOSTEREOSCOPE

Noaillon's concept of introducing oscillatory barrier motion about the COC was well founded but, as previously mentioned, when it came to turning theory into practice, progress was surely hampered by significant and frustrating implementation issues. Interestingly, Noaillon's family demonstrated a long-term commitment to his work as in 1963 his widow, Henriette Louise Marie Lamare, and daughter Monique Noaillon filed a further related patent (see US Patent 3,196,456).

As previously discussed, in the case of coarse raster barriers such as those described by Noaillon, key objectives for introducing barrier motion were to eliminate barrier visibility and avoid segmentation of the displayed image scene. In these respects, Noaillon's goals were soundly based and primarily floundered as a consequence of his use of reciprocating motion.

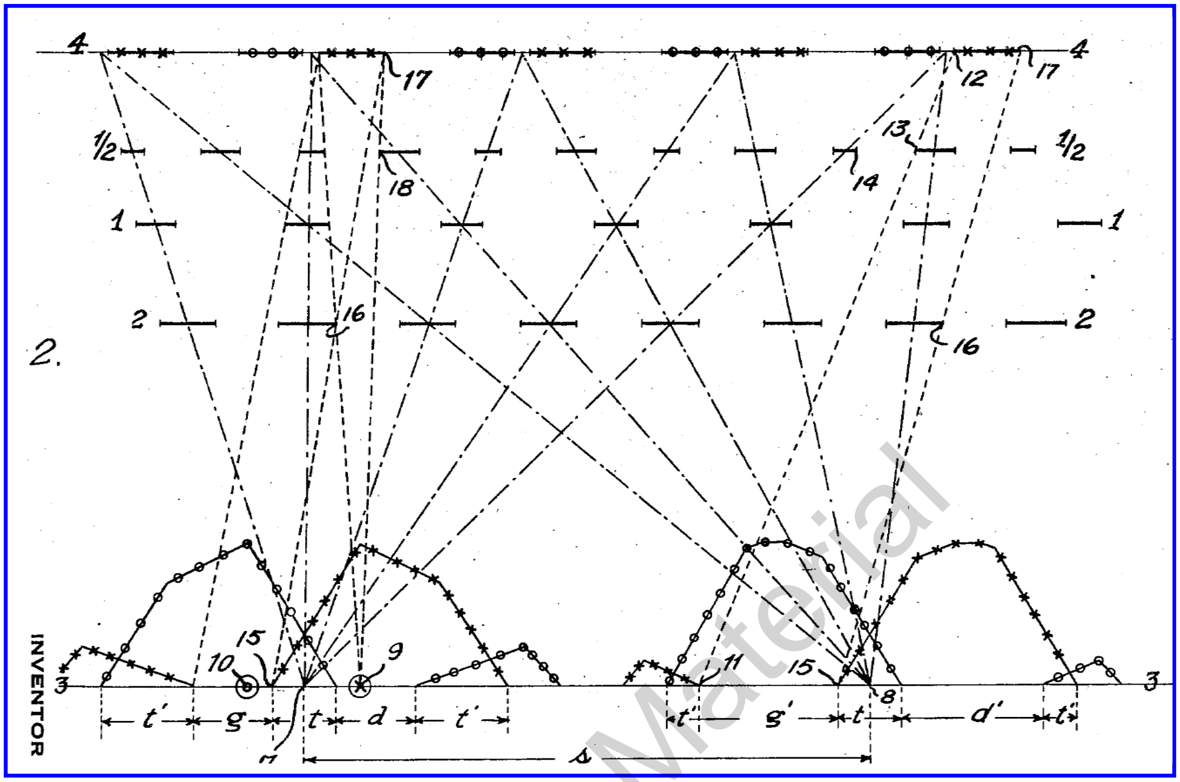


Figure 33: A plan view showing a cross-section through a fragment of the multi-layer radial barrier and screen (4). The projectors (9 and 10) which generate the stereopair are distinguished by a circle and asterisk. (Reproduced from US Patent 2,198,678.)

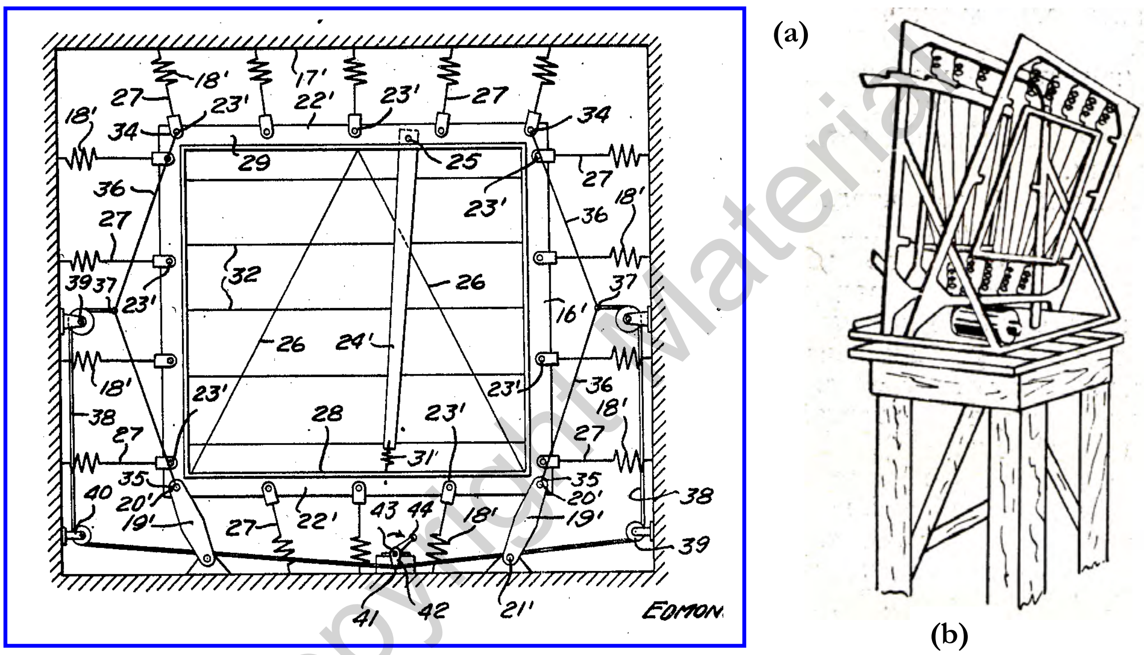
Today, the oscillatory motion of parallax barriers (which are admittedly much smaller than the radial barriers that formed the focus of Noaillon's work) may be achieved without recourse to mechanical means. Here, the barrier may be implemented using a liquid crystal panel in which case the location of the transparent and opaque regions can be defined electronically. This general approach makes it possible to switch areas of a display screen between 2D and 3D modes of operation (see, for example, Lueder [2012]). Alternatively, when used in association with vantage point tracking systems, the ability to vary barrier characteristics makes it possible to optimize display performance according to the location of the user (see, for example, Schreer *et al.* [2004]).

When used in conjunction with opto-electronic displays, cyclic barrier motion can ameliorate a weakness of autostereoscopic systems employing the spatial coding technique. Specifically, the pixel bandwidth (B_p) of the display is shared between the left and right stereo views and so each eye is presented with the visual output from $B_p/2$ pixels. In a more general case consider a parallax barrier-based display that outputs n stereoscopic views of an image scene (thereby providing limited support for motion parallax in the horizontal direction (H,POD)). Each view is now formed from $B_p/2n$ pixels. In principle, barrier motion (which may be achieved through physical barrier movement or, in the case that an LCD panel is employed, may take the form of virtual motion) can be used to enable all (B_p) pixels to contribute to each view – although this assumes that the display is able to support a sufficiently high frame rate (see, for example, Kalai and Siegel [1998]).

Barrier motion has also underpinned the operation of several other forms of autostereoscopic display. In this section, we focus on the Cyclostereoscope[20] which is an example of a highly innovative display technique invented by Francois Savoye, a member of the Commission of Colour and Relief of the French National Cinema Centre. The interested reader is also referred to the Appendix where we briefly review an earlier approach in which Savoye applies rotational motion to a cylindrical barrier structure.

In his book '3D Kinematography', Adrian Cornwell-Clyne [1954] writes:

> '*Savoye's Cyclostereoscope represents the most successful attempt so far to solve the problem of true autostereoscopy. The observer requires no viewing aid and the rotating grid works its magic.*'



(a)

(b)

Figure 34: In (a) the support and drive system surrounding Noaillon's raster screen assembly. Element 24' represents one of the opaque members from which each layer of the barrier is formed. The drive stimulus is derived from element 42 and is applied to the barrier assembly via cables (38). Linkages (19') ensure oscillatory motion about the COC. Cables (26 and 32) increase the rigidity of the assembly. In (b) a sketch of experimental apparatus employed by Noaillon in designing a multi-layer form of radial barrier. (Diagram (a) reproduced from US Patent 2,198,678 and diagram (b) reproduced from Ivanov [1945].)

Certainly the technology gained considerable attention – below is a loose translation of an extract from an article appearing in Paris Match [1954]:

> '*Francois Savoye's apparatus – the Cyclostereoscope – is already known by a few Parisiens. In fact, a little after the war, its inventor installed a small stand at LunaPark and there he presented films in relief. For ten years Francois Savoye has worked to perfect his apparatus.*

[20] The work of Alexandre Fillippi and Jean Colas is reviewed in another chapter.

One auditorium in Paris – the Clichy-Palace which has 1,000 seats – is in the process of being equipped with a Cyclostereoscope. Its owner, Monsieur Kowlowski, member of the Superior Technical Commission for cinema, has completely transformed his auditorium to accommodate the special equipment which weighs 1 tonne. The inauguration will take place in a few weeks. Completely enveloping the screen – base 6m 50cm – is a selector grill [radial raster barrier] *in the form of the truncated cone which will rotate at a speed of 15 turns per minute…'*

Some ten years earlier, the inventor filed patents in both the UK and US (see British Patent 607,961 and US Patent 2,441,674) in connection with the Cyclostereoscope and in the text that follows we focus on the former.[21] This display is fundamentally based on the principle of Noaillon's radial barrier - although as illustrated in Figure 35, the barrier is no longer planar and takes the form of a frustum of a cone. If extended, the trapezoidal opaque and transparent barrier strips meet at the cone's apex – which is consequently the location of the COC. A stationary screen is positioned *inside* the barrier and is located on a diametric plane.

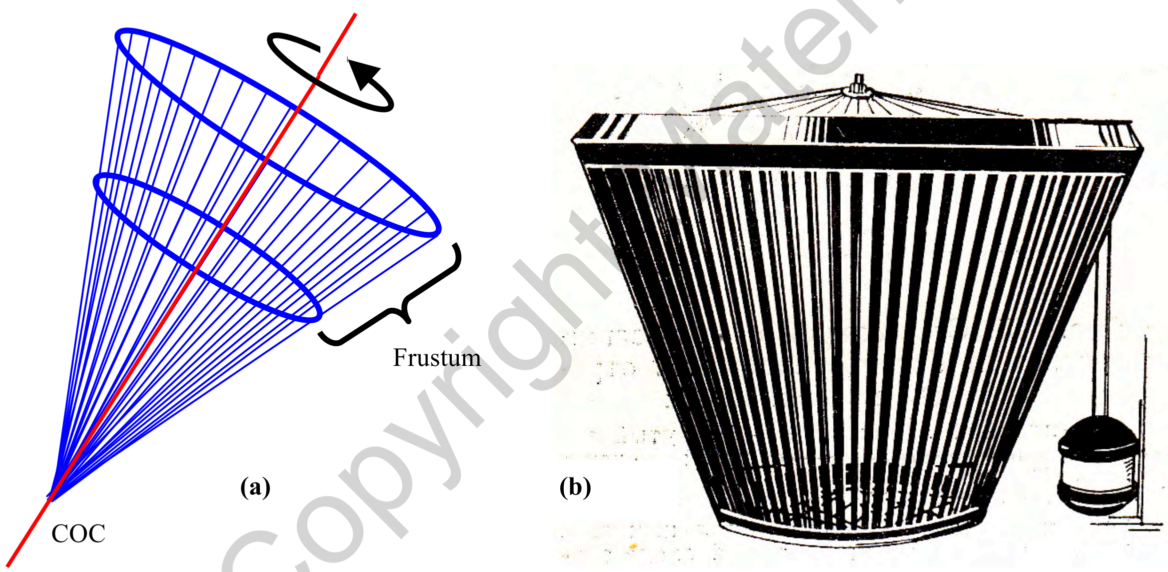


Figure 35: Central to the Cyclostereoscope is a radial barrier. This takes the form of a frustum of a cone and if extended the barrier slits converge to the cone's apex. This is therefore the location of the centre of convergence (COC). (Image (b) reproduced from Ivanov [1956].)

In Figure 36 a diagram from Savoye's British patent is reproduced and gives an overview of a particular embodiment of the Cyclostereoscope. In the diagram, *O* denotes the location of the COC and the line *OX* is the axis about which the barrier rotates. The motor (*m*) is located below the frustum and is used to rotate the barrier and drive the stereo projector (*p*). For convenience, the left and right stereo views are reflected by a mirror (*m*) onto the rotating barrier and thence to the stationary screen.

[21] Note that although these two patents describe the same technology, there are some differences in content.

In common with the radial barriers employed by Noaillon and Ivanov *et al.* the conical barrier generates a set of axial viewing lines which radiate from the COC. The vertical position and orientation of these lines is indicated by OS_2 (which connects the COC to point 3 (representing the point from which light emanating from the mirror (and cast onto the barrier) appears to originate)). Thus seating is arranged so as to place each spectator's eyes within close proximity to one of the axial viewing lines which lie in the same horizontal plane as OS_2.

For simplicity let us initially put barrier motion to one side. The configuration of the projection system described in the patent is such that it casts light onto the screen through the lower part of the barrier – whereas spectators view light emanating from the screen through the upper part of the barrier.[22] Consequently, as is evident from Figure 35(b), the width of the transparent and opaque regions which impact on the passage of light travelling from projector to screen differ from those encountered by light emerging from the screen. This is in contrast with the manner in which the barriers employed by Ivanov and Noaillon were employed (both arranged for incident and emergent light to pass through identical barrier geometries).[23]

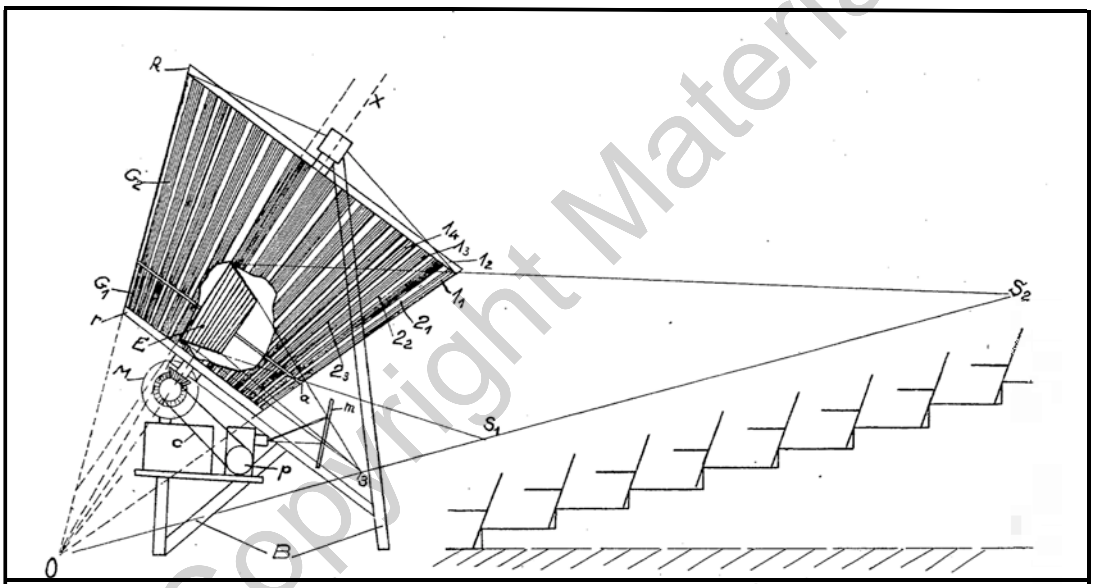


Figure 36: The general configuration of the Cyclostereoscope as described in Savoye's 1945 patent. (Diagram reproduced from British Patent 607,961.)

Thus in the case of the configuration described in Sayoye's British patent we can consider the two portions of the barrier as performing separate functions. Namely the lower part of the barrier carries out a coding function by re-imaging the output from the stereo projector onto the screen, whereas the upper part of the barrier performs a converse decoding function and ensures that the images are correctly distributed to the audience. As outlined in the Appendix,

22 This approach ensures that the light emanating from the projector is not directly cast onto the portion of the barrier through which the audience views content. (Recall Noaillon's efforts in reducing barrier visibility by minimising or re-directing reflected light in such a way that it was not visible to the audience.)

23 However, in the context of cinema, when a projection system is implemented such that the screen is illuminated from one side and viewed from the other, then the light must traverse two separate barriers. In this scenario the barriers could, in principle, exhibit different geometries.

the use of different barrier geometries for light travelling towards and away from the screen is a theme of Savoye's earlier patent which discloses the use of a cylindrical barrier.

Consider two viewers – one seated on the front row (S_1) and the other at a more distant location (S_2). In watching the screen, the two people will look through different parts of the barrier such that the further that viewer is from the screen (and hence the higher their seating), the wider are the opaque regions which obstruct the passage of light from screen to their eyes. Figure 37 provides a plan view in which the two concentric circles on the left represent the upper and lower ends of the barrier. Lines (blue) extending from S_1 and S_2 intersect the vertical edges of the screen and so form two triangles. The interior angles of these triangles at S_1 and S_2 denote the angles subtended at the eye by the screen. Since viewing locations S_1 and S_2 are at different heights, it follows that the lines drawn from S_1 intersect a lower part of the barrier (where the opaque regions are narrower) and the lines from S_2 pass through a higher part of the barrier (where the opaque regions are wider). With judicious design (which includes the need to tilt the barrier's axis of rotation towards the audience), it is possible to ensure that from these vantage points (and intermediate vantage points) viewers see the screen through an equal number of transparent slits. This suggests that from both locations the viewer will (in principle) be presented with image content that has the same horizontal extent and to which the barrier is able to have equal effect in passing the left and right stereo views. This is discussed by Savoye in his patent – although it should be noted that it is only fully applicable to more central viewing locations.

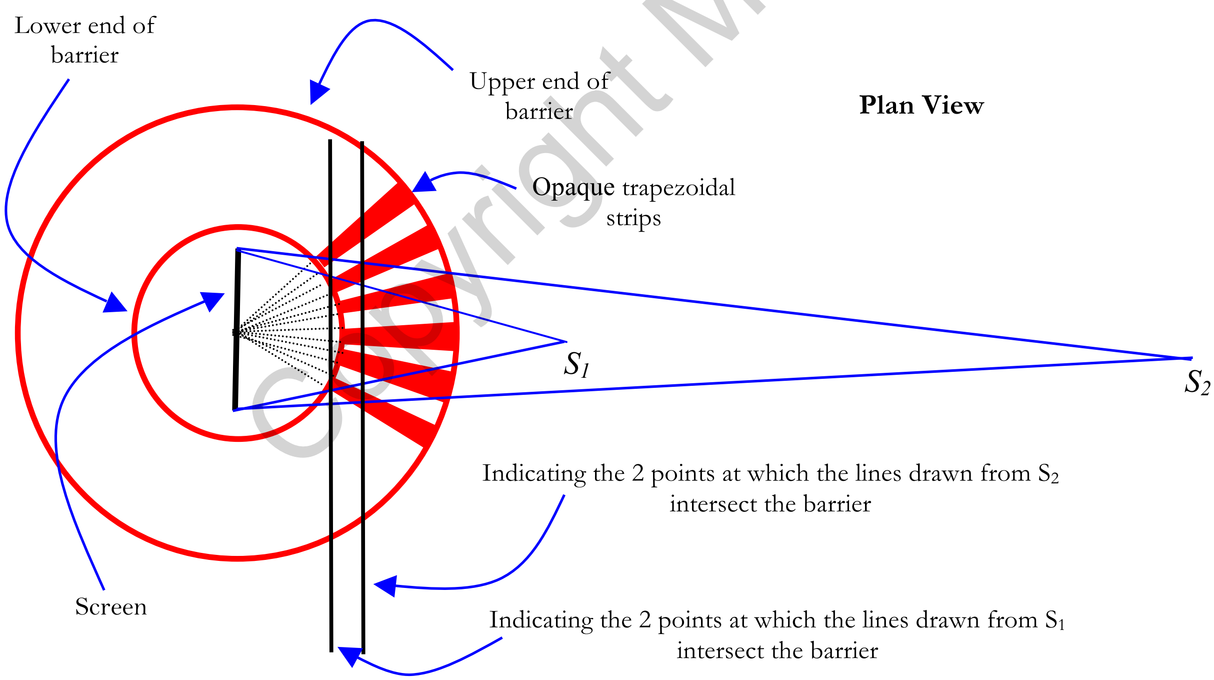


Figure 37: Indicative plan view showing two viewing locations. S_1 denotes a front row position and S_2 is a more distant location. The blue lines indicate the angle subtended at the eye by the screen. The vertical black lines show the assumed locations at which the blue lines intersect the barrier (bearing in mind that location S_2 is higher than S_1). Thus viewers at S_1 and S_2 see the screen through an equal number of transparent slits. However, this does not apply to all viewing locations.

Recall (Figures 9(b) and 30) that Noaillon went to considerable lengths to ensure constant raster pitch (as measured over any horizontal cross section). In contrast when Savoye's conical barrier is projected onto a vertical plane, the raster does not exhibit constant pitch over any horizontal cross-section. In essence, this non-uniformity denotes an approximately constant variation from the ideal case – whereas in contrast, the approach adopted by Noaillon gave rise to continuously changing and significant variations. Unfortunately, without viewing a Cyclostereoscope in operation, it is difficult to fully appreciate the extent to which this geometrical consideration negatively impacts on perceived 3D image quality.

In the absence of barrier rotation, the trapezoidal profile of the opaque strips would cause more distant members of the audience to experience more severe image segmentation. However, a key feature of the Cyclostereoscope relates to its ability to effectively capitalise on barrier motion and circumvent the difficulties that Noaillon experienced in implementing a reciprocating form of barrier movement. In the case of the Cyclostereoscope, the barrier rotates with uniform angular speed about its central axis. In terms of eliminating the visibility of the coarse barrier structure and reducing/eliminating image segmentation, this achieves the result sought by Noaillon.

The rotational frequency of the barrier is determined by (a) the speed at which the opaque slits need to travel in order that they are no longer visible, (b) the speed at which image content must be presented to the human visual system so as to ensure fusion - and hence the elimination of perceived (barrier-based) segmentation. Consequently, in principle, the rotational frequency can be reduced as the barrier diameter is increased. Additionally, the frame rate of the projector system T_p must be synchronized with barrier rotation such that the period of barrier rotation (T_b) is an integer multiple of T_p.

Figure 38(a) provides a further insight into the operation of the Cyclostereoscope. Here, the left and right views of the stereopair are shown projected from *P* and *P'* through barrier slits to the edges of the screen. Locations labelled *og* and *od* denote exemplar positions from which these views are visible. On first inspection, this diagram can appear to be slightly confusing since both the left and right views are shown projected to the same screen locations. However, recall from previous discussion (summarised in Figure 22) that barrier motion causes a continuous exchange of corresponding image strips from the left and right-hand stereoviews. Consider the case that the frustum is equipped with n_f opaque strips and rotates at a frequency f_f. The rotating barrier will allow corresponding image strips of the left and right stereo images to occupy the same spatial position on the screen – but will ensure that they are separated in the temporal domain with each able to occupy the position for a time T_s – such that:

$$T_s = \frac{1}{2n_f f_f}. \tag{10}$$

Consequently, Figure 38(a) should be interpreted as providing an indication of both the spatial and temporal aspects of the system. For a small version of the Cyclostereoscope (supporting a screen measuring 18x24 inches) Jennings and Vanet [1952] indicate a rotational frequency of ~4Hz. The general specifications of this system are summarised in Table 2 – and as may be seen, this model employs a frustum comprising 108 opaque strips. From Eq.10, it follows that T_s~1.2ms. In Table 3 summary information is presented concerning four commercial models of Cyclostereoscope that were available in ~1952.

Parameter	Indicative Value
Screen size	18x24 inches
Cone (diameter at top)	36 inches
Rotational frequency	4Hz
Cone angle to central axis	20°
Number of opaque strips	108 (aluminum)
Gap to strip ratio (top)	3:5
Gap to strip ratio (bottom)	2:5
Zones of vision	~4°
Overall operating field	~40°
Correct range of viewing distance	5 to 12 feet

Table 2: Design data for a small version of the Cyclostereoscope. (Source Jennings and Vanet [1952].)

8. GABOR'S EARLY WORK

Dennis Gabor's pioneering work in the development of holographic imaging is widely recognized and the brief paper (Gabor [1948]) in which he first elucidated the principles of holography must now figure highly on the citation index for research publications[24]. Gabor was a prolific scientist and engineer and unfortunately key work that he carried out across a diverse range of subjects is less well known. This includes his innovative work in developing techniques able to support viable glasses-free 3D cinema.

In extensive British and US patents filed in 1940 (British Patent 541,751 and US Patent 2,351,033)[25], Gabor provides an in-depth account of a projection based system employing a parallel set of lenticules capable of not only meeting the fundamental requirement of supporting 3D viewing across the length and breadth of an auditorium – but of also supporting audiences located on two levels (traditionally often referred to as the 'pit' and 'gallery'). In parallel, he filed a related patent (US Patent 2,351,032) detailing a camera and projector system which made use of lenticular film (the gofferings being located in the horizontal plane). This was intended to enable the left and right stereo views to be recorded in a single image frame.

Suggested Audience Size	Screen Size (cm)	Upper Cone Diameter (cm)	Lower Cone Diameter (cm)
8-10	45x34	65	35
15-20	70x50	94	54
30-40	100x75	145	84
70-90	150x100	215	120

Table 3: Commercial versions of the Cyclostereoscope glasses-free 3D display produced by Anciens Etablissements A. Mattey of Paris *circa* 1952. By today's standards the screen dimensions are small for the suggested audience sizes. (Source Linssen [1952].) [26]

[24] In fact for over a decade, Gabor's original publication attracted very little attention. It was not until the development of the laser that holography became a truly practical proposition.

[25] Also see related US Patent 2,351,034.

[26] In fact, Linssen [1952] quotes upper and lower barrier *circumferences*. Clearly this is in error and so in the above table 'circumference' has been amended to 'diameter'.

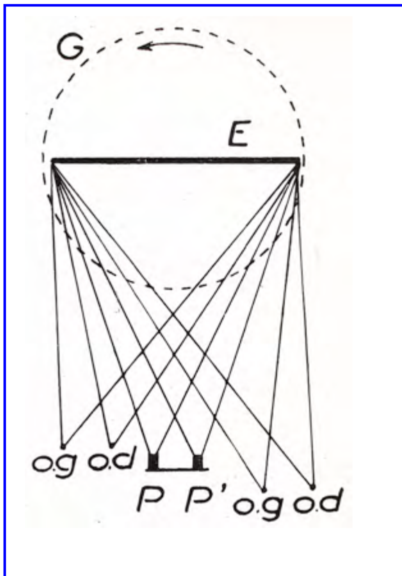


Figure 38: Diagram (a) provides a further insight into the operation of the Cyclostereoscope. Here, *P-P'* denotes the locations from which the left and right stereo views are projected. Locations *og* and *od* indicate exemplar positions from which the 3D image may be observed. See text for discussion. In (b) a view of an image as seen through the barrier.

(a)

(b)

Gabor's interest in glasses-free 3D cinema was not short lived, and in the mid 1960's he filed other patents in the area. In this Section we focus on aspects of his early work (specifically material disclosed in British Patent 541,751 and US Patent 2,351,033)[27] and provide a more detailed review of both his early and later work in Chapter 5.

From the outset, Gabor considers the design of the screen/re-imaging subsystem in terms of two key functions that act on the images formed at the projector aperture. In terms of glasses-free 3D cinematic projection, there is firstly a need to replicate these images and secondly, each copy must be mapped to the appropriate 'column' of spectators (here the seating plan is specified in terms of rows and columns). Gabor refers to these as 'multiplication' and 'spreading' functions. Both the traditional parallax barrier and lenticular panel approaches (employing parallel lenticules) are able to satisfactorily perform the multiplication function but are deficient in terms of the spreading function (recall that in both

[27] Also filed in Canada – application number: CA 407,358.

cases viewers must be at an approximately fixed distance from the screen). In contrast the radial raster is in principle able to carry out both functions – although viewing conditions vary with location.

Gabor describes several related techniques that may be used to effectively carry out both the multiplication and spreading functions and at the same time enable the screen (and associated re-imaging structure) to be located in a vertical plane. These vary in complexity and in the simplest scenario, the system caters for a single tier audience with the projector being located at the rear of the viewing plane. Aspects of this system are briefly outlined below.

As indicated in Figure 39, the overall structure is formed from two bulk transparent plastics – termed the 'base plate' and 'front assembly'. These differ in refractive index – that of the base plate being the larger. The multiplication function (which occurs in the horizontal plane) is achieved by a set of vertical lenticules. These form a parallel raster and are located at the interface between the front assembly and base plate. Naturally the lenticules are fabricated from a material whose refractive index is greater than that of the surrounding plastics.[28]

Central to the implementation of the spreading function (which occurs in the vertical plane) is an array of 'mirrors'. These are readily created by constructing the front assembly from two sheets of plastic into which 'saw tooth' ridges are formed. When brought together, alternate (horizontal) edges come into close contact whereas the sloping edges are fabricated in such a way as to ensure that they remain separated by a small gap (on the order of the wavelength of light – or greater) – see Figure 39(b). As illustrated in Figures 39 (c) and (d), in the case that the angle of incidence of light falling onto a gap exceeds the critical angle, then the light will be reflected. In contrast if the angle of incidence is smaller that the critical angle, then the light will pass through the air gap and given its minimal thickness, lateral displacement will be negligible.

The formation of the overall structure is further summarised in the perspective drawing reproduced in Figure 40(a). Gabor discloses several approaches for the fabrication of the rear surface of the base plate – see Figures 40(b) and (c). Here, the essential objectives are to support broad reflectance characteristics in the horizontal plane (thereby enabling the lenticules to effectively carry out the multiplication function) whilst at the same time limiting the angular range over which light is returned in the vertical plane. In this latter respect (and assuming that the projector is located at the rear of the viewing plane) the aim is to only return rays at angles to the horizontal which are smaller than those of the incident rays. This ensures that returned light is not cast beyond the projector – where it is assumed there will be no audience. Clearly in the case that the projector were to be positioned at the front of the viewing plane then it would be necessary to reverse this strategy and only return rays at angles to the horizontal which are larger than those of the incident rays.

In the case of the approach adopted in Figure 40(b), the ledges are scored with a set of fine parallel lines and in addition a reflective coating is applied. These measures are intended to provide the appropriate characteristics in the horizontal and vertical directions. An alternative arrangement is illustrated in Figure 40(c). In both cases the vertical (fine) line spacing is ~50μm.

[28] Although this is a little more complicated when aplanatic gofferings are used.

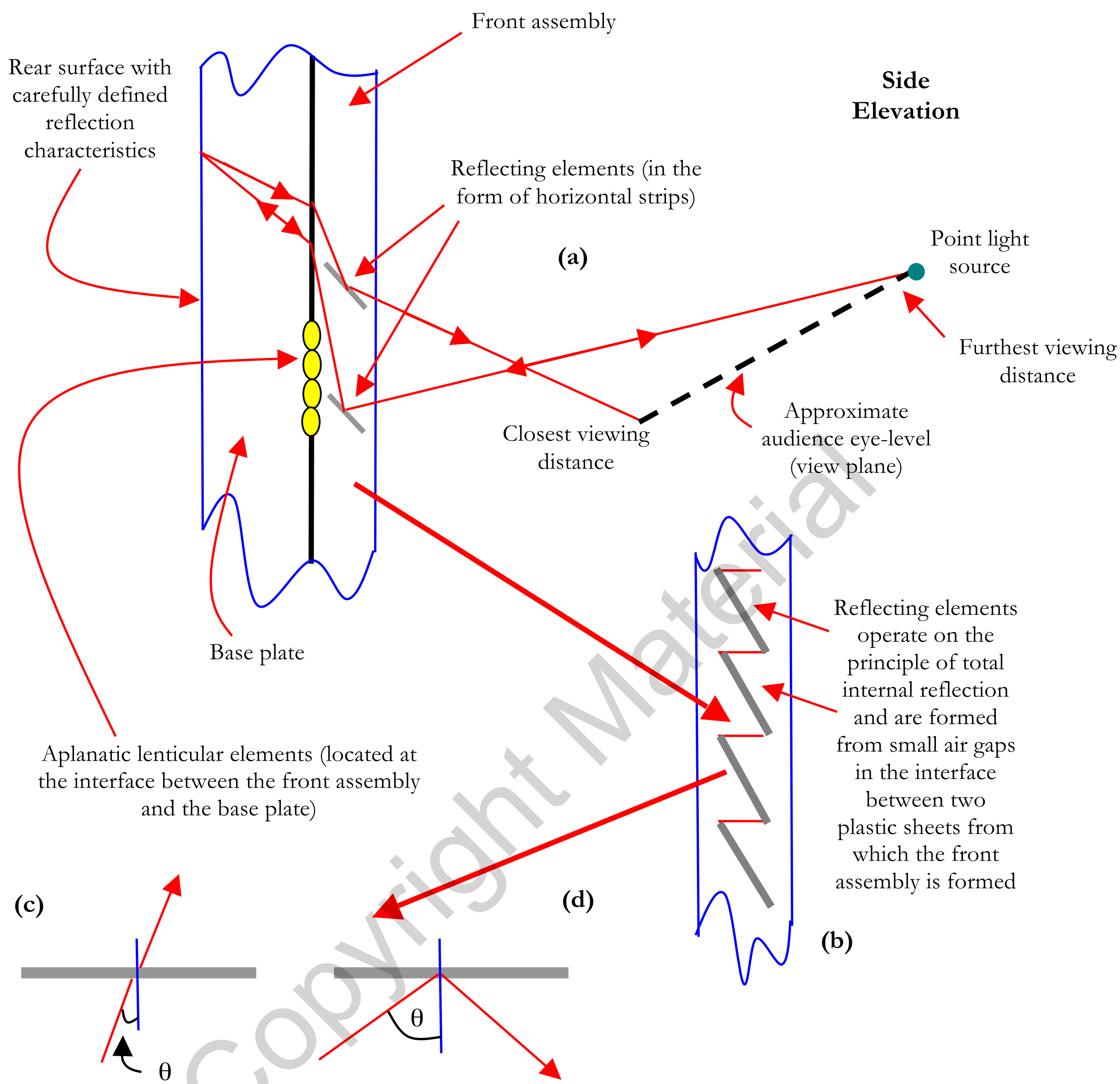


Figure 39: Diagram (a) provides a simplified overview of the general approach adopted by Gabor for the case that the projector is located at the rear of the viewing plane and that the audience are seated on a single level. In (b) the configuration of the 'mirror' array is summarised (for clarity of ray trajectories, in (a) the vertical separation of the two exemplar mirrors has been increased). Each 'mirror' (depicted in grey) is formed from an air gap (on the order of the wavelength of light – or larger). Diagrams (c) and (d) illustrate the operation of a 'mirror' element. In (c) θ is less than the critical angle and hence the ray passes through the air gap whereas in (d) θ exceeds the critical angle and so, on the basis of total internal reflection (which occurs at the plastic/air boundary) the ray is reflected.

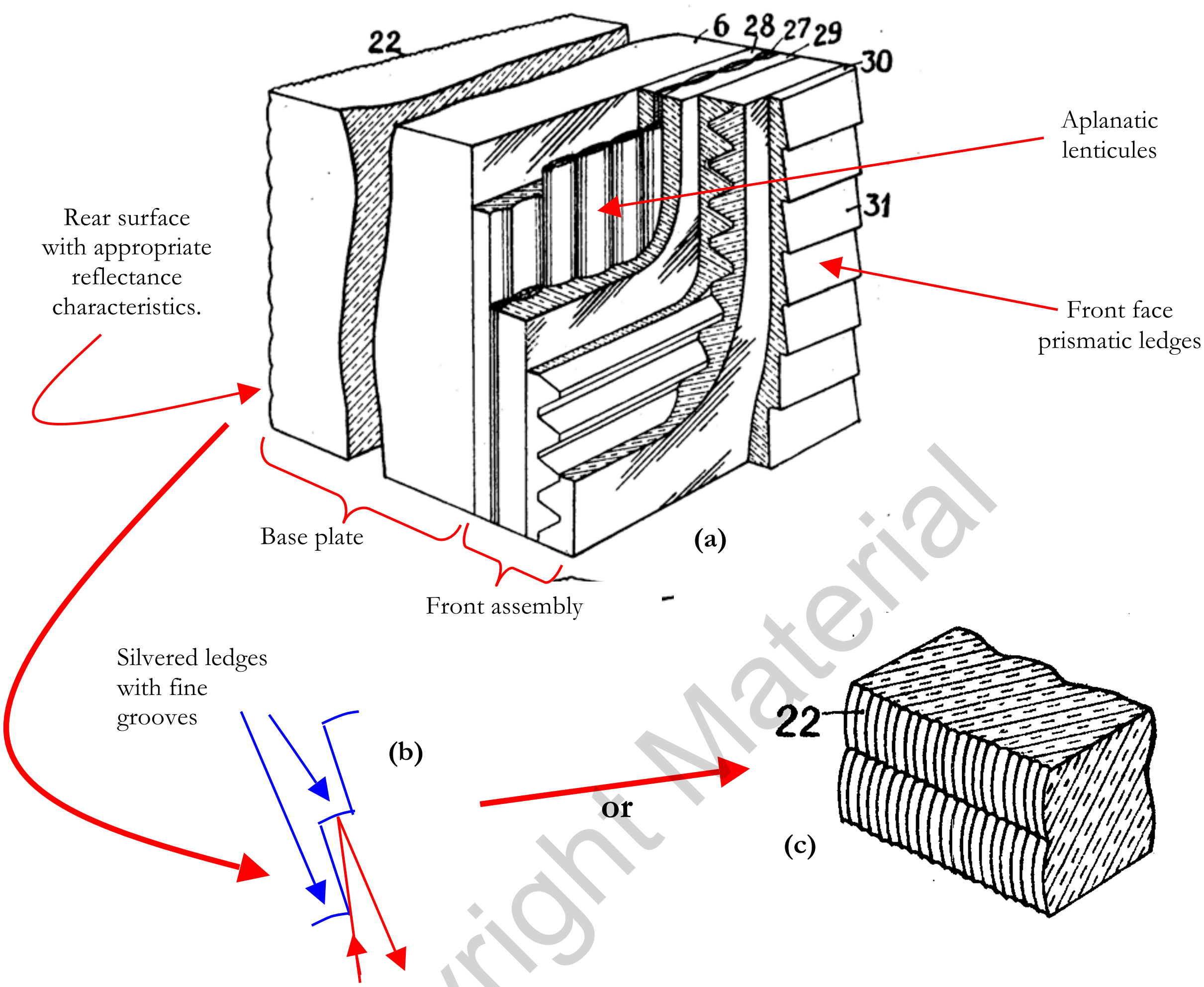


Figure 40: In (a) a cutaway perspective view of the structure of a fragment of the optical assembly devised by Gabor to support glasses-free 3D cinema for an audience located in a single plane. Diagrams (b) and (c) illustrate two approaches that may be used in the implementation of the rear face of the base plate. (Diagrams (a) and (c) adapted from Canadian Patent Application CA 407,358.)

Turning to Figure 39(a) in which for simplicity a point light source is used, if we were to remove the 'mirror' array and incorporate a surface at the rear of the base plate exhibiting the usual reflectance model, then it is evident that we would effectively return to the scenario depicted in Figure 4 (although this diagram makes use of a parallax barrier). Thus the set of vertical lines of light generated by the source on the rear surface of the base plate would be completely visible from a set of equally spaced positions – these being located within a plane lying parallel to the optical structure (we neglect refraction occurring as the light enters or emerges from the front assembly).

Gabor's innovative use of the mirror array enables these viewing zones to be mapped onto the view plane. An indicative explanation can be discerned from the two rays depicted in the illustration. One ray emerges from the source, enters the front assembly and as a consequence of the angle of its trajectory is reflected by a mirror. After passing through a lenticule, it is imaged onto the rear face of the base plate. A portion of this light returns along the converse path.

As discussed above, the optical characteristics of the rear surface are such that the light is distributed over a wide angle in the horizontal plane (thereby enabling the lenticules to perform their multiplication function and so generate a plurality of viewing zones). However in the vertical plane light distribution is somewhat more restricted – indeed the second ray indicated in Figure 39(a) represents the extreme case. Following this ray's transit through the lenticules, it is reflected by a mirror and is visible at the front of the view plane. Thus rays returned from intermediate angles on the rear surface of the base plate will in principle ensure that the exemplar ray cast by the light source is visible from a set of parallel planes located in the viewing plane.

The perspective cutaway view presented in Figure 41 illustrates the optical arrangement disclosed by Gabor for use in cinemas in which the audience is located on two tiers. The system uses three mirror arrays and is discussed in Chapter 5.

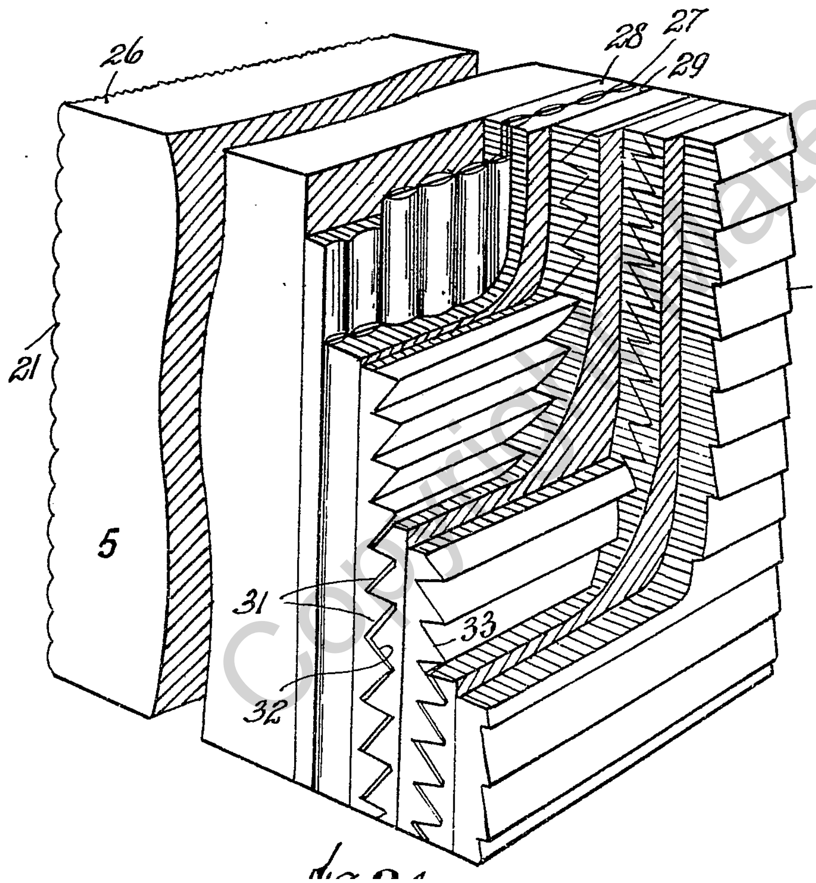


Figure 41: A cut away fragment of the optical structure designed by Gabor to provide glasses-free 3D cinema to audiences located on two tiers ('pit' and 'circle'). Notice that three mirror arrays are now employed (elements 31, 32 and 33). Unfortunately in the 1940's the implementation of such a structure with useful dimensions would have been extremely challenging. See Chapter 5 for discussion. (Reproduced from British patent 541,751.)

The perspective diagrams reproduced in Figures 40 and 41 reveal that the front most face of the structure comprises a series of prismatic ledges. As with the earlier work undertaken by Noaillon, Gabor recognized that direct reflections occurring at the front face of the structure should not cause light emanating from the projector to be visible to the audience. Hence the incorporation of these ledges which ensure that reflected light is not cast into the audience's visual field.

The patents filed by Gabor in 1940 are extensive and include a comprehensive analysis of the optical systems together with other innovative advances. In this latter respect, Gabor discusses the elimination of abrupt changes in refractive indices at material boundaries and describes approaches that may be used to implement graded-index boundaries. Additionally he incorporates aplanatic lenticules into his design.

9. DISCUSSION

In recent literature the extensive work independently carried out by Edmond Noaillon and Semyon Ivanov *et al.* has received relatively little attention and, from a technical perspective, their major contributions in pioneering early forms of glasses-free 3D cinema are frequently overlooked.[29]

There can be little doubt that Noaillon should be credited with the invention (*circa* 1927) of the radial raster form of barrier and with the introduction of cyclic barrier movement. Unfortunately, in applying these approaches, Noaillon became involved in the development of ever-more complex mechanical techniques and was handicapped by the difficulties of successfully causing a large and cumbersome barrier to undergo rapid oscillatory motion. Other techniques described by Noaillon were highly innovative – particularly his use of a micro-filter to map light into barrier slits – thereby increasing the efficiency of the barrier in relation to the passage of light to the screen. Noaillon's work with the multi-layer form of barrier is a further example of his inventive spirit and willingness to experiment with bold and original concepts.

As outlined in previous sections, Noaillon disclosed many original ideas in his 1927/28 patent It is therefore quite likely that his work inspired Russian researchers to pursue the vision of radial raster based autostereoscopic cinema. From the outset they adopted a practical approach – particularly in terms of the design and implementation of the radial raster barrier. The fact that within a short time their technology was able to deliver a 3D glasses-free experience to significant audience numbers is a testament to their success. Nikolai Valyus who made important contributions to this work reports that for his efforts, Semyon Ivanov received the State Laureate Award (Valyus [1966]).

Early in 1954 a second glasses-free 3D cinema opened in Kiev and later, audiences in Leningrad and Astrakhan were also able to experience 3D without glasses. Figure 42 provides a plan view of an auditorium. Note that the screen and radial raster are located within a special alcove. This would have played an important part in ameliorating edge effects - Valyus [1966] indicates that it '…*considerably enhanced the stereoscopic effect.*'.

Valyus also reviews some of the key problems and describes opportunities to further refine the delivery of glasses-free 3D. In relation to the 1941 system, he writes:

> '*It was not easy for spectators to adopt the correct position. This difficulty arose largely because the different seats were not related to the positions of the viewing zones.*'

Clearly well planned seating arrangements are vital and, despite the associated investment, there can be little doubt that electrically adjustable seating is an essential ingredient in the future application of the spatial coding technique to cinema.

Rugged glasses-free 3D has the potential to advance not only cinema and television but also numerous other applications. These include large-scale digital signage, mobile and desktop applications, medical and scientific visualisation systems, etc. However, we continue to encounter difficulties similar to those experienced by workers some 70 years ago. These include the identification of optimal ways of implementing the 'multiplication' and 'spreading'

[29] For a broad overview of 3D Cinema see, for example, Smith *et al.* [2011].

functions described by Gabor, support for viewing freedom, elimination of cross-talk, invariance of image quality with viewing position, support for appropriate screen size/form, commercial viability etc. Indeed developing a multitude of ubiquitous glasses-free solutions requires bold investment in innovative techniques.

Certainly the work carried out by Noaillon, Ivanov *et al*, Savoye, Gabor and many other pioneers (to be discussed elsewhere in Volume II of the '3D Displays and Spatial Interaction' book) demonstrates the practicality of delivering autostereoscopic 3D to quite large audiences. However, armed with today's materials, technologies and know-how, we are far better placed to develop viable glasses-free solutions that harmoniously integrate with the human visual system.

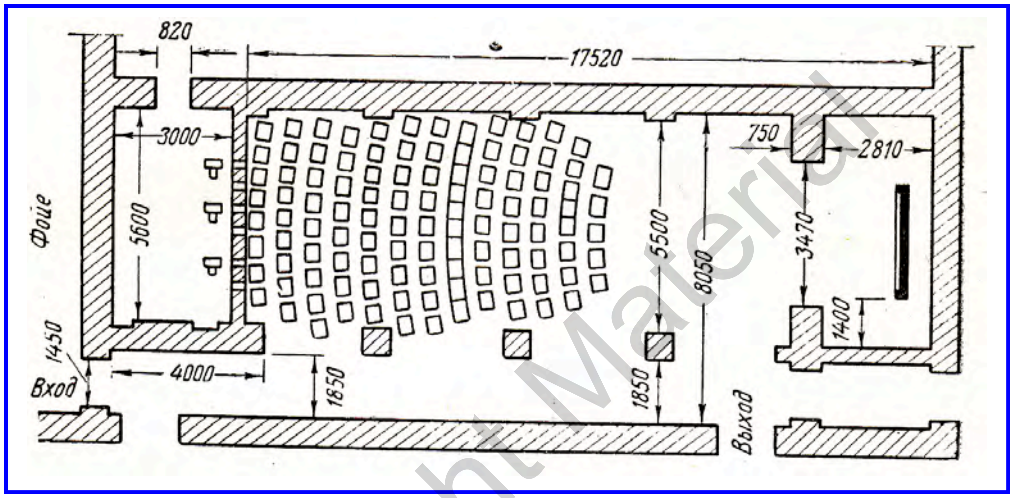


Figure 42: The layout of a small post WWII Russian cinema. Note that the screen and radial raster (lenticular-based) are located in a special bay – this would have significantly improved the 3D experience by reducing edge effects. Subsequent cinemas were equipped with both 2D and 3D screens (the former being retractable). (Reproduced from Ivanov [1956].)

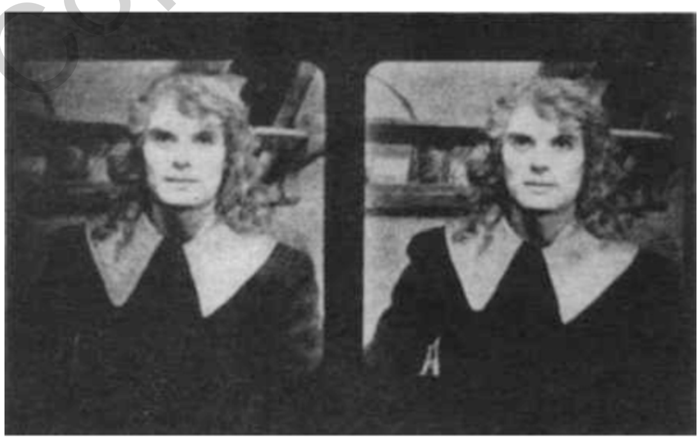


Figure 43: Stereo frames from Robinson Crusoe. Released in ~1947 for glasses-free viewing in Moscow (in the building which previously housed the Vostokkino). This stereopair may be easily fused by slightly crossing the eyes. (Reproduced from Sammons [1992].)

APPENDIX

SAVOYE'S CYLINDRICAL, PARALLEL RASTER BARRIER

As previously discussed, the use of a barrier-based display system in which the COC lies at infinity (i.e. all slits are parallel), gives rise to viewing locations which are at an approximately fixed distance from the screen. Consequently, if such a barrier were to be used in cinema then, as indicated by Takanori Okoshi:

> '…*more than one observer could not occupy the optimum viewing positions unless they were stacked vertically*.' Okoshi [1976]

However, in a patent filed in the US early in 1942 (initially filed in France in January 1941 (that is at around the same time as the opening of glasses-free cinema in Moscow)) François Savoye details an alternative solution. From a mechanical perspective his approach was both complicated and cumbersome – but represents yet another interesting milestone in the early development of glasses-free cinema. Indeed an understanding of this approach provides an insight into the evolution of the Cyclostereoscope, for in the patent Savoye replaces Noaillon's reciprocating motion of a planar barrier with the rotational motion of a *cylindrical* barrier. However, he adopted the more traditional parallel slit raster and sought to identify a technique by which this form of barrier could support glasses-free 3D across the length and breadth of the cinema auditorium. The result was an unwieldy and impractical apparatus which sharply contrasts with Savoye's subsequent design of the rather elegant Cyclostereoscope.

Savoye recognised that in the case of the parallel raster barrier, the optimal viewing zones lie at a fixed distance from the screen. The basic geometry is summarised in Figures 44 and 45 (although these diagrams depict a parallax barrier used in conjunction with an optoelectronic display panel). From this latter figure and on the basis of similar triangles (indicated in green), it is apparent that:

$$\frac{b}{z} = \frac{d}{e}.$$

Thus if the left and right stereo image strips that are depicted on the screen are of fixed width and for a given interocular distance:

$$\frac{b}{z} = constant.$$

Ideally this should apply to all viewing locations. Savoye's approach to satisfying this requirement is summarised in Figure 46. As may be seen in generating diagram (b), the configuration of screen, barrier and optimal viewing plane illustrated in (a) is rotated – with the relative positioning of these entities remaining unchanged. This gives rise to a system in which the audience seating is positioned on an inclined floor and the bulk of the display apparatus (including the screen) is suspended from the auditorium's ceiling. V_1 and V_2 denote exemplar viewing locations and in the diagram these are connected to an exemplar point (A) on the screen. The intention was to ensure that the distance from A (for example) to the barrier divided by the distance from the barrier to the view point was constant for all viewing positions.

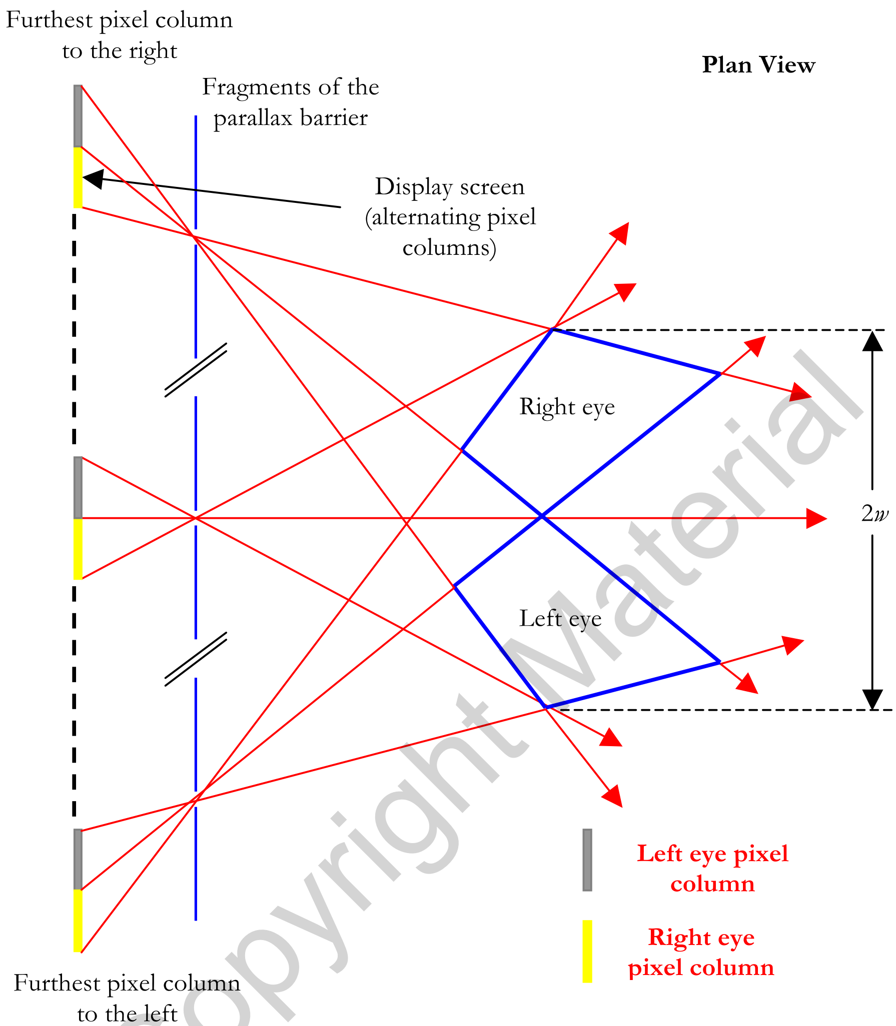


Figure 44: The general principle of operation of the parallax barrier technique for providing spatially-coded stereoscopic views. The configuration illustrated here provides a *single* view onto the image scene. The two views that comprise the stereopair are interleaved in alternating columns of pixels on a flat screen display, and the barrier ensures that from the correct viewing zones each eye sees only the corresponding (designated) view. The two quadrilaterals indicated by the thicker blue lines denote the viewing window ('sweet-spot' regions) within which stereoscopic vision is fully supported. For example, in the case of the upper region all right-eye pixel columns are simultaneously visible to the right eye. (Reproduced from Blundell [2011a].)

Figures 47 and 48 provide a general overview of the apparatus. A static screen was placed within a rotating cylindrical barrier structure - the opaque and transparent barrier slits being arranged around the cylinder's periphery – running between its lower and upper ends. As with the Cyclostereoscope (Section 7), the speed of rotation of the cylinder was the lowest needed to ensure that the opaque slits were not visible and that all image content was presented to the human visual system so as to ensure fusion - and hence the elimination of perceived (barrier-induced) segmentation.

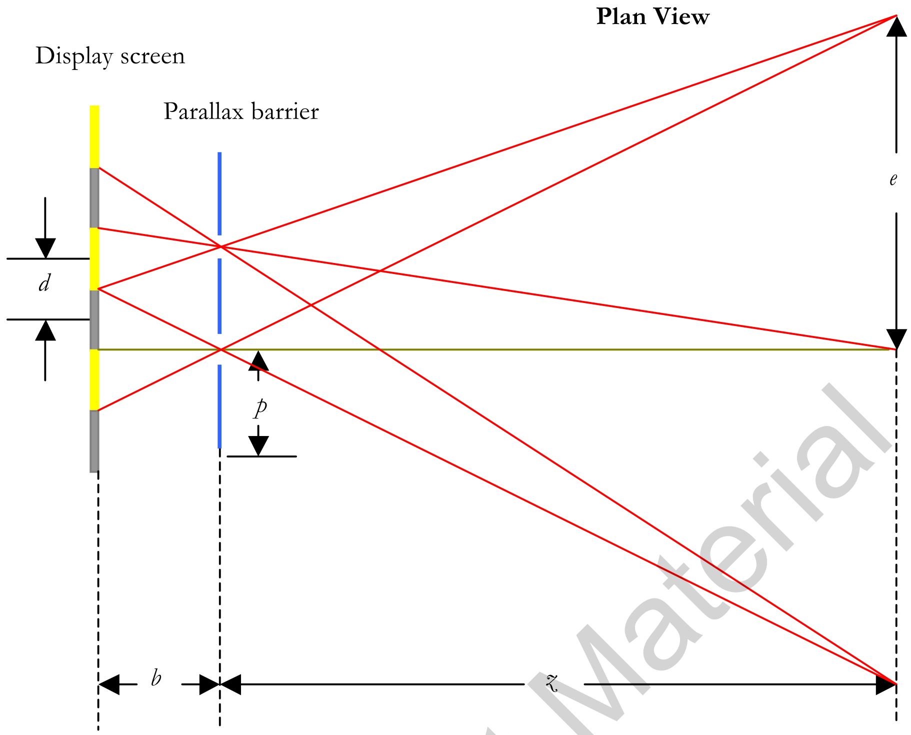


Figure 45: The basic geometry of the conventional parallel raster barrier. Here, *e* denotes the interocular distance. See text for discussion. (Reproduced from Blundell [2011a].)

Also as with the Cyclostereoscope, barrier rotation and projector frame rates were synchronised. For a cinema applications, the screen size and hence the barrier diameter would have been quite large and so frequency of rotation would have been quite manageable.

A key inventive step in Savoye's approach was to use two different barrier geometries – one for the coding process (in which strips of the left and right stereo views are interleaved on the screen) and another for the decoding process (in which light emanating from the screen is correctly directed to the audience). For this purpose the cylinder was divided into two parts – the lower end dealing with coding onto the screen and the upper end handling the distribution of the left and right views to the audience (Figure 47). The barrier pitch was uniform along the length of the cylinder – but the width of the slits differed (those in the upper part being narrower). In this context, Savoye sought to support broader viewing zones and enhance audience comfort.

At the time of writing there is no indication as to the extent to which Savoye implemented this somewhat unwieldy system. However, it is evident that in designing the overall approach Savoye made a number of advances which brought him closer to the development of the somewhat more practical Cyclostereoscope.

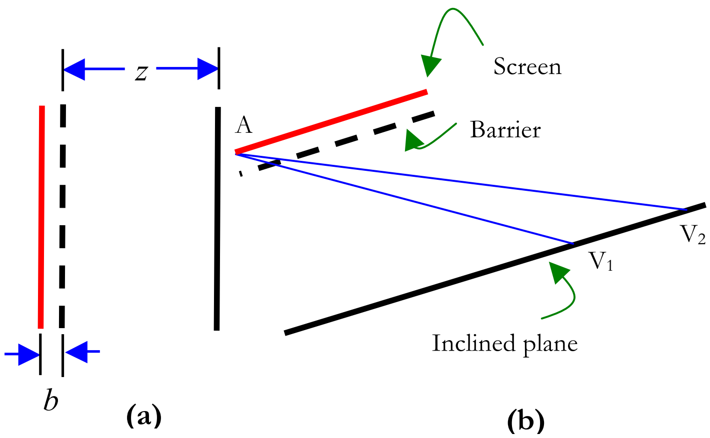


Figure 46: In (a) the screen (red), barrier and plane denoting optimal viewing distance are parallel and hence b/z is constant for all viewing positions. Diagram (b) summarises Savoye's approach in which he effectively rotates diagram (a) and maintains the same relative positioning of the screen, barrier and viewing plane. The audience seating is fixed to an inclined floor and the main part of the display system (including the screen) is attached to apparatus fixed to the ceiling of the auditorium. V_1 and V_2 denote exemplar viewing locations. In using a cylindrical form of barrier, it is evident that in cross-section (i.e. normal to the cylinders axis), the distance between the barrier and screen is no longer constant.

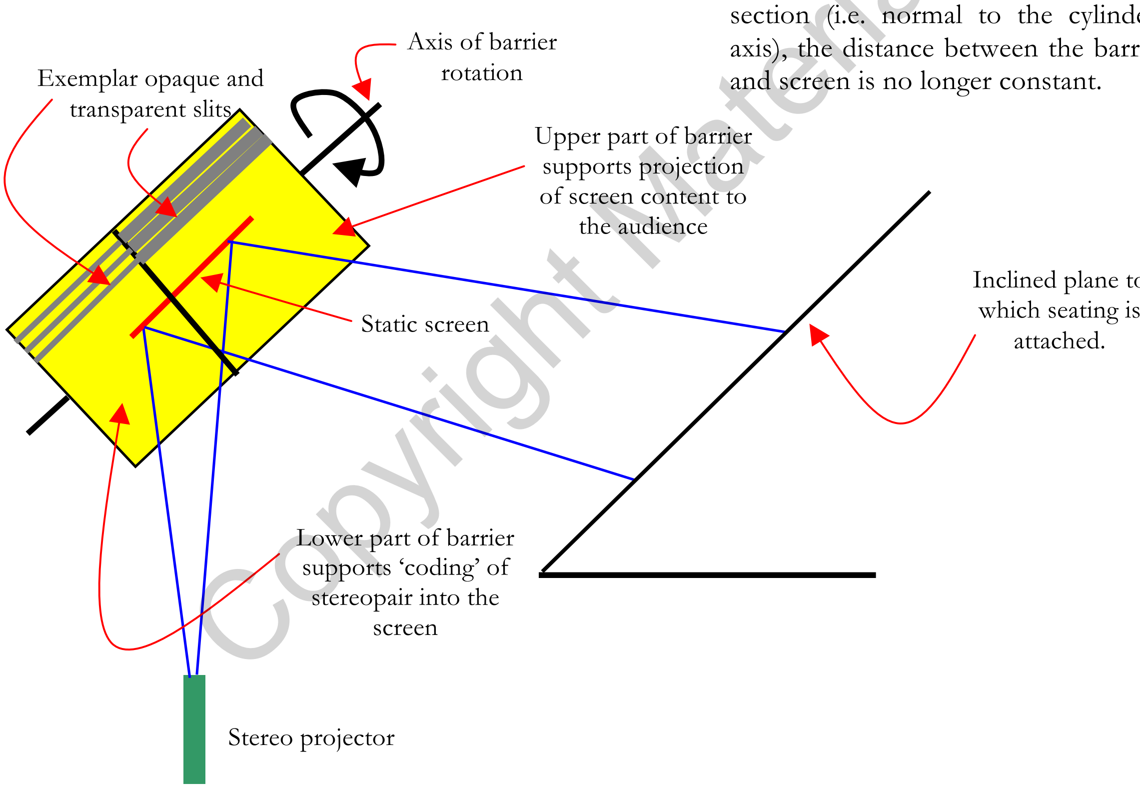


Figure 47: A general summary (side elevation) of key components employed in Savoye's early patent. In yellow, the rotating cylindrical raster barrier within which the static screen (red) is located. Audience seating is arranged on an inclined floor which lies parallel to both the axis of the barrier (cylinder) and screen. The projector casts the stereo content through slits in the lower part of the cylinder onto the screen. Light emanating from the screen passes through slits in the upper part of the cylinder. Although the barrier pitch is uniform over the cylinder's length, the opaque regions in the upper part are wider than those in the lower part. This represents an important inventive step.

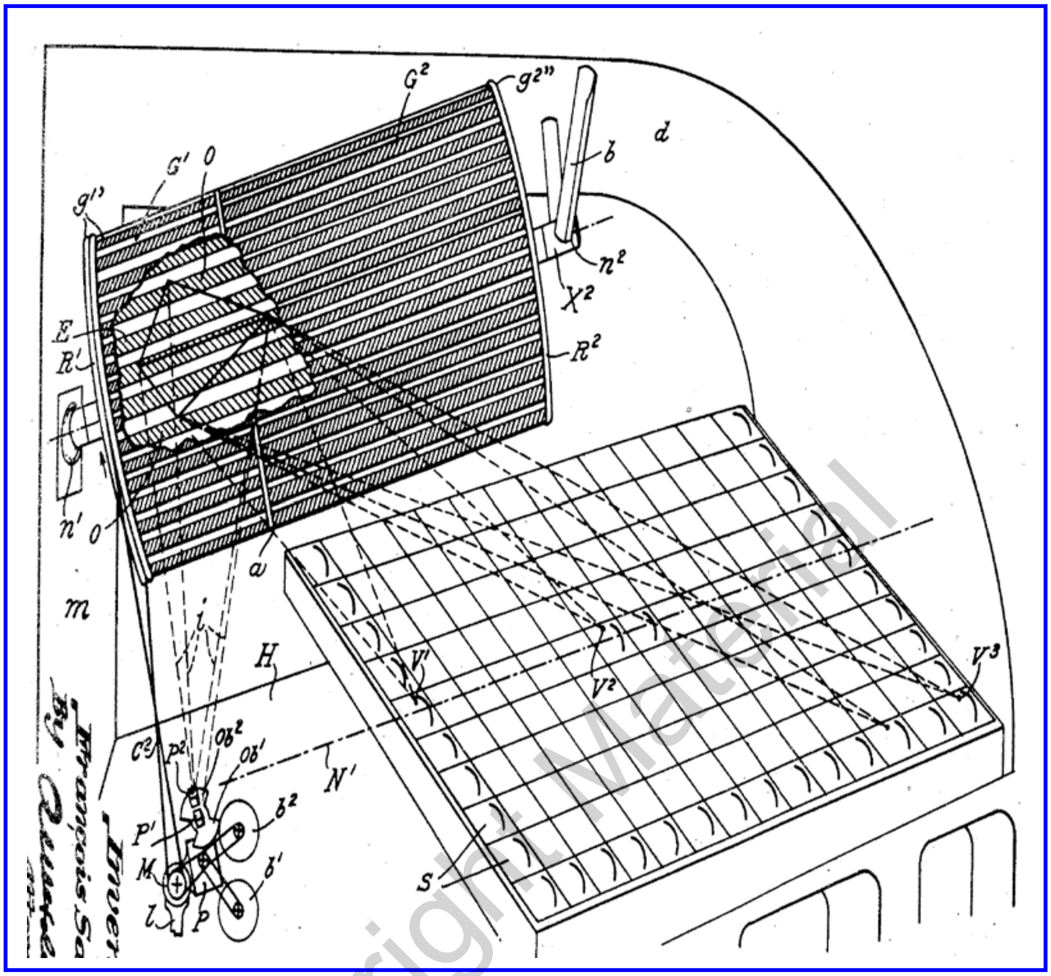


Figure 48: Showing the general arrangement of Savoye's somewhat unwieldy cylindrical barrier system. The rotating cylindrical barrier is suspended from the ceiling and the audience seating is arranged on an inclined floor. The inventor's subsequent adoption of the radial raster (in the form of the frustum of a cone) for the Cyclostereoscope led to a more practical configuration. (Diagram reproduced from US Patent 2,421,393.)

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Note: The dates given here respectively correspond to when the patent was filed and when it was granted. When only one date is given, this relates to the filing date (the indication being that the patent was not actually granted).