Design and Applications of A High Resolution Insert Head Mounted Display

Akitoshi Yoshida
TTRIP FH Rheinland-Pfalz
Erenburgerstraße 17
D 67544 Worms
Germany

Jannick P. Rolland
Department of Computer Science
University of North Carolina at Chapel Hill
Chapel Hill, North Carolina

John H. Reif
Department of Computer Science
Duke University
Durham, North Carolina

Draft

June, 1994

Abstract
In this paper, we propose and design a new Head Mounted Display (HMD) that provides a large field of view with a high resolution insert. Previously, this type of HMDs has been designed using mechanical or sequential scanning devices. Our HMD uses only electronic devices that can be easily integrated with the optical components. We describe the design principles and envisioned applications of our HMD, and demonstrate the feasibility of our HMD by designing a prototype model.

1. Introduction

The field of Virtual Reality (VR) has recently received considerable attention, rightly due to the potential to create unique capabilities for human-computer interaction [Foley 87, Fisher 90]. Such advanced interaction can include: interactive control and diagnostics systems, teleoperation systems, and entertainment systems. For these applications, HMDs are typically used to provide the visual information to the user [Chung et al 42]. However, conventional HMDs usually do not provide enough resolution or field of view to give the user the realistic feeling of being in the displayed world.

Two features of the HMD must be met to give the user the feeling of being in the displayed virtual world [Howlett 92]. First, the display must provide a field of view large enough to surround the entire view. Second, it must provide resolution high enough to render the fine detail of the image. When the field of view is not large enough, the user sees the frame of the display and feels s/he is looking through a window. To remove this annoying window effect, the field of view must be at least 80 degrees. When the resolution is not high enough, the user sees pixels and the fine detail of the image is lost. To match the human visual acuity, the pixel size must be about 1 arc minute. However, the human retina does not provide uniform visual acuity. The high visual acuity is only available at the fovea, a small area of about 5° in angular extent at the center of the retina. The visual acuity degrades rapidly as the distance from the fovea increases; at the angular distance of 5° from the center of the fovea, it is about a quarter of the highest acuity, at the angular distance of 15°, it becomes only one seventh. Therefore, the resolution does not have to satisfy this limit over a large field.

For a fixed number of pixels in a display, these two features are contradictory. A large field of view leads to low resolution, and high resolution leads to a small field of view. Consequently, most HMDs do not provide these two features adequately. To overcome this dilemma, HMDs that combine a low resolution, large field background image with a high resolution small field insert image have been developed [Thomas et al 89, Burbidge & Murray 89]. The idea is based on the fact that human vision has high visual acuity only over a narrow region around the fovea. A small area of high resolution insert can be superposed on a large field of low resolution image to virtually create a large field of view with high resolution. The position of the insert is dynamically controlled by the gaze point.

These systems provided significant improvements over the ordinary display. They use a bundle of optical fibers to transmit the images to the eyes. They are considered the best displays available, however they are very heavy and extremely expensive.

Thus, the currently available HMDs are either low-cost-low-performance or high-cost-high-performance models. Our approach is to develop a low cost system that uses fully optoelectronic components. The use of fixed optoelectronic components allows the whole system to be fabricated with less alignment errors. The system is immune to mechanical failure and in general more tolerant to vibrations.

2. Applications

In this section, we describe applications of our HMD. The primary advantage of our HMD is its large field of view with a high resolution insert superposed at the user's gaze point. The user can observe dynamic scenery over a large field at high resolution. The additional advantage is its increased interaction capability. The use of eye tracking is not limited to finding the gaze point for positioning the insert. The eye can respond to stimulus much faster than the hands [Girolamo 91]. Thus, the eyes can be used for fast and effective input, selection, and control methods.

In the following subsections, we describe three applications that are particularly suited for our HMD.

2.1. Graphical User Interfaces

The gaze point of the eye can be used to select and manipulate objects in the scene. An HMD that provides a high resolution, large field view can support effective working environments for complex tasks. Many windows can be opened and organized in three dimensional environment, and various interaction methods using the hand, body, eye movements are possible [Bolt 81, Herot 80, Feiner et al 82, Bryson 91, Jacoby & Ellis 92].

Updates in the environment do not have to occur simultaneously at high resolution. The portion of the environment near the gaze point may be updated quickly at high resolution. However, other portions of the environment may be updated less frequently or at lower resolution to reduce both the computational load and transmission bandwidth.

The area near the gaze point has an important use particularly for a large field environment. Information that requires the user's immediate attention may be displayed near the gaze point.

2.2. Multimedia and Databases

Multimedia information such as computer generated graphics and video can be displayed effectively by an HMD that provides a high resolution large field view. The user can observe images with a large field at high resolution. As it is the case for the general user interfaces, updates to the portion of the images near the gaze point can be made at different rates from those to the other regions. Furthermore, when hierarchically compressed video is to be displayed, the gaze point can provide an efficient decompression and transmission of the data. In this case, the low resolution background is decompressed and transmitted first. The high resolution insert is subsequently decompressed and transmitted. At the receiving site, these two data are combined to reconstruct the image.

Interactions with databases can be improved by such a HMD with the gaze point information. The eyes can select windows and objects by fixation. The user can observe a specific object at high resolution while maintaining a larger view representing the structure and hierarchy of other objects in the database.

2.3. Remote Sensing and Teleoperations

Remote sensing and teleoperations are important applications of HMD technology [Fisher et al 86, Fisher et al 87, Cole et al 92]. The faithful presentation of visual, radar, sonar, and infrared sensory information allows the user to effectively observe the remote environment and maneuver the remote vehicle. The remote vehicle must be able to monitor a large field at high resolution so that the human operator can observe the remote environment as if s/he is present at the remote location. The use of a large field low resolution background sensor and a small field high resolution insert sensor can lead to an efficient system that provides high fidelity images with a low bandwidth requirement. A small area of interest can be monitored at extremely high resolution while a large field of view is kept within the user's view. The amount of information that has to be transmitted from the remote vehicle to the user is kept much lower than that would otherwise be required if the whole field were monitored at high resolution. If the monitored scene requires extensive signal processing, the reduction of computational load is achieved by processing the insert and the background separately at different accuracy. Another use of the insert is to superpose different kinds of images at the gaze point. X-ray, ultrasound, or infrared heat images may be superposed over the regular visual spectrum images. For the fixed insert, such systems have been developed [unc ref]. The dynamic insert of these images allows the user to observe and diagnose the situation with more freedom.

3. System Description and Design Objectives

Our HMD inserts a small area of the high resolution image on a large field of the low resolution image, as shown in Figure 1. Using eye tracking information, it dynamically places the high resolution insert at the gaze point. Thus, the HMD provides the user visually both high resolution and a large field of view. There are several methods with different accuracy to track the eye movement and the gaze point [Young & Sheena 75]. The electro-oculography method detects the change of electric field in the tissue surrounding the eye and determines the orientation of the eye. This electric tracking method is the simplest method with moderate accuracy. The limbus tracking method detects the position of the limbus, which is the boundary between the iris and the sclera, and determines the gaze point. The pupil-corneal reflection method measure the corneal reflection with respect to the center of the pupil. These two optical tracking methods are much more accurate than the electric tracking method, however they require more complex hardware for processing. In order to determine the gaze point for superposing the high resolution insert, we require only the accuracy of the electro-oculography. To implement some of the complex interaction methods using the gaze point, we may require the limbus tracking or the pupil-corneal methods. In either case, once the gaze point is determined, the superposition of the high resolution insert over the low resolution background is carried out using liquid crystal devices and fixed optical components. This will result in a low cost reliable system.

The schematic diagram of our HMD is shown in Figure 2. There are two displays: one for the background and the other for the insert. The image of the insert display is optically duplicated to fill the entire background, where a liquid crystal device array is used to select one element of the array. This means that only one copy of the display image passes through the liquid crystal array, and all the other copies are blocked. The image of the insert display and that of the background display are then combined using a beam splitter.

For a simple system, the insertion may be made at these discrete non-overlapping locations, as shown in Figure 3. In this case, the liquid crystal array blocks all the duplicated images except for one copy. The high resolution part of the image is directly displayed from the insert display. Its duplicated images are formed at the liquid crystal array and, the array blocks all the images except for the one at the desired location. For a more complex system, the insertion may be made at continuous locations (up to the pixel level) as long as the size of the insert is not larger than the size of a single duplicated image. In this case, the high resolution part of the image is partitioned and displayed from the insert display. The partition is made so that its duplicated images at the liquid crystal array form the duplicated images with the desired offset. The liquid crystal array blocks all the images except for the one with the desired offset.

The final goal of the design is to build an HMD that provides both a field of view large enough to surround the entire view and resolution high enough to match the human visual acuity. The background must have a field of view of at least 80 degrees and resolution of 10 arc minutes, and the insert must have a field of view of at least 20 degrees and resolution of 1 arc minutes. It must provide a stereoscopic view in color. The whole system must be integrated, folded, and packed in small volume so that the user can wear it without difficulty.

In the following section, we design a prototype model that is a scale-down version of the final model. The purpose of this prototype design is to demonstrate the feasibility of our HMD.

4. Prototype Design

First, we determine the design parameters. Then, we develop a paraxial model and design a real model using an optical design tool, Zemax from Focusoft [Focusoft 94].

4.1. Basic Configuration

The main component of our high resolution insert HMD is an optoelectronic system for duplicating the insert image and bringing the image to the eye. The basic configuration of this component can be organized in three stages, as shown in Figure 4. We describe each stage separately from the display to the eye. The first stage is the objective which collimates light from the display. The second stage is an array of telecentrics which duplicate the display image from the collimated light. We call this array of telecentrics the duplicator. The third stage is the eyepiece which produces collimated light from the duplicated image at the eye pupil.

We note that there are other possible configurations. For example, we may first duplicate the display image using an array of lenses and then collimate the duplicated images at the eye pupil. However, this configuration may suffer from significant offaxis aberration. Thus, we employ the above configuration for our prototype design.

We assume the following basic design parameters:

	Background	Insert
Field	50°	12.5°
Pixels	400 x 400	400 x 400
Resolution	7.5 arc minutes 8 pixels/degree	1.875 arc minutes 32 pixels/degree

The distance between the back of the eyepiece and its focal plane must be at least its paraxial image height so that a beam splitter can be placed between the eyepiece and the duplicator to combine the insert and background images.

4.2. Paraxial Model

We develop a paraxial model and determine the system parameters. In this paraxial model, we use p_0, p_1, ..., p_5 to denote planes along the optical system, where the eye pupil is at p_0, and the display object is at p_5. The eyepiece uses a lens with focal length f_1 placed at p_1. The intermediate object at p_2 is viewed by the eye placed at p_0. The telecentric system used in the duplicator uses two lenses with focal lengths f_2 and f_3 placed at p_2 and p_3, respectively. Collimated beams at p_3 are imaged at p_2. The objective uses a lens with focal length f_4 placed at p_4. Beams from the display object at p_5 are collimated at p_4. We use l_i to represent the distance between planes p_i and p_{i+1}, and use ai to represent the diameter of the aperture at p_i . We denote the number of duplicated images along the vertical or horizontal axises with k. We represent the largest angles of the eyepiece and the objective with t_e and t_o, respectively.

From the imaging condition of the eyepiece, we have

$$f_1 = l_0 = l_1,$$

and

$$l_0 \tan t_e = \frac{k\, a_2}{2}.$$

From the imaging condition of the telecentric, we have

$$f_2 = f_3 = l_2,$$

and

$$l_2 \tan t_o = \frac{a_2}{2}.$$

From the imaging condition of the objective, we have

$$l_4 \tan t_o = \frac{a_5}{2}.$$

From the telescopic relationship between planes p_0 and p_4, we have

$$\frac{a_0}{a_3} = \frac{l_1}{l_2}.$$

From the relationship among the lens apertures, we have

$$a_1 > l_0 \tan t_e + \frac{a_0}{2},$$

$$a_4 > k\, a_2,$$

$$a_3 = c\, a_2 \text{ where } 0 < c \le 1.$$

We assume the following parameter values:
$a_0 = 8$mm, $a_5 = 25$mm, $t_e = 25°$, $t_o = 6°$, $k = 4$, $c = 0.8$.

Solving the above equations, we determine the other parameter values as follows.

$$f_0 = l_0 = l_1 = \frac{a_0}{2\ c\ \tan t_o}$$

$$l_4 = \frac{a_5}{2\ \tan t_o}$$

$$a_2 = \frac{a_0\ \tan t_e}{k\ c\ \ \tan t_o}$$

$$a_3 = \frac{a_0\ \tan t_e}{k\ \ \tan t_o}$$

$$f_2 = f_3 = l_2 = \frac{a_0\ \tan t_e}{2\ k\ c\ \tan^2 t_o}$$

Thus, we have the following parameter values [mm]:

i	a_i	f_i	l_i
0	8.000	-	47.572
1	52.366	47.572	47.572
2	11.092	52.765	52.765
3	8.873	52.765	1.000
4	44.368	118.930	118.930
5	25.000	-	-

The paraxial model layout at two different telecentric positions is shown in Figures 5-(i) and (ii).

4.3. Real Model

Since our purpose of designing the prototype is to show the feasibility of our approach, we assume monochromatic light and limit our design to the use of only spherical lenses of the same glass material (BK7). For more complete system, we expect to correct chromatic aberration by using different glass materials or more surfaces. We further limit our design to the use of identical telecentrics in the duplicator.

We design a real model using the parameter values determined from the paraxial model. In this prototype design, the three stages are independently designed. The performance of the system may be improved by optimizing the system entirely by balancing aberrations from each stage.

The eyepiece uses four lenses and its layout is shown in Figure 6-(i). There is enough room for a beam splitter to be placed between the back lens surface and the focal plane. The MTF of this eyepiece is shown in Figure 6-(ii).

The duplicator uses an array of telecentric systems. All the telecentric systems are identical and each uses three lenses. These lenses are imbedded in a square form. The layout of a single telecentric system is shown in Figure 7-(i). The MTF of this telecentric system is shown in Figure 7-(ii).

The objective uses three lenses and its layout is shown in Figure 8-(i). The MTF of this objective is shown in Figure 8-(ii).

The layout of the entire system for two different telecentric positions are shown in Figures 9-(i) and 10-(i). For simplicity, the figures do not show folding of the system nor combining the insert and the background. The folding and combining can be made between the eyepiece and the duplicator. Further folding can be made within the duplicator and the objective. The MTFs of the entire system for these two telecentric positions are shown in Figures 9-(ii) and 10-(ii).

5. Discussion and Future Research

In this section , we discuss the performance of our prototype model and future research.

5.1. Prototype Performance

We designed each stage independently with its target performance. For the eyepiece, the required spatial frequency is 18 lp/mm, which corresponds to 200 lp in 11.092 mm. For the telecentric, the required spatial frequency is also 18 lp/mm. For the objective, the required spatial frequency is 8 lp/mm, which corresponds to 200 lp in 25 mm. The MTF of each stage shows that it is capable of resolving its required spatial frequency. For the entire system, the required spatial frequency is 8 lp/mm. The MTFs of the entire system show that it is capable of resolving the required spatial frequency.

5.2. Future Systems

Our prototype design is the first step to a more complete HMD system that can be used in the described applications.

We are working on the following extensions to our prototype design:

- Use of a color display,
- Use of a display with more pixels,
- Use of non spheric surfaces or binary optics,
- Integration with an eye tracker,
- Fabrication and packaging,
- System demonstration for the described applications.

In our prototype design, we assumed monochromatic light and used glasses with the same refractive index. To use a color display, we need to correct chromatic aberration using glasses with different refractive indexes. The resolution and field of view can be increased by using a display with more pixels as long as the optical system supports its spatial frequency.

For a higher performance in expense of complex structures, we may use non spherical lenses or binary optics elements to optimize the system.

We must integrate all components including the eye tracker and fabricate them as an HMD.

Finally, we must demonstrate the system performance for the described applications. A set of software tools has to be developed to utilize the functionality of the HMD.

6. Conclusion

We introduced a new high resolution insert HMD and designed its prototype model. Our HMD uses only optoelectronic devices and no mechanical devices. We presented the principles of our approach by formalizing the system design parameters, and demonstrated the feasibility of our approach by presenting the design of a prototype system.

References

[ASL 92] Applied Science Laboratories, Eye tracking systems handbook, Waltham, Massachusetts 02154 (1992).

[Bolt 81] R. A. Bolt, “Gaze-orchestrated dynamic windows,” Computer Graphics 15(3), 109-119 (1981).

[Burbidge & Murray 89] D. Burbidge and P. M. Murray, “Hardware improvement to the helmet mounted projector on the visual display research tool (VDRT) at the Naval Training Systems Center,” Proc. SPIE Vol. 1116, 52-60 (1989).

[Bryson 91] S. Bryson, “Interaction of objects in a virtual environment: a two-point paradigm,” Proc. SPIE Vol. 1457, 180-187 (1991).

[Chung et at 89] J. C. Chung, M. R. Harris, F. P. Brooks, H. Fuchs, M.T. Kelley, J. Hughes, M. Ouh-young, C. Cheung, R. L. Holloway, and M. Pique, “Exploring virtual worlds with head-mounted displays,” Proc. SPIE Vol. 1083, 42-52 (1989).

[Cole et al 92] R. E. Cole, C. Ikehara, and J. O. Merritt, “A low cost helmet-mounted camera/display system for field testing teleoperator tasks,” Proc. SPIE Vol. 1669, 228-235 (1992).

[Feiner et al 82] S. Feiner, S. Nagy, and A. van Dam, “An experimental system for creating and presenting interactive graphical document,” ACM Trans. Graphics 1(1), 59-77 (1982).

[Fisher et al 86] S. S. Fisher, M. McGreevy, J. Humphries, and W. Robinett, “Virtual environment display system,” ACM Workshop on Interactive 3D Graphics, Oct 23-24, Chapel Hill, North Carolina (1986).

[Fisher 90] S. S. Fisher, “Virtual interface environments,” in The Art of Human-Computer Interface Design, B. Laurel ed. (Addison-Wesley, Menlo Park, CA, 1990), pp.423-438.

[Focusoft 94] Focusoft, Zemax optical design program user's guide ver. 3.0, Pleasanton, California 94566 (1994).

[Foley 87] D. Foley, “Interfaces for Advanced Computing,” Scientific American 257(4), 126-135 (1987).

[Girolamo 91] H. Girolamo, “Notional helmet concepts: A survey of near-term and future technologies,” US Army NATICK Technical Report NATIK/TR-91/017 (1991).

[Herot 80] C. Herot, “Spatial management of data,” ACM Trans. Database Systems 5(4), 493-514 (1980).

[Howlett 92] E. M. Howlett, “High-Resolution Inserts in Wide-Angle Head-Mounted Stereoscopic Displays,” Proc. SPIE Vol. 1669, 193-203 (1992).

[Jacoby and Ellis 92] R. H. Jacoby and S. R. Ellis, “Using virtual menus in a virtual environment,” Proc. SPIE Vol. 1668, 39-47 (1992).

[Thomas et al 89] M. L. Thomas, W. P. Siegmund, S. E. Antos, and R. N. Robinson, “Fiber optic development for use on the Fiber Optic Helmet Mounted Display,” Proc. SPIE Vol. 1116, 90-101 (1989).

[Young & Sheena 75] L. Young and D. Sheena, "Survey of eye movement recording methods," Behavior Research Methods, Instruments and Computers Vol. 7, 397-429 (1975).

Figures

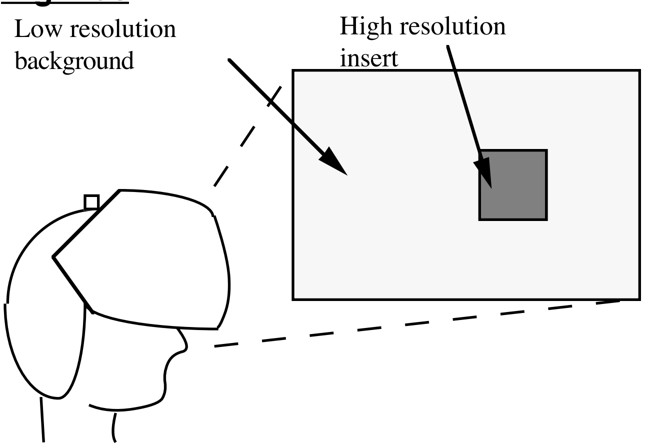

Figure 1. High resolution insert HMD

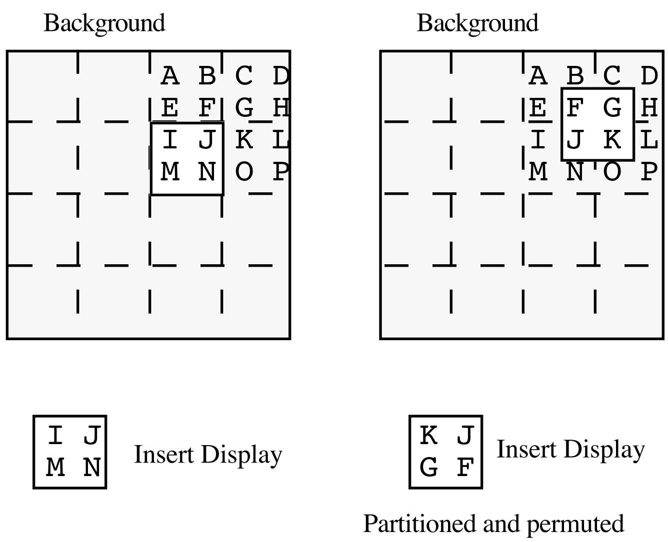

Figure 2. Superposition of the insert display.

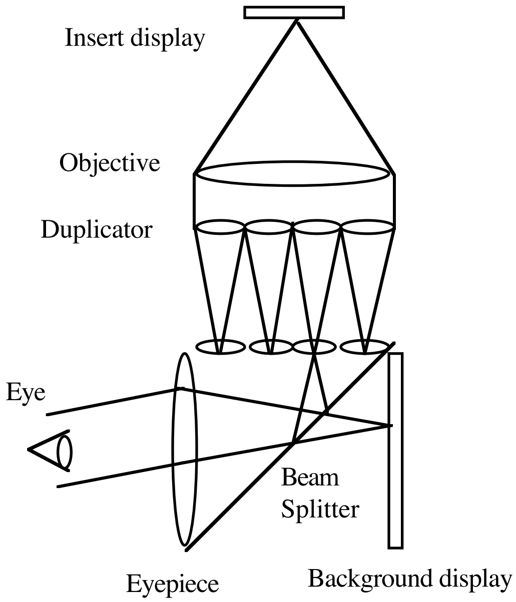

Figure 3. Schematic Diagram of the HMD

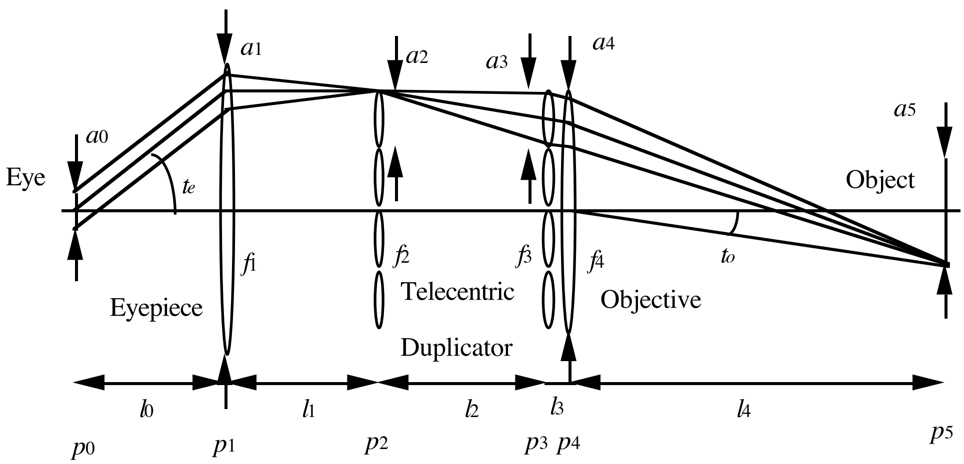

Figure 4. System parameters of the HMD

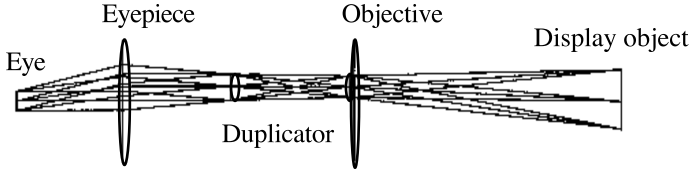

Figure 5-(i). Paraxial model layout at position 1

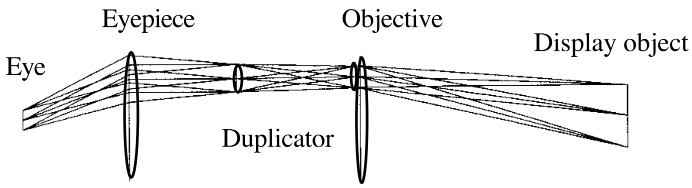

Figure 5-(ii). Paraxial model layout at position 2

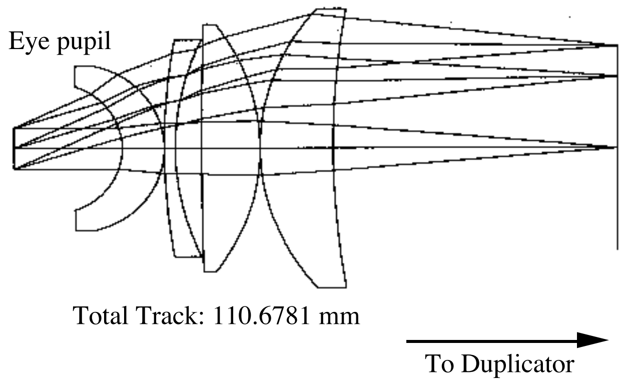

Figure 6-(i). Eyepiece layout

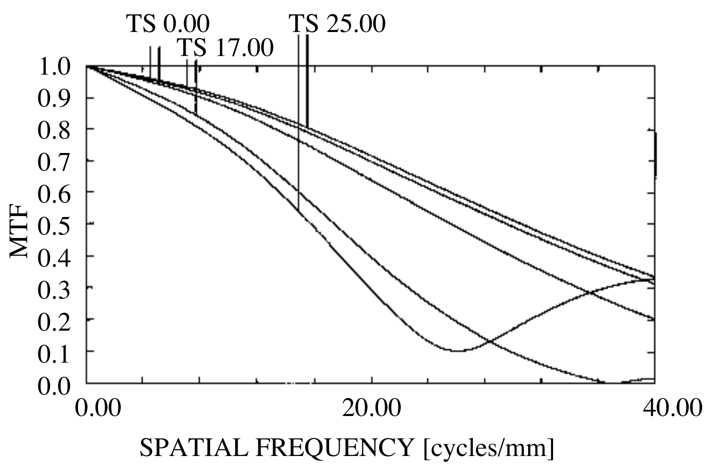

Figure 6-(ii) Eyepiece MTF

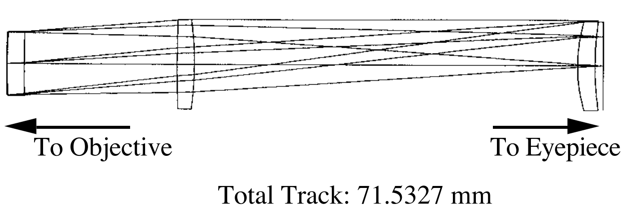

Figure 7-(i). Duplicator layout

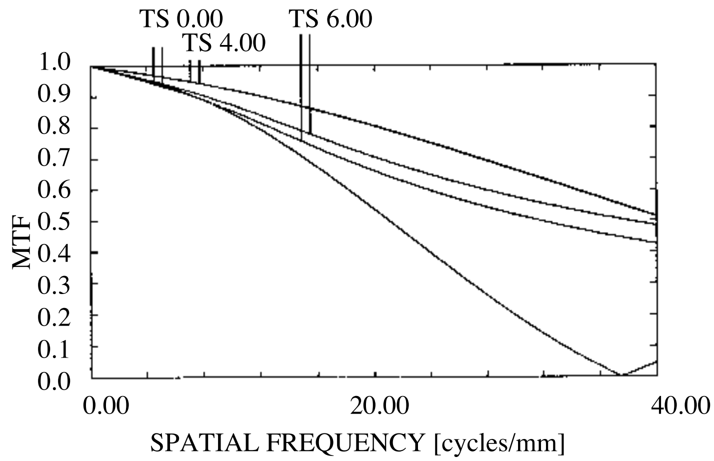

Figure 7-(ii). Duplicator MTF

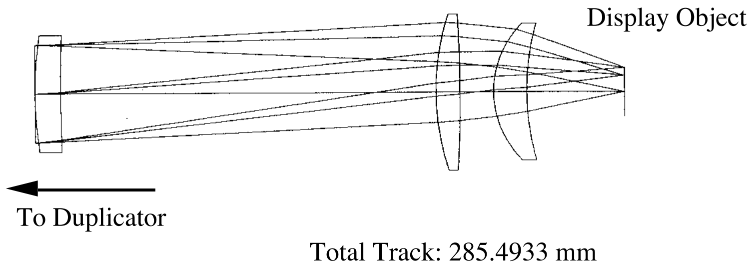

Figure 8-(i). Objective layout

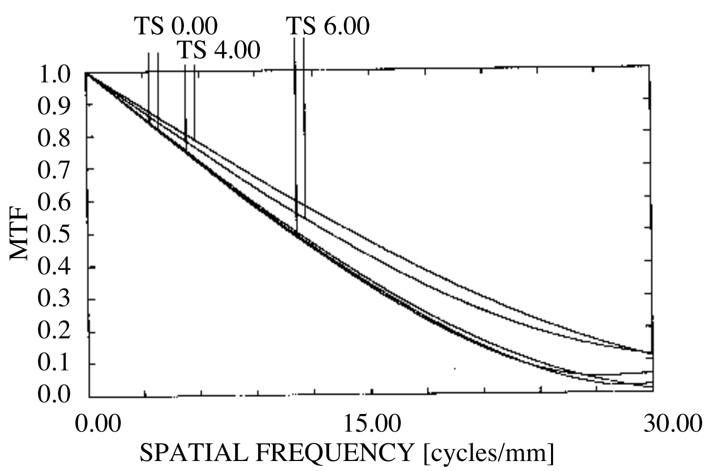

Figure 8-(ii). Objective MTF

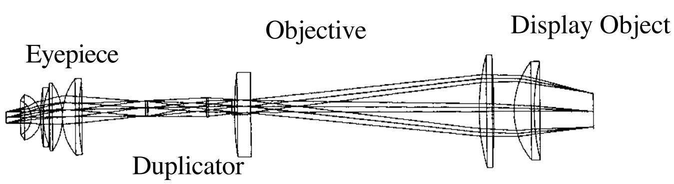

Figure 9-(i). Real model layout at position 1

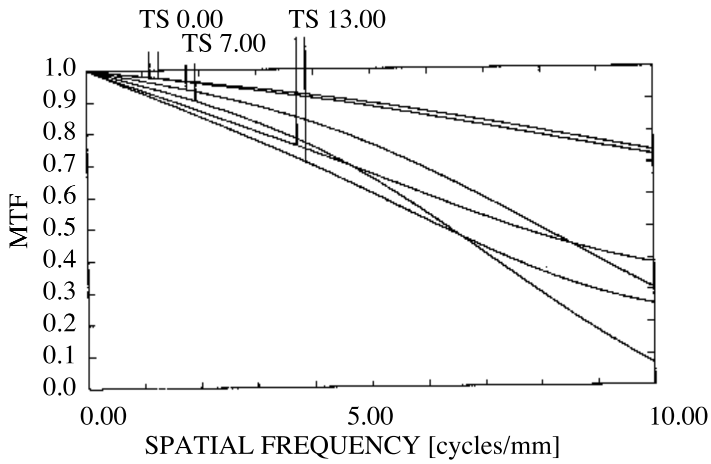

Figure 9-(ii). Real model MTF at position 1

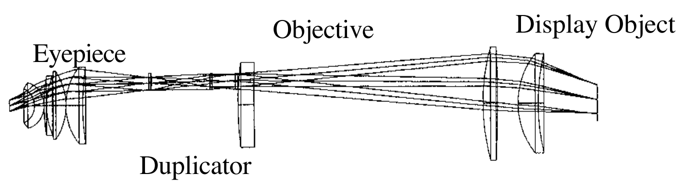

Figure 10-(i). Real model layout at position 2

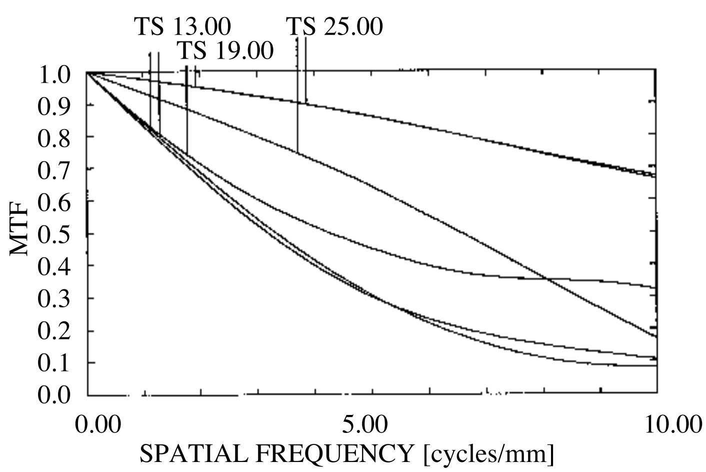

Figure 10-(ii). Real model MTF at position 2