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TECHNICAL REPORT

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3D display devices –
Part 51-1: Generic introduction of aerial display

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FOREWORD

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IEC TR 62629-51-1, which is a Technical Report, has been prepared by IEC technical committee 110: Electronic displays.

The text of this Technical Report is based on the following documents:

Draft TR	Report on voting
110/1178/DTR	110/1190/RVDTR

Full information on the voting for the approval of this Technical Report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62629 series, published under the general title *3D display devices*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

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- withdrawn,
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- amended.

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INTRODUCTION

This document intends to gather technical information on aerial displays, and to clarify the relationship to normative aspects of the standardization in this technology area.

3D DISPLAY DEVICES –

Part 51-1: Generic introduction of aerial display

1 Scope

This part of IEC 62629, which is a Technical Report, provides general information for the standardization of aerial displays. This document includes an overview of the technology, critical performance characteristics, issues of optical measurements, and other information.

2 Normative references

There are no normative references in this document.

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
aerial display
display that forms a real image in mid-air by use of an incoherent light-source display and a passive optical component to converge diverging light from the light-source display

Note 1 to entry: See 4.1 and 4.2.

3.2 Abbreviated terms

AIRR	aerial imaging by retro-reflection
BS	beam splitter
CMA	crossed-mirror array
CTF	contrast transfer function
DCRA	dihedral-corner-reflector array
DFD	depth-fused 3D
FPD	flat-panel display
FPGA	field programmable gate array
GPU	graphics processing unit
HMD	head-mounted display
HOE	holographic optical element
HUD	head-up display
LCD	liquid-crystal display
LED	light-emitting diode

LMD light measuring device

MLA micro-lens array

MTF modulation transfer function

NA numerical aperture

OLED organic light-emitting diode

PD photo detector

PL polarizer

PSF point-spread function

QWR quarter-wave retarder

RR retro-reflector

SMA slit-mirror array

4 Aerial display technologies

4.1 General

In a general sense, an aerial display refers to a display that shows information in mid-air, where there is no hardware. Thus, a display carried by a drone or a balloon is not an aerial display. There are a variety of display techniques that show information in mid-air. Perception of a floating image can be evoked by use of conventional 3D display techniques, such as stereoscopic displays, holographic displays, and light-field displays. In a stereoscopic display, the perceived 3D position depends on the viewer's eye positions. However, the real image of a light-source display is perceived at the same 3D position for everyone.

Classification of 3D display techniques is shown in Table 1. 3D display techniques are classified as real-image formation and virtual-image formation with or without hardware on the image. Aerial displays in the general sense are indicated in the upper left side in Figure 1.

Table 1 – Classification of displays that show an image in mid-air

	No hardware on or in front of the image	Hardware on or in front of the image
Real image	Holographic display Light-field display Information screen that is formed by use of a passive optical component, such as lens, MLA, DCRA, SMA, RR, and HOE	Transparent display Light-field display Semi-transparent screen, such as nano-diamond screen, fog, mist with a projector Rapid motion of a display hardware Laser-induced plasma
Virtual image	None	Pepper's ghost HUD HMD

The essentials of an aerial display in a strict sense are shown in Figure 1. An aerial display in the strict sense forms a real image in mid-air by use of an incoherent light-source display and a passive optical component to converge diverging light from the light-source display.

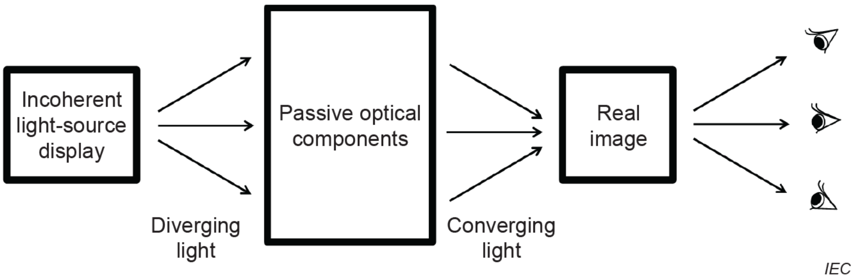

Figure 1 – Essentials of aerial display in the strict sense

As shown in Table 1, a holographic display can form a real image in mid-air. However, a holographic display is not an aerial display in the strict sense because the electric holographic display uses a coherent light source and an active optical component for image formation.

A light-field display can be composed of an incoherent source display and a passive optical component, such as an MLA on an FPD. Furthermore, some light-field displays can converge light rays and form an information screen in mid-air. As illustrated in Figure 1, the optical component in the aerial display converges the diverging light rays from the light-source display, while a light-field display controls the direction of the semi-paralleled lights from the MLA. The aerial display does not reproduce the light field.

Real-image formation makes possible aerial applications. Aerial displays for interaction and public signage require the following features:

a) the image can be handled directly with a naked hand;
b) the image position is the same for everyone;
c) the image is visible to the naked eyes without eyewear;
d) the image is altered within a sufficiently short latency.

The features a) and b) are maintained by forming a real image in mid-air without hardware on the screen. Because feature c) depends on the applications of the aerial display, the requirements and performance factors will be discussed based on the interaction, including human factor, in the future. Note that a passive optical component does not increase latency.

Use of an incoherent light source is free from laser safety issues. For use by the general public, a limited group of aerial display techniques is suitable with regard to eye safety, cost, mass production, and 3D position. Use of mass-produced passive optical elements reduces their production cost and driving circuit. The real image in mid-air is perceived at the same position by multiple viewers. Thus, the aerial display maintains the requirements mentioned above.

The depth perception of the aerial image is given with physiological depth cues. Thus, the aerial display is a kind of 3D display, which is defined as a display device giving depth perception with physiological depth cues.

4.2 Principle

An aerial display can be realized by use of a light-source display and some imaging optics, [1] to [10][1]. The following methods use a passive optical component. The role of the passive optical component in the aerial display in the strict sense is to converge diverging light rays from the light-source display to the aerial real image. The incoherent light-source display emits diverging light rays. The diverging light impinges on the passive optical component, which changes the direction of each light ray so that light converges to the image position in mid-air. Thus, the real image of the light source is formed because diverging plural rays emitted from a source position converge to the single position. The formed real image is visible over a wide range of angles

[1] Numbers in square brackets refer to the Bibliography.

when light rays from a wide range converge to the image position. Furthermore, the 3D position of the aerial image is determined by the optical system and independent from the viewing position. Thus, the 3D position is the same for multiple viewers.

Thus, this document deals with aerial displays that are formed by use of a conventional display device such as LCD, OLED, and LED as an incoherent light-source display and a passive optical component such as Fresnel lens, MLA, DCRA, SMA, RR, or HOE.

Figure 2 shows the typical structures of an aerial display. Figure 2a) is a transmissive imaging type using a Fresnel lens or two layers of MLAs. The real image is formed on the other side of the light-source display relative to the optical component. Thus, the light-source display is located behind the optical component. The image position and the image size are not always the same as the light-source display. The light-source display sometimes becomes noticeable behind the aerial image. Figure 2b) is a plane-symmetrical imaging type using a DCRA, SMA, or RR. The real image is formed on the plane-symmetrical position and the size of the light-source display with respect to the optical component. This structure features the blocking of the direct viewing of the light-source display. Figure 2c) is a reflective imaging type using a HOE. The real image is formed on the same side of the light-source display. The existence of the light-source display is noticeable.

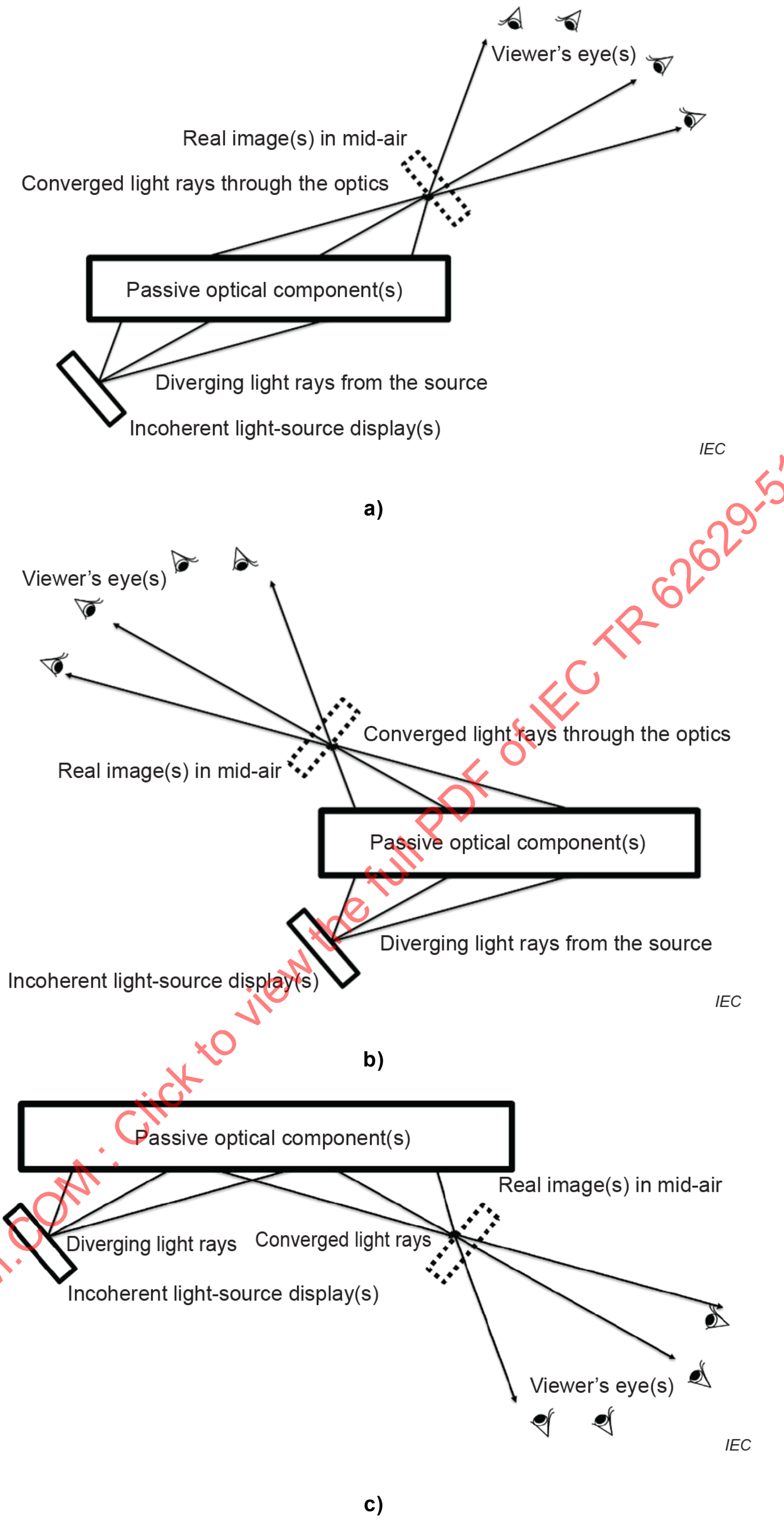

Figure 2 – Typical structures of aerial display

Figure 3 shows examples of formed aerial images. The aerial image is formed between the hands in the air. There is no physical hardware on the information screen. The aerial image is visible over a wide range of angles.

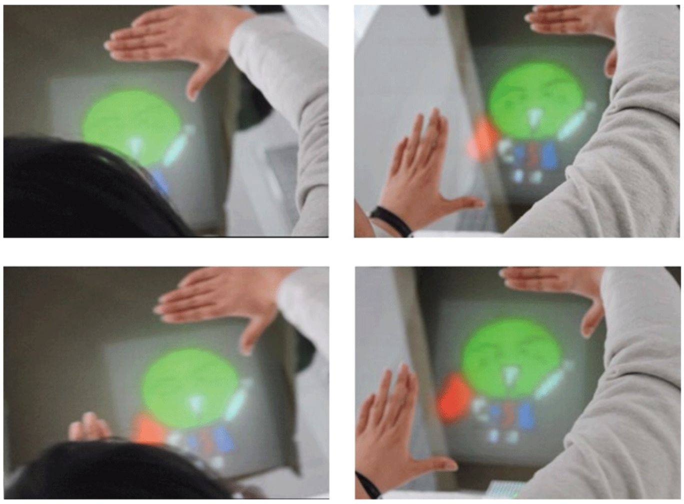

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Figure 3 – Observation of an aerial image from different directions

Figure 4 shows the confirmation of real-image forming. The aerial image of a LED sign is formed in the air. By placing the observation screen at different distances from the optical component, a fine image is observed at the image position. The image is defocused when the screen is moved forward or backward from the image position.

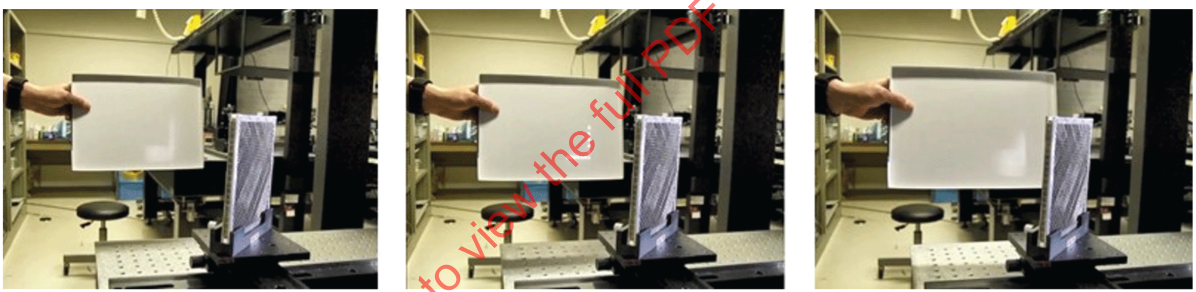

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Figure 4 – Observation of an aerial image by placing a screen at different distances

4.3 Variations of optical components

4.3.1 Convex lens

A source display is imaged by use of a convex lens including a Fresnel lens. Although the viewing angle of the aerial screen is limited by the NA of the lens, this technique can magnify the screen size.

4.3.2 Dual micro-lens arrays (MLAs)

Unlike the light-field display, this method employs two-layered MLAs. Elemental lenses in the first MLA and the second MLA compose relay optics so that each pair of lenses forms an erected image. The NA of the elemental lens is higher than the Fresnel lens and gives a wider viewing angle.

4.3.3 Dihedral-corner-reflector array (DCRA)

The DCRA is composed of pillars [1]. Each pillar contains two perpendicular reflection surfaces, as shown in Figure 5. Light from a source display impinges on the pillars. After double reflections, the light converges to the plane symmetrical position of the light source with respect to the DCRA, as shown in Figure 6.

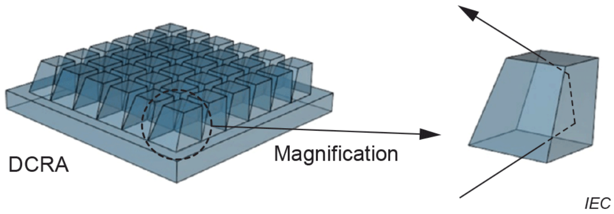

Figure 5 – DCRA

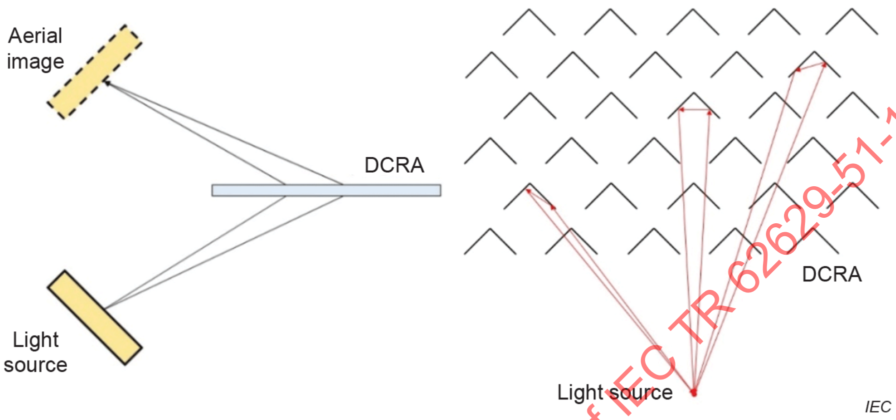

Figure 6 – Converging lights using a DCRA

4.3.4 Dual slit-mirror arrays (SMAs)

Dual SMAs are composed of two layers of arrays of slit mirrors. The direction of the second layer is orthogonal to the first layer, as shown in Figure 7. Light from a source display is reflected vertically and horizontally and converges to the plane-symmetrical position of the light source with respect to the dual SMAs, as shown in Figure 8. Its light-use efficiency becomes higher than a DCRA with the same thickness.

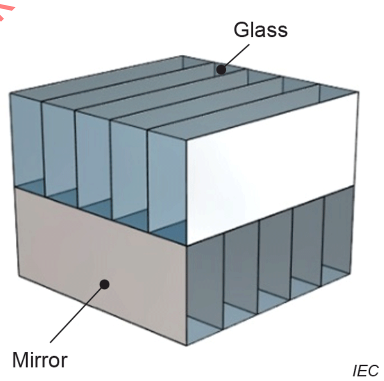

Figure 7 – Dual SMAs

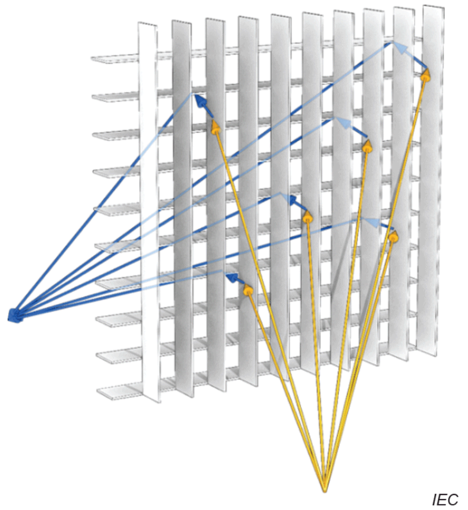

Figure 8 – Converging light using dual SMAs

4.3.5 Retro-reflector (RR)

The RR reflects incident lights reversely along their incident directions, as shown in Figure 9. As shown in Figure 10, AIRR consists of three elements, which are a light-source display, a BS such as a half mirror, and an RR. Light from the source flat-panel display (FPD) is reflected on a half mirror and impinges on the RR. Retro-reflected light reversely travels the optical paths. A portion of the retro-reflected light is reflected on the half mirror and converges to the original source point. However, the retro-reflected light that transmits through the half mirror converges to the aerial image position. The aerial image position is the plane-symmetrical position of the light source position regarding the half mirror.

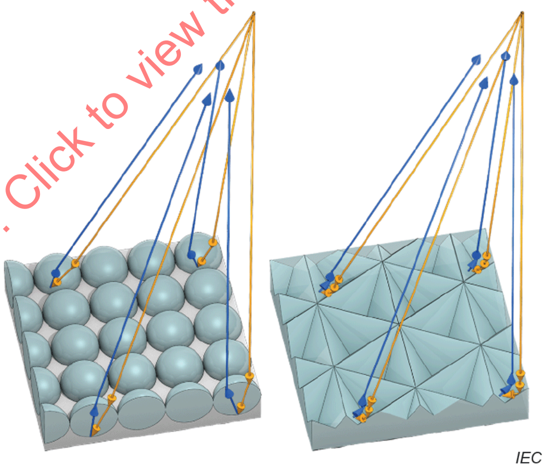

Figure 9 – RR

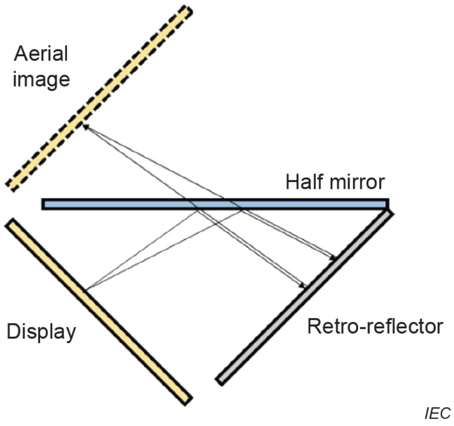

Figure 10 – Converging light using an RR

4.4 Variations of the real image

4.4.1 General

The combination of a light-source display and an optical component generates a wide variety of real images in the air. For example, when a stereoscopic display is used for the light-source display, the aerial screen gives a stereoscopic effect.

4.4.2 Aerial 3D display

Depth-fused 3D (DFD) [11] has been proposed as a 3D display method without special glasses. DFD changes a layered 2D image into 3D. Reproduced depth with a DFD display depends on the luminance ratio between the front and the rear images. Figure 11 shows an optical system to form two-layered aerial images. Light emitted from Light source 1 is reflected by Beam splitter 1 and reaches Retro-reflector 1. Light that is retro-reflected by Retro-reflector1 transmits through the beam splitter and forms Aerial image1. Regarding Aerial image 2, light emitted from Light source 2 is reflected by Beam splitter 2 and reaches Retro-reflector 2. Light that is retro-reflected by Retro-reflector 2 transmits through Beam splitter 2 and reflected at Beam splitter1. After these transmissions and reflections, Aerial image 2 is formed. Aerial image 1 and Aerial image 2 are formed closely. Therefore, these two aerial images can be overlapped and depth-fused. In order to overlap the two aerial images, it is necessary to separate Aerial image 2 from Beam splitter 1.

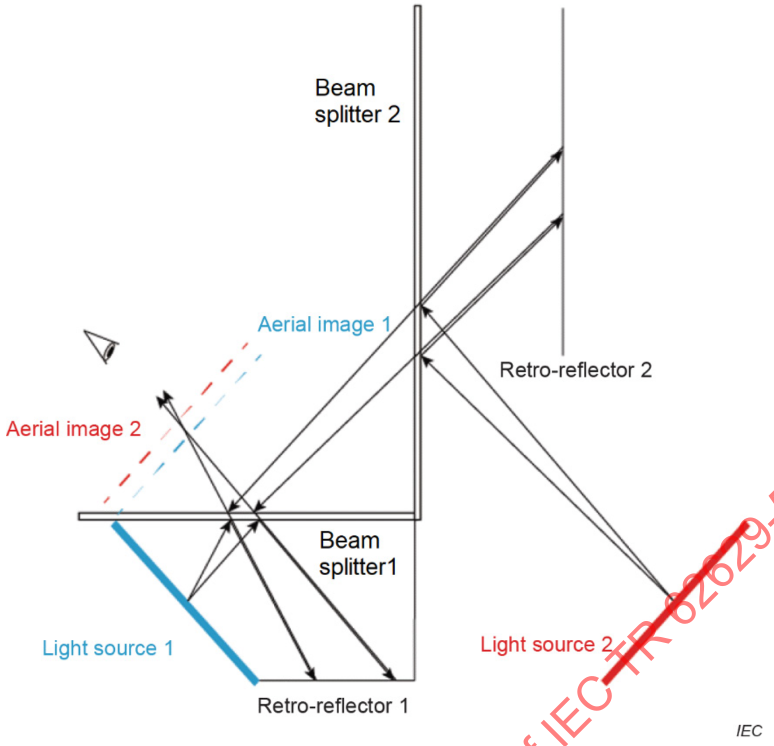

Figure 11 – Optical system to form two-layered aerial images for depth-fused 3D display

4.4.3 Aerial light-field display

By using a light-field display as the light-source display, the light field is reproduced from the aerial screen. A typical optical system for an aerial light-field display is shown in Figure 12. Because the real image that is formed with AIRR is the plane-symmetrical of the light-source display with respect to the beam splitter, the source light-field display shows a 3D image in the reversed perspective. Thereafter, the perspective of the formed aerial image is reversed back through the imaging optics and gives a normal 3D image in the air.

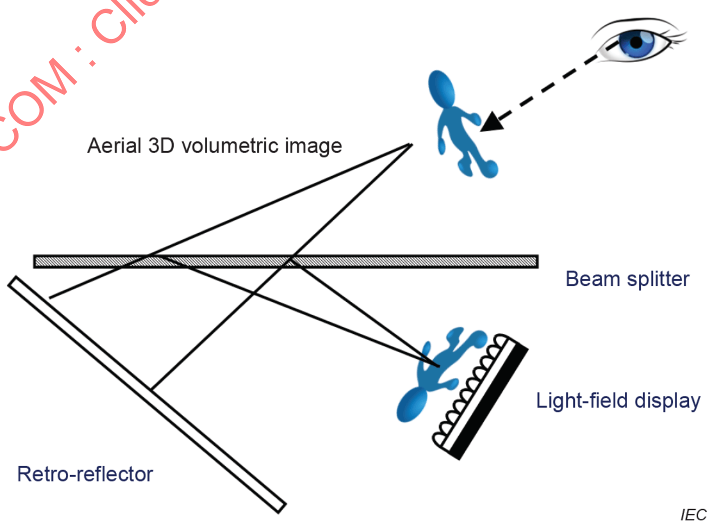

Figure 12 – Optical system to form an aerial light-field image with AIRR

4.4.4 Multiple aerial-image generation

In order to form multiple images of a single light source, the method employs beam splitters that are placed in parallel. The optical configuration to form multiple aerial images is shown in Figure 13. The light source is located between a pair of parallel beam splitters. The light is reflected repeatedly on a pair of parallel beam splitters. Light rays are transmitted through the bottom beam splitter and reflected reversely toward the incident direction in the retro-reflector. The retro-reflected lights are transmitted through the top beam splitter and form multiple aerial images of the light source.

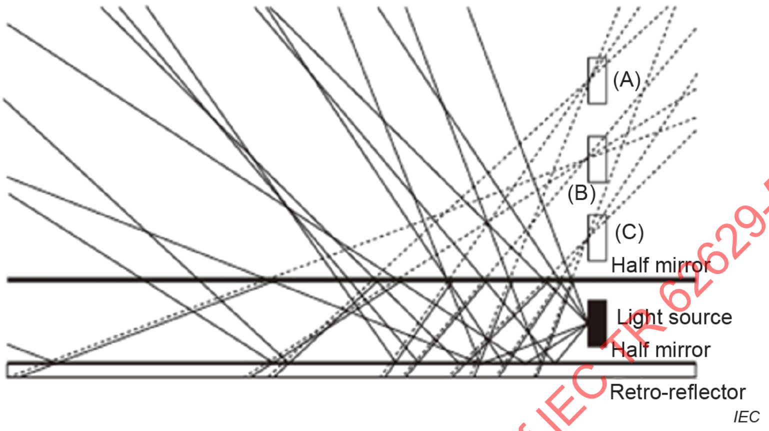

Figure 13 – Optical system to form multiple images in the air by use of a single light source

4.5 Key optical elements

State-of-the-art optical components are used to form aerial images. The key optical elements and fabrication techniques are as follows:

– glass optical plate;
– plastic optical component and its fabrication process;
– anti-reflection coating and film;
– reflective polarizer;
– retarder film.

4.6 Applications

A market report forecasts that the aerial display market will be over 30 billion USD in 2040 [12]. Half of the market is related to the car industry. The rest concerns the entertainment and signage industries. Typical application technologies include:

a) aerial gesture interface;
b) aerial head-up displays (HUDs);
c) aerial screens in theatres and concerts;
d) aerial digital signage;
e) aerial touch panel;
f) aerial buttons.

5 Performance characteristics and specifications

5.1 General

The performance characteristics and specifications for aerial displays include not only the optical performance, but also the mechanical, electrical, and temporal performance. This document mainly focuses on the optical performance because requirements for the other performances are quite specific to the applications. As a visible display, optical performance is one of the most important factors for applications of the aerial display.

5.2 Optical performance

5.2.1 Items related to conventional image quality

The image quality in the formed aerial image includes luminance, colour, and contrast. These characteristics can be measured with conventional equipment by adjusting the focus on the measured pixel.

In an aerial display, the viewer always sees the optical component behind the aerial image. Reflection and scattering on the optical component decrease the contrast of the apparent image. Therefore, the contrast of the aerial image depends on ambient lights. The measurement methods in 62977-2-2 [15] might not be applicable because the geometries are different from flat panel displays.

5.2.2 Items related to resolution

Unlike a conventional FPD, the resolution of an aerial display does not always correspond to the number of input pixels per physical length unit of the display. The resolution of the aerial display depends on the optical component and optical setups because the real image is formed by converging the diverging light (see Annex A). For example, the aperture limitation of each optics causes diffraction. Diffraction reduces image resolution. Furthermore, the wavefront of the converging light is discontinuous and does not form a fine image because each wavefront does not exactly converge to a single point.

When the resolution measurement shows a different result from the input signal resolution, the definition of the pixel might not be satisfied. The pixel as the unit of display resolution might be inappropriate for the unitless of the display resolution. Thus, the resolution can be evaluated in the optical performance characteristics that are used in the imaging systems, such as PSF and MTF. Theoretically, PSF and MTF are related in the Fourier transformation, and MTF measurement [13] is considered to show resolution performance.

5.2.3 Items related to floating distance

One of the specific characteristics in aerial displays is floating distance. The floating distance is measured by the distance between the real image and the optical component. The position of the real image is determined by placing a screen on the real image, where the sharpest image is observed on the screen.

While depth of focus of the aerial image can be determined by the acceptable circle of confusion, the acceptable limit depends on the application and the viewing conditions.

5.2.4 Items related to viewing direction range

Viewing direction range is one of the important factors for selecting the best aerial display for an application. Use of an optical component limits the viewing direction. The aerial image is visible within the position where the optical component is visible because there is no scattering material in mid-air. Furthermore, the aerial image is not always visible while the optical component is visible. For example, a DCRA and dual SMAs converge light after double reflections. There is a limited range of incident angle to converge light. Beyond the limited angle, the aerial image is suddenly invisible. Unlike the conventional FPD, luminance of the aerial image does not always decrease gradually. Thus, the viewing direction range cannot be determined by the luminance at the centre.