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# 33.2: Viewing Angle: A Matter of Perspective

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**Abstract**

Setting viewing-angle requirements and specifications for displays depends on how viewing-angle is defined. There is significant confusion in the industry regarding the definition and use of horizontal and vertical viewing-angle. Moreover, the relations between viewing-angle defined in Cartesian coordinates and common representations in spherical and goniometer-specific coordinates are often confused. This paper will show how incorrect definitions of viewing-angle and failures to apply appropriate transformations between coordinate systems lead to errors in setting specifications and reporting results.

**Introduction**

The optical performance characteristics of many current display technologies exhibit strong viewing-angle dependencies. The rendered luminance, contrast and color change rapidly across viewing-angle. These effects are most commonly associated with liquid crystal displays (LCDs); but even the venerable CRT display with its nominally lambertian viewing characteristics exhibits viewing-angle dependent behavior when there is an anti-reflection or contrast enhancement treatment on the faceplate or when an external anti-glare or privacy screen is employed.

Many display applications bring with them fairly stringent viewing-angle requirements: military and civilian avionic displays for cross-cockpit viewing are examples, as are displays for other vehicle applications. Displays for industrial and medical applications also have viewing-angle performance requirements; and, of course, large flat panel displays for desktop workstations are called upon to substantially match the viewing-angle performance of CRTs which are currently the dominant displays on the desktop.

The basis for setting viewing-angle requirements and specifications naturally depends on how the viewing-angle is defined. There are at least four different definitions of viewing-angle currently in use in the display community: spherical, horizontal/vertical, north polar goniometric and east polar goniometric [1]. Spherical coordinates are defined with respect to the display, horizontal/vertical viewing-angles are defined with respect to the viewer's environment, and the goniometric viewing-angles are defined with respect to a specific display measurement system. There is often significant confusion among the last three viewing-angle definitions. For instance, viewing-angles from a goniometric measurement are often confused with horizontal/vertical viewing-angles or goniometric viewing-angles are transformed to spherical coordinates in an incorrect fashion. These errors are not readily apparent until the viewing-angle is greater than about 35° or 40° off the display normal in a non-principal direction, that is, at a compound viewing-angle. All of the definitions, in fact, coincide along the principal horizontal and vertical viewing directions. Since many current and future viewing-angle requirements call for good image fidelity out to 60° or more, it is imperative that display customers, vendors, and component suppliers employ functionally equivalent definitions of viewing-angle performance.

This paper will carefully define each of the four viewing-angle coordinate systems and their relations to one another. We will show through diagram and example how incorrect definitions and assumptions about viewing-angle can lead to errors and confusion in setting performance specifications and reporting measurement results.

**Viewing-Angle System Definitions**

The set of axes of the coordinate system that we use here has its origin at the center of the screen and moves with the display. The z-axis is normal to the screen, the positive x-axis is to the right side of the screen and the positive y-axis is to the top of the screen. See Figure 1.

The definition of viewing-angle in spherical coordinates is a natural starting place since this system is familiar to many in the display industry. It is often used to report modeling and measurement results of viewing-angle dependent quantities. The viewing-angle is designated by $\theta$ and $\phi$. $\theta$ is the inclination angle from the *z*-axis and $\phi$ is the counter-clockwise angle from the positive *x*-axis in the *x*-*y* plane. See Figure 1.

As illustrated in Figure 2, horizontal ($\theta_H$) and vertical ($\theta_V$) viewing-angle in Cartesian coordinates are defined as the inclination angles of the viewing direction resolved into components in the horizontal *z*-*x*

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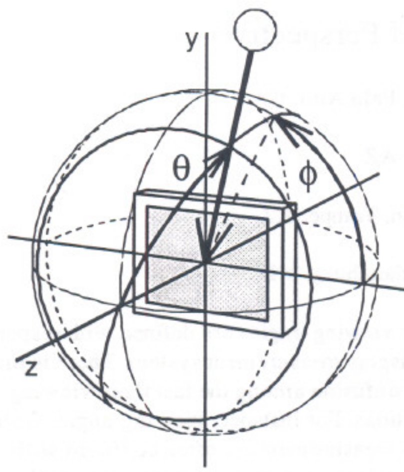


*Figure 1. Spherical Coordinates*

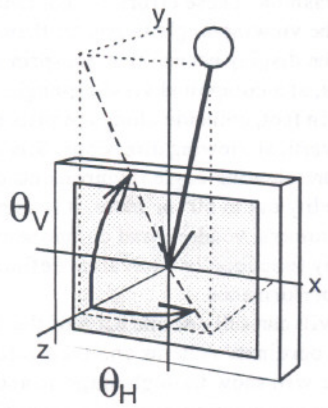


*Figure 2. Horizontal and Vertical Viewing Angle*

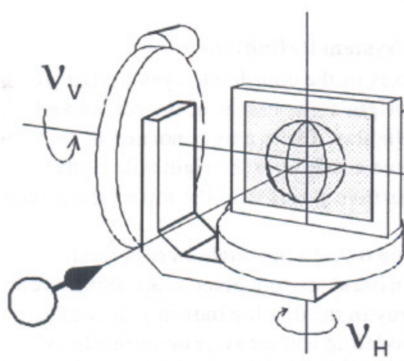


*Figure 3. North polar goniometer*

plane and vertical $z$-$y$ plane, respectively. This viewer-centric representation is often used to define viewing volumes for human factors or ergonomic specifications, such as for workplace layouts or cockpit integration of avionics displays [2,3]. These angles are not the same

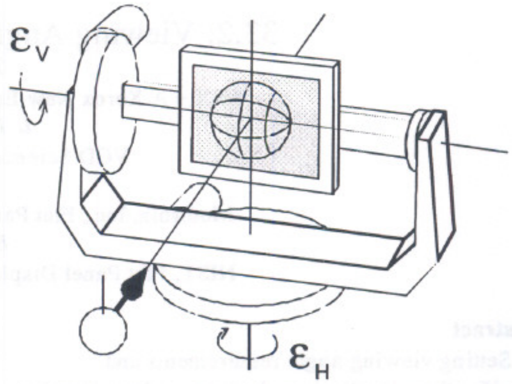


*Figure 4. East polar goniometer*

as those associated with goniometric measurement systems, which we will now define.

A goniometer is an apparatus with two orthogonal axes of rotation that rotates an object (and perhaps a detector) to a particular orientation in order to measure direction-dependent quantities of the object. Goniometers are used in the illumination [4] and display [5] industries to characterize devices. The device under test (DUT) is situated on the goniometer system such that the point on the DUT to be measured is coincident with the two rotation axes of the goniometer. This alignment is essential in order to keep the point of interest on the DUT fixed in space for all goniometer orientations. There are two common goniometer systems that we describe here: north polar and east polar. Both of these systems rotate only the DUT. These kinds of goniometers have two orthogonal rotation axes such that one axis rotates with the rotation of the other axis. The axis that remains fixed is the independent axis while the axis that rotates with the rotation of the independent axis is the dependent axis. In each case the axis that defines the name of the system, i.e. the polar axis, is the dependent axis.

In the north polar goniometric system, the independent axis is horizontal and the dependent axis is rotated by the horizontal axis in a vertical plane. Figure 3 shows the north polar goniometer with a display oriented such that a detector or observer is aligned along the normal to the display. The circular arcs on the sphere shown on the display are traced out by the stationary axis from the observer to the measured spot on the display as it is rotated by the goniometer. In this system, the vertical rotation is designated as $\nu_V$ and the horizontal as $\nu_H$.

Figure 4 shows the east polar goniometric system where the independent axis is vertical and the dependent axis is rotated by the vertical axis in a horizontal plane. The figure shows the east polar goniometer with a display oriented such that a detector or observer is aligned along the normal to the display. The circular arcs on the sphere shown on the display are

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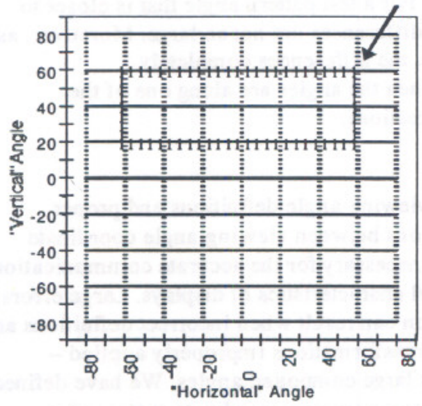


*Figure 5. Horizontal/Vertical and goniometer test pattern.*

traced out by the stationary axis from the observer to the measured spot on the display as it is rotated by the goniometer. In this system, the vertical rotation is designated as $\varepsilon_V$ and the horizontal as $\varepsilon_H$.

**The Transformations**

To demonstrate how problems can develop we show the following test pattern. Figure 5 is a plot of a series of "lines of constant viewing-angle", both horizontal and vertical, at every 20 degrees along both axes (the figure also includes an inscribed volume at ±60° horizontal, +20° to +60° vertical outlined by the crosses which will be discussed later). This test pattern can be viewed as residing in any one of the horizontal/vertical, north polar or east polar systems. Such a set of angles could be accessed with a goniometer, for instance, by repeatedly setting a vertical rotation angle and sweeping the horizontal rotation axis and vice versa. The differences between the three systems are graphically seen as we map the test pattern in Figure 5 to the common system of spherical coordinates. The transformation equations are given in Table 1. Figure 6 shows how this pattern maps into the spherical coordinate system from the north polar goniometric system, i.e., $(\nu_H, \nu_V) \rightarrow (\theta,\phi)$. The resulting transformed pattern is very reminiscent of the latitude and longitude lines on a globe, with the rotation axis of the globe oriented vertically; hence the name north polar. Figure 7 shows how the test pattern from Figure 5 maps into the spherical coordinate system from the east polar goniometric system, i.e., $(\varepsilon_H, \varepsilon_V) \rightarrow (\theta,\phi)$. This pattern is also reminiscent of the latitude and longitude lines on a globe, but with the rotation axis of the globe oriented horizontally; hence the name east polar. Note the severe distortion near the "poles" of each transformed goniometric pattern. These transformed goniometric patterns exhibit 2-fold reflection symmetry, with mirror planes at 0° and 90°. This represents a lower degree of reflection symmetry compared to the original test

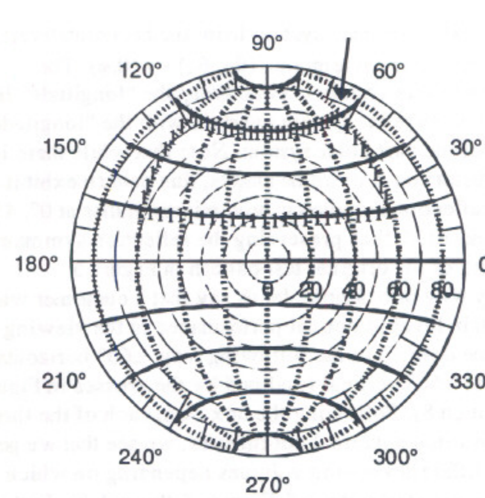


*Figure 6. Mapping North Polar to Spherical.*

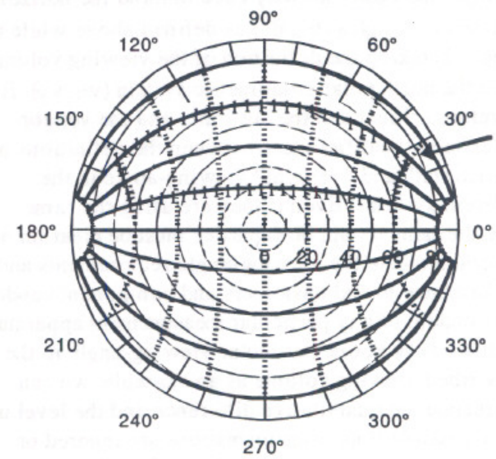


*Figure 7. Mapping East Polar to Spherical.*

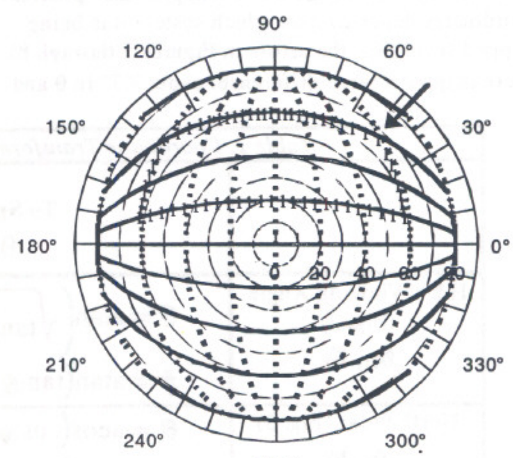


*Figure 8. Mapping Horizontal/Vertical to Spherical.*

pattern in Figure 5, which has 4-fold reflection symmetry.

Figure 8 shows how the test pattern maps into the

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spherical coordinate system from the horizontal/vertical viewing-angle system, i.e., $(\theta_H, \theta_V) \rightarrow (\theta, \phi)$. The pattern in this system is effectively the "longitude" lines of the north polar system overlaid with the "longitude" lines of the east polar system. Note that while there is still distortion at extreme angles, this pattern exhibits 4-fold reflection symmetry, with mirror planes at 0°, 45°, 90° and 135°, thus preserving the reflection symmetry, at least, of the original test pattern in Figure 5.

By way of example, let us say that a customer wants a certain level of optical performance in the viewing volume defined in the following way: ±60° horizontal, +20° to +60° vertical (outlined by the crosses in Figures 5 through 8). Following the box from each of the three systems into spherical coordinates, we see that we get very different viewing volumes depending on which system we start with (c.f. Figures 6 through 8). In this example the customer may have in mind the horizontal and vertical angles $(\theta_H, \theta_V)$ as defined above while the vendor is taking the definition of the viewing volume to be in the north polar goniometric system $(\nu_H, \nu_V)$. It is therefore critical that the customer and the vendor understand the differences between the definitions of "horizontal" and "vertical" viewing-angle in the different systems. Even if they are using the same measurement set-up, both parties must be clear on how to communicate the viewing-angle requirements and performance to end customers and component vendors independent of any particular measurement apparatus.

If we look at one particular viewing-angle in the prescribed viewing volume as an example, we can appreciate the quantitative difference and the level of error possible if the transformations are ignored or improperly understood. The original test pattern angle (+60°H, +60°V) in Figure 5 is mapped into spherical coordinates depending on which system it is being mapped from (See the arrow in Figures 5 through 8). There is quite a large difference, about 7.7° in $\theta$ and ±18.4° in $\phi$. For a test pattern angle that is closer to normal, the differences are not so large. Moreover, as noted above, the differences completely disappear when the angles are along one of the principle directions.

## Conclusion

Precise viewing-angle definitions and proper transformations between viewing-angle coordinate systems are necessary for the accurate communication of the optical characteristics of displays. Large errors and confusion can result when incorrect definitions are adopted or transformations improperly applied – especially at large compound angles. We have defined four of the most common coordinate systems for describing viewing-angle. The equations that describe the transforms between spherical coordinates and the three systems most commonly chosen for "horizontal" and "vertical" viewing-angle are reported.

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*Table 1. Coordinate Transformations to and from spherical coordinates*

| | To Spherical $\theta, \phi$ | From Spherical $\theta, \phi$ |
|---|---|---|
| H&V Viewing Angle (Fig. 2) $\theta_H, \theta_V$ | $\theta = \mathrm{atan}\left(\sqrt{\tan^2(\theta_H) + \tan^2(\theta_V)}\right)$ <br> $\phi = \mathrm{atan}(\tan(\theta_V)/\tan(\theta_H))$ | $\theta_H = \mathrm{atan}(\tan\theta \cos\phi)$ <br> $\theta_V = \mathrm{atan}(\tan\theta \sin\phi)$ |
| North Polar (Fig. 3) $\nu_H, \nu_V$ | $\theta = \mathrm{acos}(\cos(\nu_H)\cos(\nu_V))$ <br> $\phi = \mathrm{atan}(\tan(\nu_V)/\sin(\nu_H))$ | $\nu_H = \mathrm{atan}(\tan\theta \cos\phi)$ <br> $\nu_V = \mathrm{asin}(\sin\theta \sin\phi)$ |
| East Polar (Fig. 4) $\varepsilon_H, \varepsilon_V$ | $\theta = \mathrm{acos}(\cos(\varepsilon_H)\cos(\varepsilon_V))$ <br> $\phi = \mathrm{atan}(\sin(\varepsilon_V)/\tan(\varepsilon_H))$ | $\varepsilon_H = \mathrm{asin}(\sin\theta \cos\phi)$ <br> $\varepsilon_V = \mathrm{atan}(\tan\theta \sin\phi)$ |

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