**WHY 4K: VISION & TELEVISION**

Mark Schubin
SchubinCafe.com

*Abstract*

*Throughout the history of functional television, there have been moves towards higher definition, countered by the existence of lower-definition standards. Few of the choices of definition have been related to human visual acuity, however, which varies according to many factors.*

*The latest push for higher definition, to go beyond HDTV, is being driven in part by considerations unrelated to cable television, such as ease of program production and declining movie attendance and TV-set sales. The current era of bit-rate-reduced digital-video transmission, however, might nevertheless be an ideal time to offer consumers what could be the next level of increased picture definition.*

## THE ORIGIN OF DEFINITION

### Language and Vision

Although citations for other senses of the word *definition* in the *Oxford English Dictionary* date back to the 14th century, the earliest citation for the sense relating to a manufactured system's "capacity to render an object or image distinct to the eye" is from 1878 (with two slightly older citations related to visual distinctness as rendered by an artist or in a natural formation).[1] The date might be associated with a different publication.

In 1862, Hermann Snellen published (in German) a book about something that he called *optotypes*.[2] In English, the book might be called *Sample Letters, for determining visual acuity*. The book introduced two concepts that have lasted to the present day: the idea that "normal" vision is 20/20 and the familiar letters on an eye chart, such as the *T* shown in Figure 1 below.

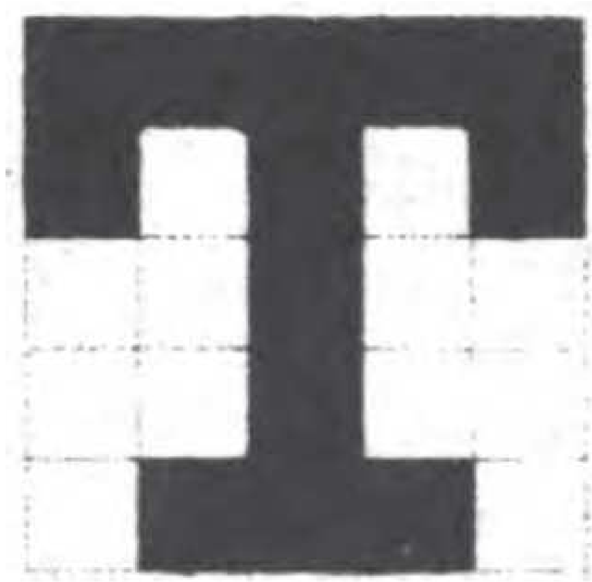

Figure 1: An 1862 Snellen Optotype

As the faint marks behind this optotype taken from his book indicate, the letter occupies a grid five units high by five units wide, and every element of the character, whether black or white, occupies one grid space. Snellen's definition of normal vision involved the ability to resolve features that subtended an angle of one arc minute (one-sixtieth of a degree) on the eye's retina.

If the whole character, therefore, were printed at a particular size and placed at a particular distance so that it would subtend an angle of five arc minutes, it would be able to be read with "normal" vision. The distance chosen was twenty feet so as to avoid visual issues associated with presbyopia (age-related inability to focus at short distances caused by the hardening of the eye's lens), a condition that usually first becomes noticeable around the age of 45.[3] In terms of visual focus, a distance of 20 feet is close to infinite.

Below is the familiar top of an eye chart based on Snellen's optotypes.[4] It was said in 1995 to have had more copies printed and sold in America than any other poster.[5] The top *E* on this chart is labeled "200 ft." on the left and "60 m" on the right.

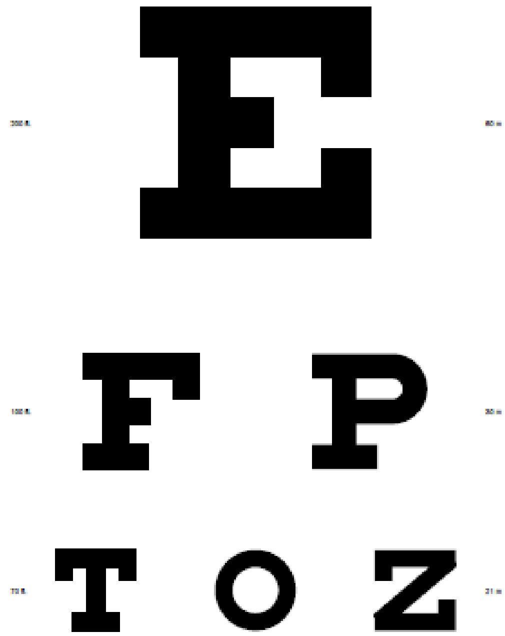


Figure 2: Top of an Eye Chart

The "200 ft." designation means that a person with "normal" visual acuity, as defined by Snellen, can distinguish that *E* at a distance of 200 feet, (or 60 meters). Vision defined as "20/20" (or "6/6") indicates an ability to see at 20 feet (or six meters) what a person with "normal" visual acuity can also see at 20 feet (or six meters).

Someone who could not read any letter smaller than the top *E* would be said to have "20/200" (or "6/60") visual acuity, the ability to read at 20 feet (or six meters) only what a person with "normal" vision can read at 200 feet (or 60 meters).

<u>Issues Associated with the Definition</u>

In nothing described to this point has anything been said about the illumination of the chart, the perceived contrast of the characters, or the definition of the edges of optotypes printed on the chart. Regarding the last, note, for example, that the edges of the *T* of Figure 1 are not as well defined as those of the *E* of the chart of Figure 2.

Snellen, himself, was aware of other issues associated with visual acuity. Below is a portion of another chart from his 1862 book. It shows not only an inversion of the color of the optotypes and the background but also a variation in contrast between the two lines of optotypes shown here. Snellen was clearly aware that contrast could affect visual acuity.


Figure 3: Portion of Snellen 1862 Chart with Color Inversion and Contrast Variation

As for the optotype edges, they contain higher spatial frequencies than the feature sizes would suggest. A pair of lines, one black and one white, suggest a cycle. If each line subtends a retinal angle of one arc minute, there would be 60 such lines in a degree. With half the lines white and half black, the spatial frequency could be said to be 30 cycles per degree (30 cpd).

Unfortunately, at a spatial frequency of 30 cpd, the edges of the optotypes would be soft.

The effect can be observed below. The *E* of Figure 2 was resized several times in image-manipulation software. Is it still readable as an *E*? It should seem clearer farther away.

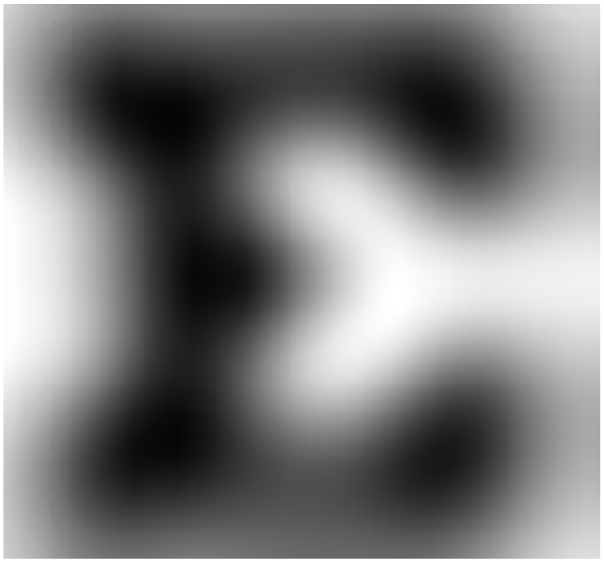

Figure 4: Snellen's *E* Filtered

The images below illustrate how sharp edges require higher spatial frequencies. Snellen's *E* is shown at the upper right. To its left is what its vertical strokes might look like if sinusoidal, and, to the left of that, a graph of the sine function between black and white.

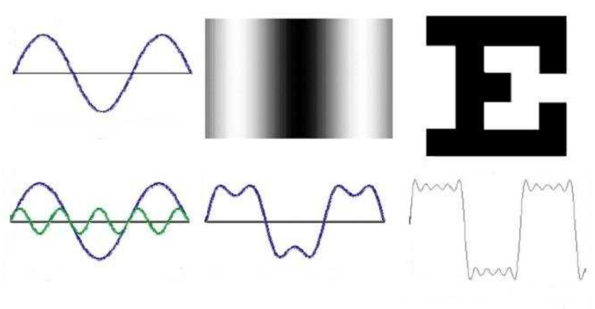

Figure 5: Adding Harmonics for Edges

In the lower row of Figure 5, at left is the same sine wave (the "fundamental") with another sine wave of three times the frequency (the third "harmonic") superimposed on it. To its right is the addition of those two waves. The transitions between dark and light are now shorter and steeper. At the far right is the sum of the fundamental and the third, fifth, seventh, and ninth harmonics. The transitions are shorter and steeper still. A perfect edge would require the sum of the fundamental and all of its odd harmonics, a square wave.

As for contrast, consider the image below. It's called a contrast-sensivity grating. Contrast increases from bottom to top, and picture definition (or spatial resolution) increases from left to right.

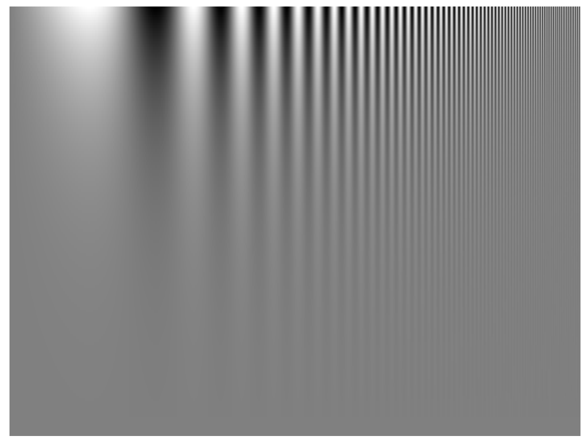

Figure 6: Contrast-Sensitivity Grating

Assuming normal printing or display and relatively normal (or corrected vision), the undifferentiated gray at the bottom of the grating of Figure 6 should appear to have a curve or "V" on top, the left and right edges higher than what is between them. In fact, there is no such curve in the grating. It is being added by the viewer's visual system.

Just as human hearing is most sensitive to middle sound frequencies, so, too, is human vision most sensitive to middle spatial frequencies (varying between about one and eight cycles per degree). Those who are familiar with the Fletcher-Munson curves of loudness sensation might find the visual contrast-sensitivity curve to be similar.[6]

An example of how important the contrast-sensitivity function (CSF) is in human vision may be seen in the pair of composite images of Figure 7 at the top of the next page. They

Figure 7: "Angry Man/Neutral Woman," © 1997 Aude Oliva & Philippe G. Schyns

were created by Aude Oliva of Massachusetts Institute of Technology and Philippe G. Schyns of the University of Glasgow. They are used here with permission.[7]

To a viewer with relatively normal or corrected vision looking at the images from an ordinary reading distance, the image on the left will appear to be that of an angry-looking man, while the one on the right will appear to be that of an emotionally neutral-looking person, perhaps a woman. As the viewer moves farther from the images, however, there will be a distance at which both images appear to be of angry-looking people, followed by a long range of distances at which the angry man appears on the right and the neutral person on the left.

The composite images were created by combining two sets of images. One set, with the angry man on the left, has spatial frequencies intended to be seen near 6 cpd. The other, with the angry many on the right, has spatial frequencies intended to be seen near 2 cpd, in the lower insensitive section of a typical human CSF. As the viewer moves away from the images, both sets of spatial frequencies increase, the lower ones moving into the more-sensitive region of the CSF and the higher ones into the upper insensitive region of the function.

## TELEVISION DEFINITION

### Early History

The Alfred P. Sloan Foundation's Technology Series includes a book about the invention of television. Its preface has the following: "But who invented television? Nobody knows."[8]

Nevertheless, as acknowledged by that book and many other sources, the first person to achieve a video image of a recognizable human face seems to have been John Logie Baird. And the first reception apparatus that he used operated with just eight scanning lines at eight frames per second (fps).[9]

That was a drop from the spatial definition of previous image-transmission systems. Although recognizable-face television wasn't achieved until 1925, television proposals are older and actual, working facsimile-transmission systems older still. British patent 9745 was issued in 1843 to Alexander Bain for a fax system.[10]

A slightly later fax system, Giovanni Caselli's Pantelegraph (developed in 1856) saw extensive commercial service. Figure 8, on the next page, shows an actual fax page received via Pantelegraph.[11]

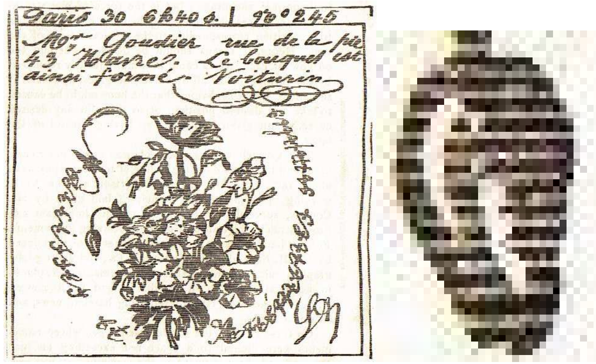

Figure 8: Pantelegraph Fax and Portion

The image at left shows the complete fax page. The image at right shows a magnified portion of just the flower bud on the left side of the arrangement. Fifteen scanning lines can be counted in the bud, alone.

Below is a drawing from German patent 30105, issued in 1885 to Paul Nipkow for an "electric telescope." Television historian Albert Abramson called it "the master television patent" for its video scanning.[10] Each rotation of the scanning disk would produce one video frame. As the scanning disk drawing shows ("D1" through "D24"), Nipkow chose 24 scanning lines per frame.[12]

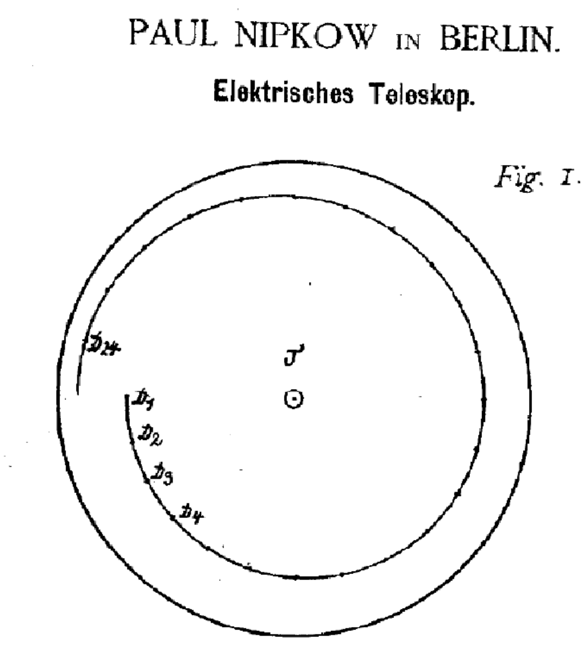


Figure 9: Nipkow's 24-line Scanning Disk

Although Baird and Nipkow might not have conducted studies of optimum image definition, Herbert E. Ives, who headed facsimile and television research at Bell Telephone Laboratories and was also an expert on photography, did. In his introduction to television in *The Bell System Technical Journal* in 1927, he described the definition requirement for what was, at the time, considered primarily an extension of one-to-one telephone service:

"Taking, as a criterion of acceptable quality, reproduction by the halftone engraving process, it is known that the human face can be satisfactorily reproduced by a 50-line screen. Assuming equal definition in both directions, 50 lines means 2500 elementary areas in all."[13]

The 50-line system was soon used, however, to capture larger scenes. In 1928, employees swinging a tennis racquet (as shown below) and a golf club were shown in a video demonstration, and a Bell Laboratories engineer was quoted as saying "We can take this machine to Niagara, to the Polo Grounds, or to the Yale Bowl, and it will pick up the scene for broadcasting."[14]

Figure 10: Tennis Swing Televised in 1928 [15]

In fact, the 50-line definition of the Bell Labs system was relatively high compared to that of most of its contemporaries. The second issue of *Television* magazine in the U.S., dated the same month as the Bell Labs demonstration, in its editorial content and advertising listed picture definitions of 24 through 50 lines.[16]

Only August Karolus, in Germany, went to higher definition in 1928. At the 5th German Radio Exhibition that year, he showed images with 96-line definition.[17] They are compared below to 30-line images from Dénes von Mihály at the same event.[18]

Figure 11: 96- & 30-line TV Pictures in 1928

## The First High-Definition Era

Even before television moved from electromechanical scanning to all-electronic systems, there was great interest in higher-definition images. In 1935, a Television Committee, headed by Baron William Lowson Mitchell-Thomson Selsdon, reported to the British Parliament that the government should mandate "high-definition television." It was defined in paragraph 28: "it should be not less than 240 lines per picture...."[19]

Beginning in 1936, British television broadcasts alternated between a 240-line electromechanical system and an all-electronic system with 405 total scanning lines, of which 377 were active (picture carrying). When, in 1952, the Television Society (UK) heard a talk about the events that led to the 405-line broadcast standard, the presentation was called "The Birth of a High Definition Television System."[20]

The use of the term "high-definition television" wasn't restricted to the United Kingdom. Reporting on RCA's 441-line (383 active) television demonstrations at the 1939 New York World's Fair, *Broadcasting* magazine noted, "The exposition's opening on April 30 also marked the advent of this country's first regular schedule of high-definition broadcasts."[21]

When the first National Television System Committee (NTSC) began its work on a U.S. standard in 1940, it surveyed U.S. and non-U.S. proposed and working television systems ranging from 225 to 605 lines. Its last decision (*after* what was supposed to be the committee's final meeting) was a shift from 441 lines to 525 (483 active).[22]

Two other line-number standards saw significant broadcast use after World War II. They were an 819-line standard first broadcast in France in 1949 (with 737 active in the French version and a slightly higher number active in a Belgian version) and a 625-line standard first broadcast in Germany in 1950.[23]

The 625-line (575 active) number was later adopted by most of the world's countries, including France (1963) and the UK (1962).[24] The exceptions were those adopting the U.S.-standardized 525-line system. Although there were many different transmission systems (primarily for the 625-line countries), those two line numbers dominated the standardized, analog, all-electronic television period.[25]

In the previous, largely electromechanical television era, viewers could generally clearly perceive picture improvements with increasing line numbers, as in Figure 11, above left. There were, however, some anomalies even back then.

As early as 1914, Samuel Lavington Hart applied for a patent for interlaced scanning (scanning the image at a lower line number and then re-scanning at a slightly different position to fill-in between the lines), issued the next year.[26] Beginning in 1926, Ulises A. Sanabria applied a three-to-one interlace to electromechanical television, using three, slightly offset scans of 15 lines each to form a complete image of 45 lines.[27] Among advantages reported by an independent observer were a reduction of image flicker and line visibility (called "strip effect),[28] the opposite of complaints about interlaced scanning today.[29]

Studies have shown full, limited, or no effect on perceived definition from interlace over the number of lines in a single scan even in a still image.[30] Increased line visibility and flicker (or "interline twitter") in still images may be seen in video images, which are readily available on the Internet.[31]

Aside from interlace, many other factors could affect image-quality perception. In 1955, a delegation of U.S. engineers went to England to study television there and reported the perceived quality of the 405-line pictures superior to those of America's 525-line pictures. Possible reasons ranged from better operational practices to better allocation of bandwidth to different filtering.[32]

## Combining Vision and Television

Ignoring all other television technical characteristics (in scanning system, scene, lens, camera, transmission, reception, display type, and display settings) that could affect image definition, many have reported an optimum viewing distance based only on the number of active scanning lines and Snellen's "normal" visual acuity of one minute of visual arc per scene element. According to that theory, NTSC's approximately 480 active scanning lines, if filling eight degrees of visual arc, would exactly match one arc minute of acuity. That condition occurs when the viewer is slightly farther from the screen than seven times the picture's height.[33]

It is the case that there is an optimum viewing distance. Farther than the optimum distance, the viewer's visual acuity precludes seeing the full resolution being presented. Closer than the optimum distance, elements of the display structure become visible, effectively preventing the viewer from "seeing the forest for the trees."

Consider the image below, an extreme example of this phenomenon. It is possible that you have seen it previously in this paper. It is a lower-case *O* in the Times New Roman typeface used in this text, as it might be depicted on some computer's color LCD screen. As in Figure 7, at a sufficient viewing distance (squinting might help), the image will change, this time from colored blocks to a round, black, lower-case *O*.

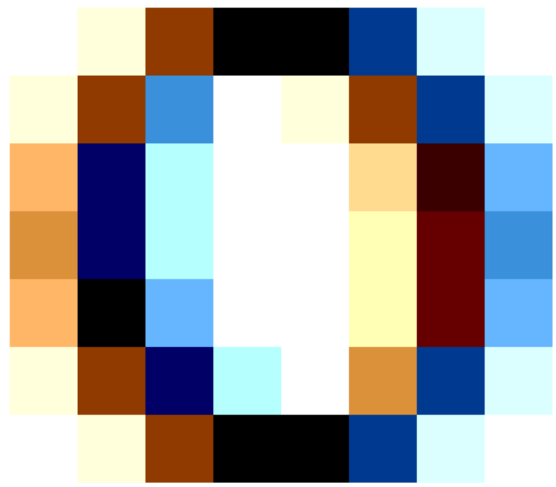

Figure 12: A Fixed-Grid Display *O*

If Snellen were correct about normal visual acuity being 30 cpd, and if active scanning lines (in interlaced television) directly determined perceived resolution, then it *would* be accurate to say that the optimum viewing distance for NTSC video is about seven times the picture height. It would still *not* be accurate, however, to say that viewers typically watched NTSC video at seven times the picture height.

Bernard Lechner, a researcher at RCA Laboratories, conducted a survey of television-viewing distances during the NTSC era. What he found was that those he surveyed watched television from a viewing distance of approximately nine feet, regardless of screen size, a figure that came to be known as the Lechner Distance. Richard Jackson, a researcher a Philips Laboratories in the UK, conducted a similar survey and found a similar three meters, the Jackson Distance.[34]

Assuming, again, that normal visual acuity allows detection of features subtending one minute of visual arc and that active scanning lines determine television resolution, then at the Lechner Distance it would be essentially impossible to see greater than NTSC resolution on a 25-inch four-by-three TV screen. The picture height of a 25-inch screen is 15 inches (1.25 feet); seven times its height is 8.75 feet. The optimum viewing distance for 480 active lines is actually 7.15 times the picture height (1/(2*tan(8 degrees/2))), which means the optimum 25-inch NTSC TV-viewing distance would be 8.94 feet, almost exactly the Lechner Distance.

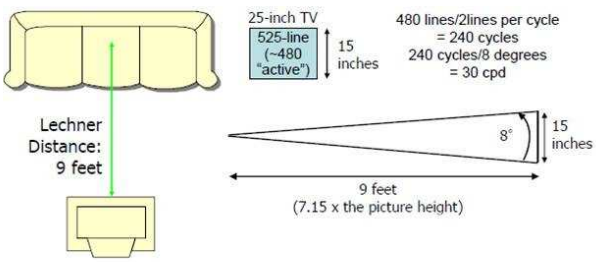


Figure 13: U.S. Standard-Definition Viewing

According to figures from the Consumer Electronics Association, the average TV-screen size shipped by factories to U.S. dealers through the year 2000 was under 25 inches.[35] Sales to consumers typically follow a year after factory sales, and TV replacement takes years after that, so, if definition beyond NTSC cannot be perceived on a 25-inch screen, there would seem to have been no incentive for a move to HDTV in the U.S.

In Japan, according to this theory, rooms are smaller, so current HDTV had its origins there. Unfortunately for the theory, TV screen sizes in Japan were also smaller.

Psychophysics

In fact, there *are* reasons why HDTV detail looks better even to American viewers. First, 30 cpd is *not* the limit of human visual perception. In testing conducted in Japan on ultrahigh-definition television (UHDTV), the test subjects were found to have an *average* visual acuity not of 20/20 but of 20/10 (i.e., able to distinguish features twice as small as Snellen's criterion).

That should have meant that their visual acuity was 60 cpd instead of 30. The testing revealed, however, that the subjects were able to distinguish the "realness" of images as high as 156 cpd (the highest spatial frequency that was measured), more than five times supposedly "normal" acuity and more than 2.5 times even 20/10 acuity. "Realness" (degree to which an image was perceived to be comparable to a real object) rose rapidly to beyond 50 cpd and then slowed, but it did increase to 156 cpd (the highest tested), and the data suggest it would continue to increase (slowly) beyond that point.[36]

*Realness*, like other words ending in the suffix *-ness*, such as *brightness* and *loudness*, is a psychophysical sensation (a psychological response to a physical stimulus). And psychophysical sensations tend to be based on more factors than just the measurable physical phenomenon most closely associated with them. Thus, luminance, alone, does not determine brightness, and sound-pressure level, alone, does not determine loudness.

Similarly, there is a psychophysical sensation associated with picture definition but not determined exclusively by it. That sensation is called *sharpness.*

At the top of the next page is a graph of a typical modulation transfer function (MTF). In the case of spatial definition of the luma (gray-scale) component of images, the modulation is changes between bright & dark.

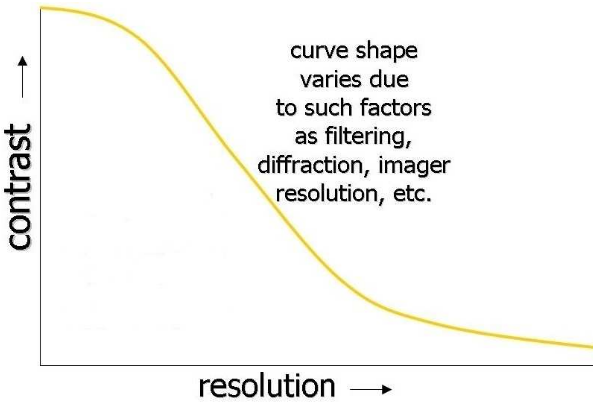


Figure 14: An MTF Curve

The curve of Figure 14 could be that of a lens or a television camera or a complete television system, "from scene to seen." Of most interest, with regard to the sensation of sharpness, is the area under the curve.

There are two significant schools of thought about the relationship of that area to sharpness. One is based on the work of Otto H. Schade, Sr. at RCA Laboratories.[37] The other is based on the work of Erich Heynacher at Zeiss.[38] The former suggests that the sensation of sharpness is proportional to the square of the area under the curve, the latter that it is proportional to the area.

In either case, as shown in Figure 14, image sharpness is most affected by the area under the "shoulder" of the curve (at left) and least by the area under the "toe" of the curve (at right). Sony took advantage of the low contribution of the highest spatial frequencies to sharpness in the design of the HDCAM recording system. It drops 25% of the luma definition at much less loss of sharpness.[39]

One of the factors affecting the shape of the MTF curve is number of digital samples. Digital sampling and reconstruction require filtering. The graph at the top of the next column is a basic filter shape, the so-called SINC or (sin x)/x function. The horizontal scale is arbitrary; on the vertical scale, *1* represents 100% modulation transfer.

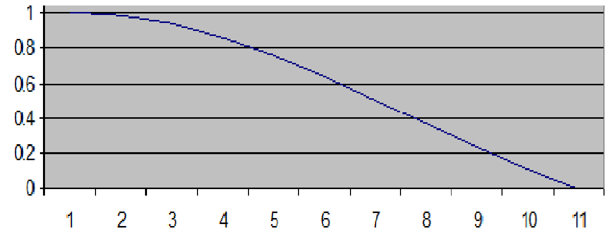


Figure 15: SINC Function Filter

If the vertical axis represents contrast and the horizontal axis represents image definition, then, if number 11 represents, say, 1920 active samples per line, the contrast at 1920 is zero. If, however, number 11 represents 3840 samples, the contrast at 1920 is 64%, a very significant difference.

The next two figures illustrate real-world examples. They are taken from the Bob Atkins Photography web site and are used here with permission.[40]

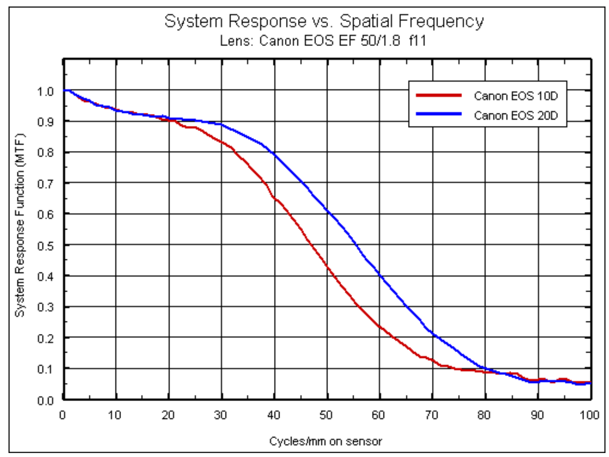


Figure 16: MTF Comparison of Two Cameras
© Bob Atkins

The red (left) curve of Figure 16 is from a Canon EOS 10D still camera, which uses an effective 3072 x 2048 photosite image sensor. The blue (right) curve is from a Canon EOS 20D camera, which uses an effective 3504 x 2336 photosite image sensor.

The horizontal linear increase in definition is just 14%, but significant additional area is created under the MTF curve of Figure 16.

The resulting increase in sharpness can be seen in Figure 17 below.


Figure 17: Sharpness Difference
© Bob Atkins

The text, photo, and drawing details above indicate very little difference in image definition, as might be expected from the small (14%) linear increase. The additional area under the MTF curve, however, makes the increased sharpness of the left image readily apparent. The vertical definition difference between so-called 1080-line HDTV and NTSC is about 225% (it is a similar 213% from 1080-line HD to so-called "4K").

## BEYOND HDTV

### Differentiating the Theatrical Experience

Average U.S. weekly movie attendance in every year from 1945 through 1948 was 90 million. By 1950, it was down to 60 million; by 1953, it was just 46 million.[41] The cause of the drop was apparently the rise of home television. The movie industry turned to wider screens, larger (higher-definition) film formats, and such offerings as stereoscopic 3D in order to differentiate the movie-going experience from that of watching television.

In 2011, there were just 24.6 million weekly cinema admissions in the U.S.[42] Only 27% of the number of movie tickets of 1948 were sold in the same year that the population grew to 213% of its 1948 level.[43] So 3D and higher-definition formats are still under consideration in a digital-cinema era.

Today, instead of 70-mm film, the movie industry discusses "4K," images having 4096 active picture elements (pixels) per row (with a number of rows appropriate to the image aspect ratio). The earliest digital-cinema projectors were "1.3K" (comparable to 720p HDTV); many current installations are 2K (comparable to 1080-line HDTV).[44]

Traditional cinema seating arrangements created a wide range of viewing distances for audiences, as shown in Figure 18 below, courtesy of Warner Bros. Technical Operations. Figure 19, courtesy of the same source, shows a typical more-recent auditorium with stadium-style seating. The scales are calibrated in picture heights.

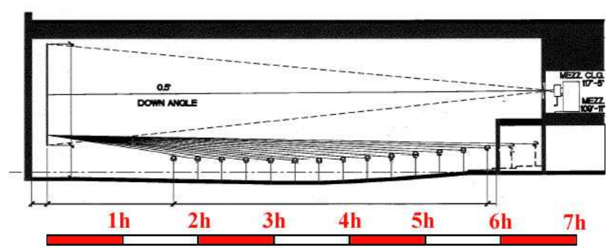


Figure 18: Traditional Cinema Seating

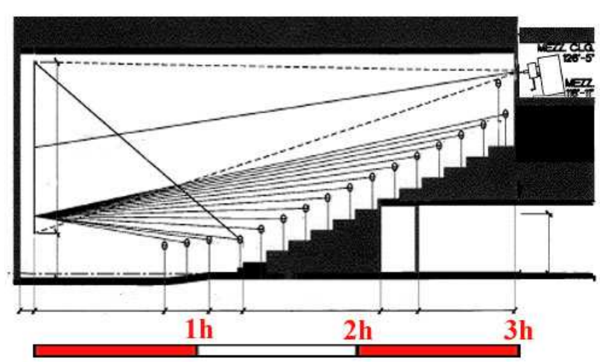


Figure 19: Cinema Stadium-Style Seating

The bulk of the audience is closer to the screen in stadium seating and, therefore, might benefit from additional image definition. Figure 20, below, courtesy of ARRI,[38] shows that definition even beyond 8K (8192 active pixels per row) should be perceptible even at just 20/20 visual acuity in some seats in some cinemas.

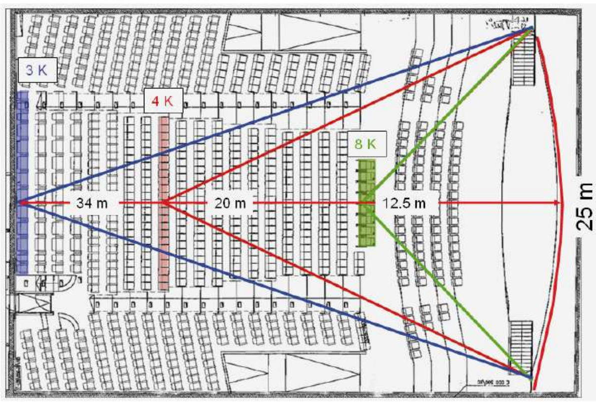


Figure 20: 20/20 Resolvable Definitions

In practice, however, unlike television consumers, who can compare picture definitions side by side in stores (and generally at closer viewing distances than they would experience in homes), cinema attendees cannot easily compare definitions in different auditoriums. Definition of 1.3K was acceptable to audiences when it was used for digital cinema. Perhaps, like "70 mm," "4K" will be a promotional tool.

Production and Post

Even before the modern HDTV era, television-camera manufacturers used oversampling (generally in the horizontal direction) to increase image sharpness. NTSC broadcast video bandwidth restricts horizontal luma definition to approximately 440 pixels; some broadcast-camera image sensors had more than 1100 photosensitive sites per row.

At the beginning of the modern HDTV era, the difficulty of making sensors with even as many as 1920 photosites per line precluded oversampling. The introduction of image sensors into still cameras, mobile telephones, laptop computers, and other devices, however, provided economies of scale allowing multi-"megapixel" sensors to be produced.

Even in the camera-tube era, some cameras used patterned color filters at the faceplate of a single imaging tube to capture color pictures instead of using color-separation prisms with an imaging tube for each of the three primary colors. In the solid-state imaging era, it has become common in still cameras to use a patterned filter over a single image sensor.

In the common Bayer pattern shown below, green-filtered photosites represent half the sites on the sensor. Red- and blue-filtered photosites represent one-quarter of the sites, each. Recreating a full-color image requires a "demosaicking" process to remove the spatial color effects of the filter.

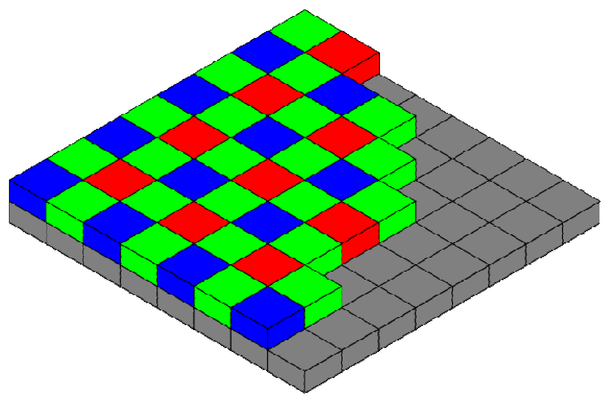

Figure 21: A Bayer-Filter Pattern[45]

There is no consensus about how on-chip color filtering should affect the description of resolution. There is also no consensus about whether 4K requires 4096 samples per line or whether 3840 (twice HDTV's 1920) are sufficient. Thus, one can find labeled 4K, at a single equipment exhibition, cameras with between 8.3 and 20.4 million photosites per image sensor, and with one to three sensors (some older "4K" cameras also used four 2.1-million photosite sensors).[46]

Aside from any advantages in visual definition or sharpness, 4K offers benefits in production and post, as the next three figures illustrate. Figure 22 shows a high-definition video image as a pixel-for-pixel subset of a 4K image, allowing reframing or even zooming after shooting.

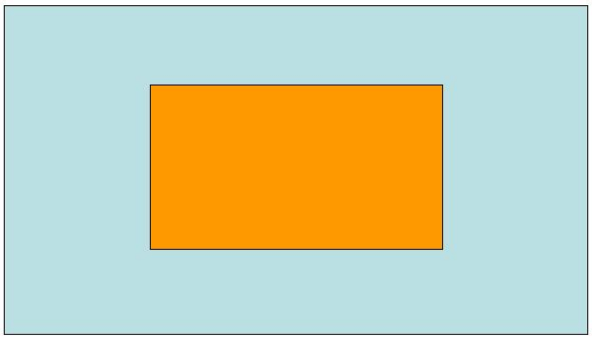

Figure 22: HD as a Subset of 4K

Figure 23, below, shows the effects of image stabilization, which normally causes trimming of the image (illustrated in available short, downloadable video clips[47]). The light inner rectangle (behind the others) is a desired HD image. The skewed rectangle in front of it is the actual image captured by an unstable camera. The smallest rectangle is the trimming that post-production image stabilization would produce. But starting with the outer 4K image allows the full desired HD image to be stabilized.

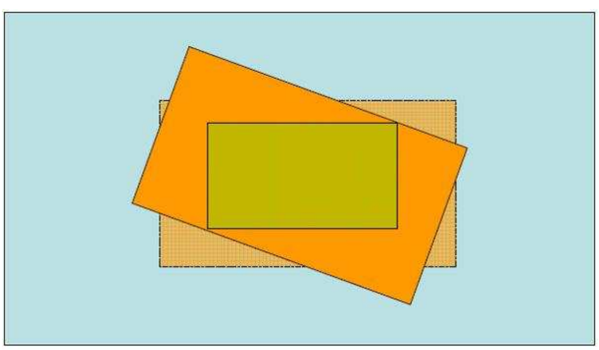

Figure 23: HD Image Stabilization in 4K

Figure 24, at the top of the next column, shows an unusual application of 4K in stereoscopic scene capture. The Zepar stereoscopic lens system attached to a Vision Research Phantom 65 camera, provides side-by-side stereoscopic images on the same image sensor, simplifying processing.[48]

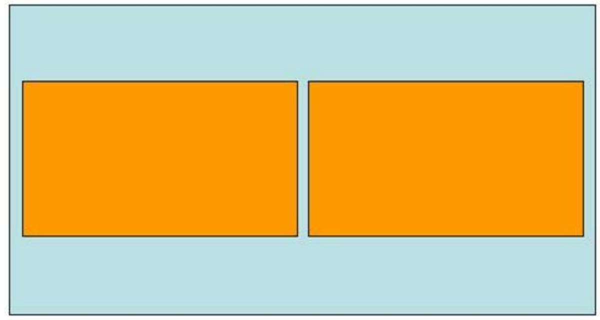

Figure 24: Stereoscopic HD on a 4K Sensor

Very Large TV Screens

When Panasonic introduced its 103-inch plasma TV, at the time the largest consumer flat-panel display, it had the common HDTV definition of 1920 x 1080. As a result, at the Lechner Distance, the image structure could have been perceptible even to viewers with visual acuity somewhat less than 30 cpd.

When the same company later (in 2008) introduced a 150-inch plasma TV, an HDTV image structure would have been even more visible, perceptible even to viewers with impaired vision. The definition of that display, therefore, was 4K (4096 x 2160).

At the top of the next page is an image created by John R. Vollaro for Leon D. Harmon at Bell Labs around 1968, used with permission. Like Figure 12, it doesn't look like what it is when its edges can be seen.

Like Figure 12, the image will appear to be as it should when viewed from a distance. Unlike the blocks of Figure 12, which were created to help make a color, fixed-grid display present black, round edges, the blocks of Figure 25 were created to obscure a natural photographic image for perceptual study.[49]

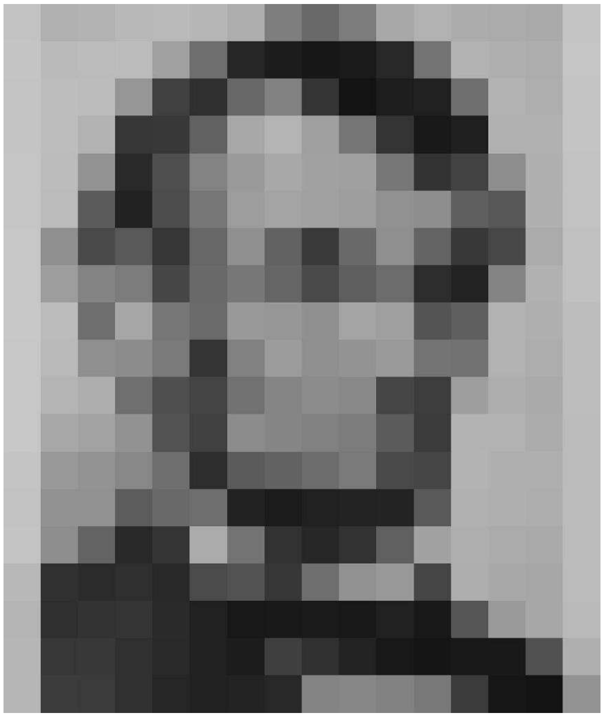

Figure 25: Bell Labs Block Version of Portrait

Surrealist artist Salvador Dali painted a version of the image in 1976, which like Figure 7, changes from one thing to another at a particular retinal angle. The name of the painting is very descriptive: *Gala Contemplating the Mediterranean Sea, Which at Twenty Meters Becomes a Portrait of Abraham Lincoln.*[50]

The effect of Figure 25 occurs because pixels are mathematical points, not little squares, rectangles, or even dots.[51] There are solutions other than increasing display definition, however, such as optical filtering to blur the edges. Holding ground glass or even waxed paper in front of Figure 25, for example, can also reveal its hidden content. Such low-pass optical filtering is commonly used in broadcast television cameras (although it becomes problematic in color-filtered single-sensor cameras: should the filter be appropriate to the luma, the green, or the other colors?).

Aside from their pixel definition and resulting sharpness, very large television displays also stimulate more of the visual field at any given distance. Research into UHDTV (which can be a form of either 4K or 8K) has shown that the increased visual angle not only increases "presence" sensation but also increases dynamic visual acuity (the ability to perceive fine detail moving relative to the eye's retina).[36] Of course, as shown in Figure 22, a very large 4K screen can also be seen as providing an HDTV image in each quadrant.

## Distributing 4K

Very large television displays are, and should continue to be, rare in homes. Again, the average screen size of TV sets shipped to the U.S. through 2000 was less than 25 inches. Screen-size increases continued slowly through 2005, followed by a spurt in 2006 as inexpensive widescreen HDTV sets became available.[52]

Size growth then slowed again. According to Display Search, in 2010, the average TV screen size for shipments to North America (which has the world's highest average) was 36 inches. In 2012, it is expected to be 37.8 inches. In 2014, it is expected to be 39.2 inches. Globally, TV screen sizes of as little as 50-inch and above accounted for only 5.3% of shipments in 2010 and are expected to account for only 6.3% in 2014.[53]

Figure 26, below, shows actual and estimated average screen sizes for global TV shipments. Not only is the average below 36 inches, but it also appears to be leveling off.[53]

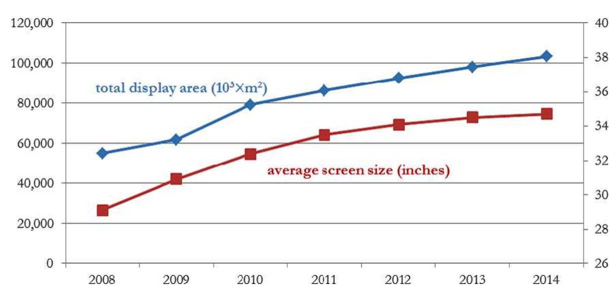


Figure 26: World TV Shipment Average Sizes

Given those screen sizes, it is unlikely that, at the Lechner Distance, average viewers will notice the pixel-grid structure of their television displays. They will also not be close enough to their displays to appreciate the high-definition detail offered by a quarter of a 4K display (or a sixteenth of an 8K display). They *should* be able to appreciate the additional sharpness that 4K image capture offers, but, as Sony's HDCAM filtering indicates, they will see the bulk of that sharpness even on ordinary HDTVs.

It would seem, therefore, that there is little for an average TV viewer to gain from 4K display resolution. The TV-set industry, however, is in a quandary. It was described this way in *The New York Times* in 2011:

"By now, most Americans have taken the leap and tossed out their old boxy televisions in favor of sleek flat-panel displays. Now manufacturers want to convince those people that their once-futuristic sets are already obsolete.

"After a period of strong growth, sales of televisions are slowing. To counter this, TV makers are trying to persuade consumers to buy new sets by promoting new technologies."[54]

That article, which appeared at the time of the 2011 Consumer Electronics Show (CES), indicated that such features as stereoscopic 3D and Internet connections "have not generated much excitement so far." At the 2012 CES, therefore, a new feature being promoted was 4K (and even 8K) definition, with demonstrations from such major manufacturers as AMD, JVC, LG, Panasonic, Sharp, Sony, and Toshiba.[55-58] *Consumer Reports* called 4K "one of the most talked about innovations" at the show.[59]

Aside from promotion by TV-set manufacturers, 4K programming is just starting to become available, primarily in the form of movies, based in part on the production and sharpness advantages of 4K and in part on the use of 4K to differentiate digital cinema from home theater. The late-2011 American version of *The Girl with the Dragon Tattoo*, for example, has been called "the first large-scale end-to-end 4K digital cinema release."[60]

Portions of the 2012 Olympic Games are also expected to be shot and shown in beyond-HDTV resolutions.[61] Thus, cable-television operators might wish to take advantage of all of the promotion by providing a 4K offering. Fortunately, it need not require a large amount of data capacity.

All else being equal, a 4K image sensor has more than four times as many photosites as a 1080-line HDTV image sensor. A 4K display similarly must deal with more than four times as many picture elements.

As might be expected, an uncompressed, 8K (7680 pixels per line, or four times HD's 1920, rather than 8192) "Super Hi-Vision" link would require 16 high-definition serial digital interface (HD-SDI) connections.[62] It is not clear, however, that 4K or 8K require multiples of high-definition data rates in the compressed domain.

There are three main reasons. One may be seen in the previous Figures 14 and 16. As detail gets finer, the energy in the signal is reduced, so there is less to compress.

Another reason relates to motion estimation in bit-rate reduction (BRR) systems that take advantage of temporal redundancy as well as spatial redundancy. The better defined a point is, the more accurately its motion can be estimated and, therefore, the lower the bit rate at which errors will be imperceptible.

Both of those factors suggest that, in an ideal BRR system, the "overhead" to increase from HDTV (or 2K) to 4K will be very much less than an additional three times the original signal value. The third factor is that, absent the very large retinal angle of a cinema screen or very large TV display, viewers are less sensitive to image defects, or, as one BRR-comparison paper put it, "the quality requirements are more stringent when the viewer is in a cinema."[63]

Figure 27, below, is based on a graph in another paper comparing BRR systems for digital cinema. The full graph compares seven BRR systems out to data rates of 260 Mbps for the test sequence called *CrowdRun*. At those high data speeds, the 2K systems all outperform the 4K systems in PSNR.[64]

The small section of the graph shown below, however, is restricted to such low data rates as might be used for delivery of HDTV on a cable-television system. As shown by the five identified data points (all JPEG2000), at those low data rates (starting at 14 Mbps), 4K actually outperformed 2K. It was only beyond roughly 26 Mbps (extrapolated) that 2K outperformed 4K.

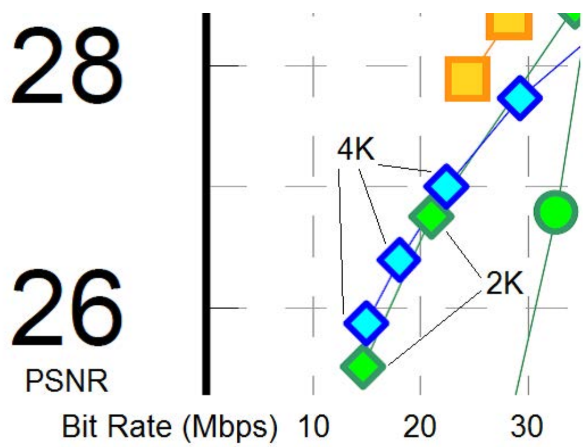


Figure 27: 2K vs. 4K BRR Comparison[64]

BRR quality results can vary according to many factors, but Figure 27 shows that 4K can be transmitted at rates comparable to HDTV with comparable results. It is certainly conceivable that a layered transmission system can also be used, adding only 4K's additional information to that already carried for HDTV. It is not clear, however, what the efficiencies of such layered transmission would be in comparison to the use of a single signal for 4K distribution.

## CONCLUSIONS

In program production, 4K is well established and growing. Cameras are available from ARRI, Astro, JVC, Red, Sony, and Vision Research and have also been shown by Canon, Dalsa, Hitachi, Ikegami, Lockheed-Martin, Meduza, NHK, and Olympus.[65]

Though the *4K* designation of some of these cameras can be questioned (largely due to the use of color-filtered single image sensors), all are intended to capture definitions beyond those of HDTV. There is even a technique to extract 4K resolution from masked HDTV image sensors, so as to reduce uncompressed data rates.[66]

In post production, 4K is also well established and growing. *The Girl with the Dragon Tattoo* might be "the first large-scale end-to-end 4K digital cinema release," but all of the individual processes used have been available for some time.

In cinema, 4K is also established and growing. NHK's Super Hi-Vision has been used in cinema-like applications (community viewing of a single, giant screen in a dark room), intended to be viewed at just 0.75 times the picture height.[67]

Super Hi-Vision is also intended to provide a home-viewing experience. Although displays with 4K and even 8K resolutions have been shown, it is not clear at this time either that sufficiently large displays will be purchased by consumers or that consumers will move sufficiently close to smaller displays to give them the “presence” and “realness” intended for Super Hi-Vision.

Figure 28, below, shows a 152-inch plasma TV. Simply getting it into a room in a home is cause for concern. Even a 152-inch size is too small for 0.75-height viewing at the Lechner distance; that would require a 294-inch screen, with a 12-foot-high image (not counting its frame). Clearly, as-intended 8K Super Hi-Vision viewing in the home will require a change in viewing-distance habits.


Figure 28: Panasonic 152-inch Plasma TV

The increased sharpness of beyond-HD-resolution imaging is largely available to viewers using existing TV sets. The extraordinary images of 4K and 8K television displays have been reported by observers who could view them at closer than home-viewing distances (e.g., the Lechner Distance).

Cable-television operators can nevertheless take advantage of the promotional aspects of moves to 4K resolution by offering 4K distribution. It is not clear whether *any* increase in bit rate is required, but, due to the low energy of the highest octave of spatial frequencies in a typical, real-world 4K-captured image, improved motion estimation provided by better-defined pixels, and relative insensitivity to compression artifacts at typical TV viewing distances and display sizes, any such increase should be minimal.

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