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Summary

In the context of subjective quality assessment of 3D video, a suitable 3D display must be selected such that the display does not affect the reliability and reproducibility of subjective results. However, crosstalk is a major contributor to quality loss and visual fatigue on stereoscopic displays. It can therefore greatly impact the quality of experience in the viewing of stereoscopic 3D content, and the subjective quality assessment. The term crosstalk has been used in several ways in the literature. Crosstalk is usually defined as the leakage of light signal from one channel into the other, using a white image as the open channel signal and a black image as blocked channel signal.

In this contribution, we report several types of measurement methods that we have used on 3D displays and discuss our observations in relation to 3D display crosstalk. These findings can help in defining criteria to select suitable 3D displays for the subjective quality assessment of 3D-TV content.

In particular, the key issues in the meaningful measurement and characterization of crosstalk of 3D displays are:

1. The spatial variation of the crosstalk
2. The angular variation of the crosstalk (crosstalk off the center axis)
3. Chromatic aspects

The measurement approaches and protocols presented in this contribution can be used as a basis to define standardized measurement protocols, which can lead to a meaningful characterization of 3D display crosstalk

Furthermore, a unified 3DTV crosstalk assessment should also be a goal. An approach to achieve such goal can be to combine several measurements, taken at different positions and angles, with different – e.g. colored – image signals. From these measurements, either an overall compound/synthetic indicator can then be built, with a weighted combination of individual crosstalk measurements/scores, or these measurements can be used with thresholds for a 'pass or fail' test on each of them. This would allow moving away from the single measure assessment of crosstalk and defining a more representative evaluation of the various usage configurations of 3D displays.

1 Introduction

Compared to 2D-HDTV, 3D display technologies bring additional constituents in the picture, some affecting image quality. 3D crosstalk, identified as the leakage of one view's information into the other channel, is a dominant degradation factor. Creating doubled contours in the image, it affects both image quality and depth perception.

Literature defines different formulas for crosstalk evaluation [1].

An example image degraded by the presence of crosstalk is shown in Figure 1.

Figure 1 – 3D image with crosstalk.

In this contribution, we present a diversity of technically distinct physical measurement methods to evaluate crosstalk on 3D displays, detailing some examples: temporal, colorimetric/spectral, spatial/angular methods.

2 3D-TV technologies vs. crosstalk

A review of crosstalk mechanisms for different 3D display technologies provides the major physical contributors for each of them [2]. The list of studied technologies covers the wide majority of existing 3D display categories. Here, we consider more particularly those that are current candidates for 3D-TV in the home. Implicitly this restricts our field of interest to Micro-Polarized 3D LCDs, Time-Sequential 3D using liquid crystal shutter (LCS) 3D glasses, either based on LCD or on PDP screens, and finally, active retarder screens combined with passive glasses.

Although crosstalk measurement can only be in respect to a display-glasses combination, we can identify the following contributions for the technologies under consideration, separating glasses/shutter and screen contributions:

- Contributions linked to 3D glasses or shutter technology:
    - Passive glasses (circular polarization analyzers):
        - Efficiency and chromaticity of $\lambda/4$ retarder film
    - Active glasses (LCS) and active retarder screen:
        - Residual transmission of blocked state

        - Temporal performances (rise and fall times)
        - Synchronization with the display
    - Other issues related to crosstalk:
        - Chromaticity
        - Non-uniformity and angular dependence
- Contributions linked to 3D display technology:
    - Micro-Polarized 3D LCDs:
        - Micro-polarizer strips contribution: optical quality, alignment and pitch relative to display pixels
        - Presence/absence of a black mask between strips
    - LCD 3D Display:
        - Pixel addressing and frame sequencing
        - Display response time
        - Position and angular dependence: spatial non-uniformity of crosstalk effect, dependence upon observer position
        - Output polarization (spatial/angular effects)
        - Potential backlight modulation / local dimming
    - PDP 3D Display:
        - Phosphor response lag
        - PDP sub-frames management
        - Luminance level dependence
    - Other issues related to crosstalk:
        - Potential built-in anti-crosstalk strategy, impacting luminance level dependent effects

Given the variety and differences between display technologies, a thorough analysis of crosstalk causes seems necessary to assess the relative importance of each contributor for each 3D glasses and 3D display technology. As detailed below, a diversity of physical measurement methods can be exploited for this purpose.

3 Crosstalk measurement

Although crosstalk can be defined simply mathematically, the physical measurement of 3D display crosstalk is not straightforward. In particular, obtaining reproducible measurements is critical.

In this contribution, we list and describe several approaches used to characterize crosstalk of 3D displays. Here, we remain focused on physical measurements, while recognize that perceptual evaluation of crosstalk is a complementary important aspect.

We have used several measurement methods: temporal, spectral, and spatial methods. Indeed, different physical phenomena can occur and can impact crosstalk perception. In this contribution, we mainly take the measurement on an active shutter glasses LCD 3D-TV as example.

3.1 Temporal measurements

We introduce the general principle of temporal measurements, insisting on the necessity to control measurement conditions with care, both on the optical side (proposing the use of a Fabry photodiode assembly to precisely control field of view) and on the electronic side (where the sensor temporal response must not be a limiting factor). The use of two identical photodiode assemblies allows the simultaneous measurement and comparison of the ON and OFF channel signals. Optical arrangements are described for the measurement and characterization of only the 3D glasses, only the 3D display and of the combination of the two. Signal analysis allows identifying synchronization issues and determining the predominant contribution to crosstalk.

Temporal measurements address mainly active displays where the sequentially displayed images and the shutter glasses contribute to the temporal separation and presentation of the stereo pairs. A temporal measurement can identify chronograms of the light emitted by the screen and their synchronism with the shutter glasses switching states. Furthermore, average leakage can be evaluated for both the ON and OFF states of the glasses. Different physical phenomena can be discriminated, such as afterglow of the screen emission for the ON state, or lack of blocking efficiency of the shutter glasses in the OFF state.

Principle and instruments

Two identical Fabry assemblies have been used for the measurements, one for each of the left and right eye positions. Based on the combination of a photosensitive cell, a lens and a pupillar aperture, this optical arrangement allows the precise control of the measured field of view (see Figure 2).

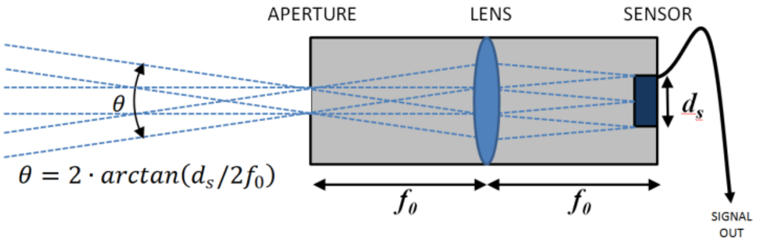

Figure 2 – Fabry assembly optical arrangement.

The following important points must be taken into account in the set-up:

- The photocell sensitivity and response time must be excellent, the noise/response time tradeoff is tuned via impedance adaptation.
- Measurement synchronization and dark offset subtraction need significant care.
- Filters in the optical path allow for the rejection of UV/IR light. Filters for the R, G or B color channels, match human color vision.
- Beam geometry is defined by the Fabry arrangement. The intercepted content, including its temporal behavior needs to be mastered.
- Stray light in the room need to be controlled/minimized.

Measuring glasses only

Measurements of passive or active glasses have common and distinct parameters. In the case of passive glasses the main parameters are transmission factor for the passing channel, blocking efficiency of the blocked channel, and chromaticity (color shift). Angular dependence of these parameters, combined with potential directional scattering, defines the usable viewing angle of the glasses. For active glasses, response time for the ON and OFF transitions, are complementary parameters. In the digital cinema context, Srivastava et al. have compared precisely four liquid crystal technologies regarding these parameters (see [3]). The reader is referred to their work for evaluating the variability in performances of the various studied solutions.

The glasses measurement setup consists in placing the photosensitive cells at the eye position behind the glasses, and illuminating them with a stabilized DC current tungsten lamp equipped with a condenser and UV/IR filters. In the chosen configuration the glasses synchronization sensor is still lit directly by the 3D-TV IR photodiode while small mirrors are used for the stable illumination lamp.

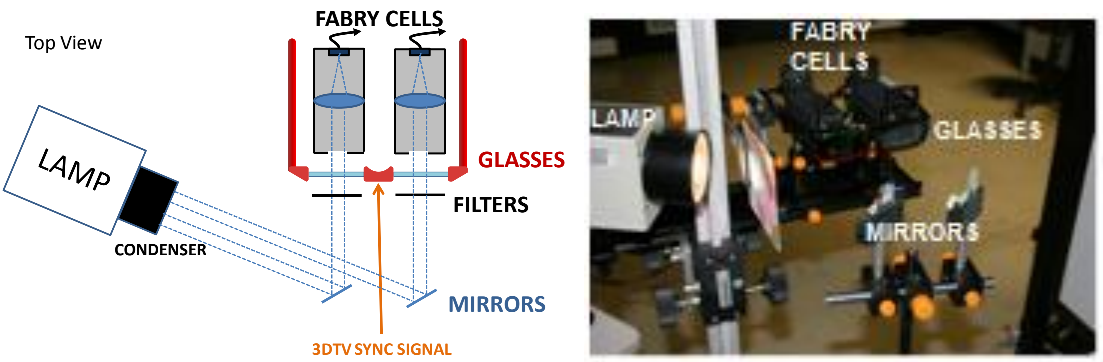

Figure 3 – Set-up for glasses measurement.

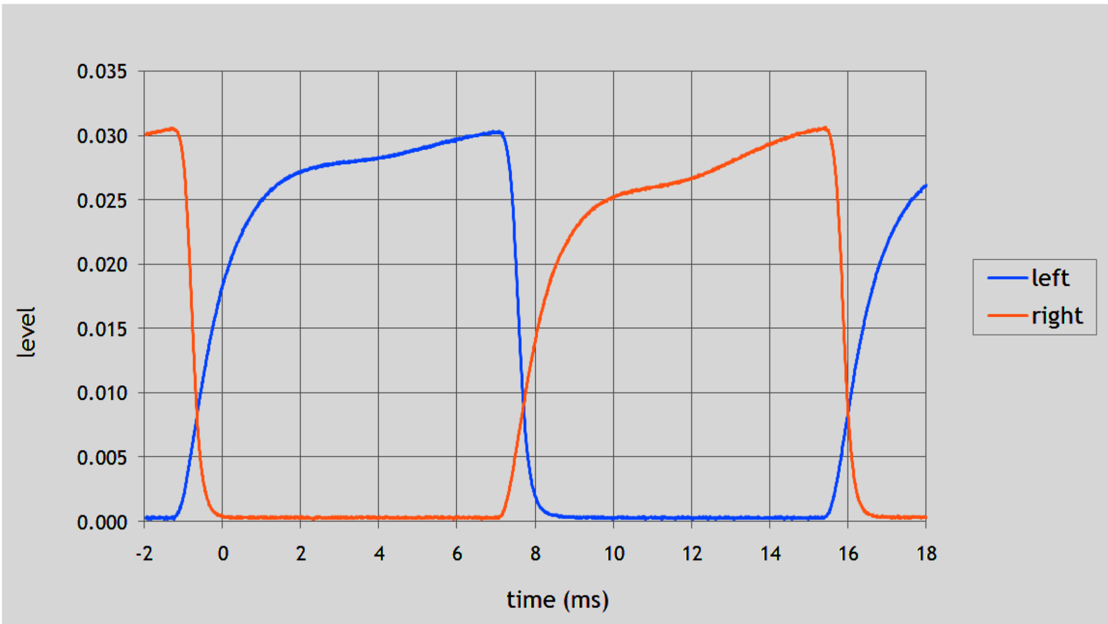

Figure 4 - Temporal measurement of glasses.

Measuring display only

Although it is not a crosstalk measurement as such, measuring the display without glasses is a very informative experiment. Indeed, the temporal variations of the signals can be really instructive about the display technology and the light management strategy selected by the display manufacturer. For example, in the case of LCD displays, backlight management, screen scanning and addressing can be analyzed, while, for plasma displays, the subfields ordering is observable.

Measuring the display with a temporal method requires the same setup as described in the previous sub-section. This time, the 3D-TV signal is observed directly with the Fabry assemblies, and, in the case of LCD displays, various vertical positions will reveal the temporal scanning, from top to bottom of the screen. This may be an issue for the correct measurement of crosstalk as a given field of view of the measurement cells may span over different screen zones, with different backlight timing or synchronization. As example, Figure 5 shows how such a wide field measurement spanned over several backlight zones.

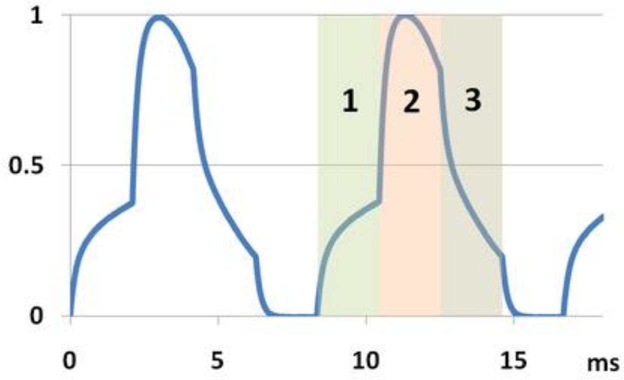

Figure 5 - Several backlight zones identified in a wide field temporal measurement.

Rise and fall liquid crystal time responses can be evaluated with this measurement method, as well as synchronization relative to the IR command pulse of the display.

Measuring display+glasses

Combining the display and glasses sets the system in its actual 3D-TV presentation configuration. The display+glasses crosstalk is measured by displaying an image signal for the left eye, no image signal for the right eye and recording simultaneously the two photocells signals during an image pair period (16.66 ms for a 60 Hz screen). By masking the image signal, black level offsets are measured. They are then subtracted. Finally the summation over the image pair period is performed for each of the L and R channels.

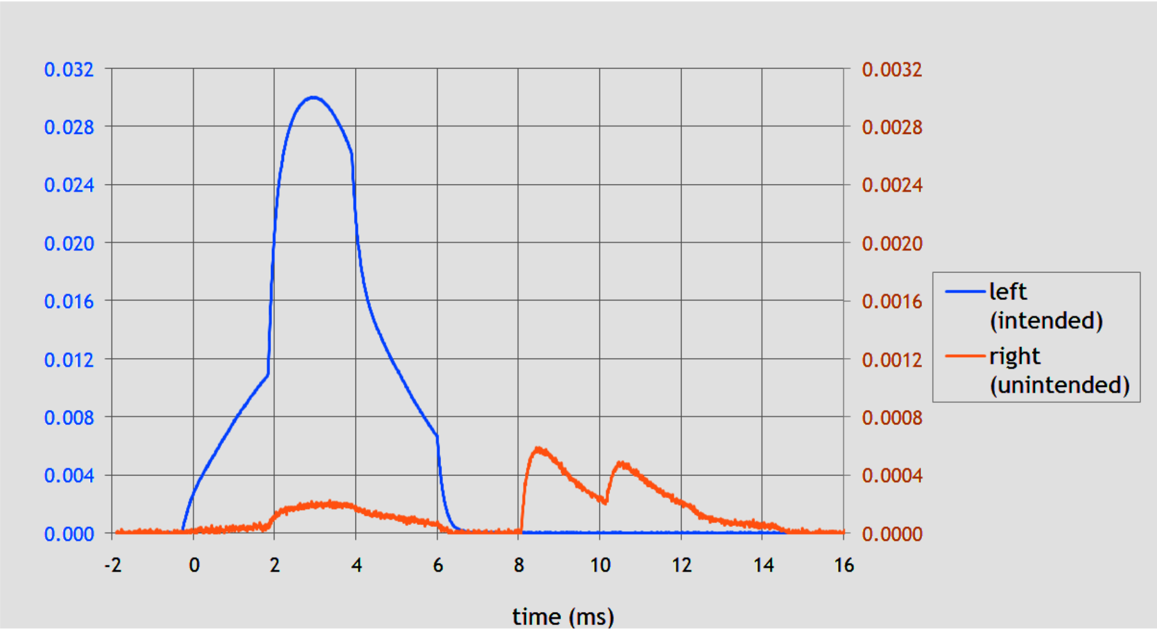

Figure 6 - Temporal measurement of display+glasses (different scales for left and right channel measures).

3.2 Spectral measurements

The spectral measurement setup is very similar to the temporal measurement setup above. The Fabry cells are replaced by a spectrophotometer, while the tungsten lamp, 3D-TV screen, and glasses are used in the same configuration. UV/IR, and R, G, B optical filters are optional for a spectral analysis, but their use is recommended to perform measurements in coherence with the temporal method. No synchronism being necessary, one glass can be measured after the other with the same instrument.

Measuring glasses only will give spectral transmittance for each glass when dividing the spectral response for a light path with and without glasses.

Measuring display+glasses can be done for the glasses opened and blocked states, for image signals being single primary (R, G or B) patches or more complex. Single primary patches allow a simpler analysis as illustrated on Figure 7. On this diagram, curves show the opened (plain curve – left scale) and blocked (dashed curve – right scale) states spectra for a red, green and blue patch respectively, displayed on the left view of the 3D-TV. In this example, blue/green light appears in the blocked state.

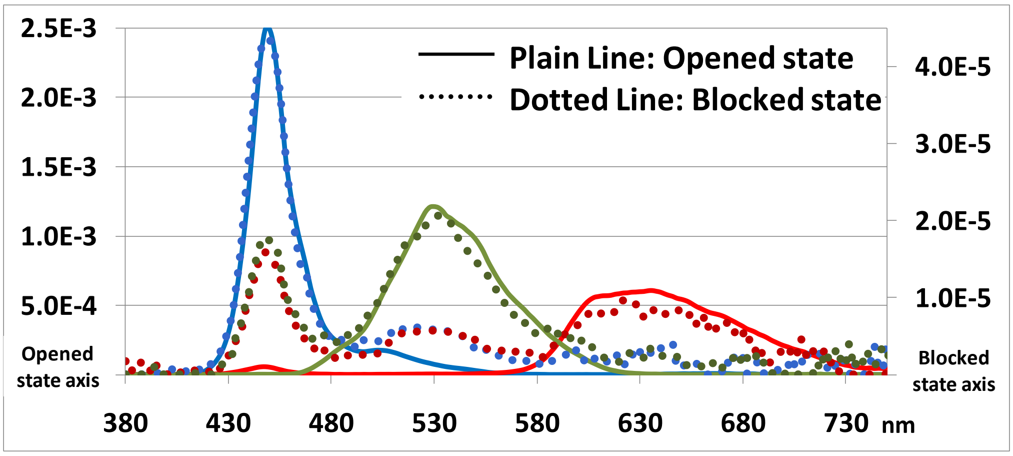

Figure 7 - Spectral measurement example.

To obtain the crosstalk, a spectral integration is performed on the visible portion of the spectrum.

The following important points must be taken into account in the set-up:

- If coherence in measurements is sought, optical filters should be reused or accurately simulated.
- For short acquisition times, preferably an integral number of periods shall be acquired to avoid noisy measurements.
- The content intercepted by the measurement beam needs to be mastered.
- Stray light in the room need to be controlled/minimized.

3.3 Spatial measurements

Another type of instrument is the imaging colorimeter. Such device provides a colorimetric measure XYZ for each point of an acquired image. For crosstalk evaluation it can be used in a very similar way as the spectrophotometer. As the R, G, B filters are part of the device to define the colorimetric observer, they should be removed from the experiment setup, keeping however the UV/IR ones. With a colorimetric imager, the central measure can easily be obtained by integrating over the desired XYZ image surface in the centre of the screen.

More spatial/angular dependent information can be obtained as the instrument has a field of view able to measure the full 3D-TV screen. Interestingly, such instrument can reveal angular variations associated with eye gaze direction as it is designed for display uniformity evaluation. Hence, uniformity or non-uniformity of crosstalk defects can be evaluated. An illustration of the spatial/angular dependency of crosstalk is depicted in Figure 8.

Measuring display+glasses can be done as well for the glasses opened and blocked states measuring an identical protocol as for the spectrophotometer. In this case, to obtain the crosstalk, a spatial integration will be performed over the selected field of view.

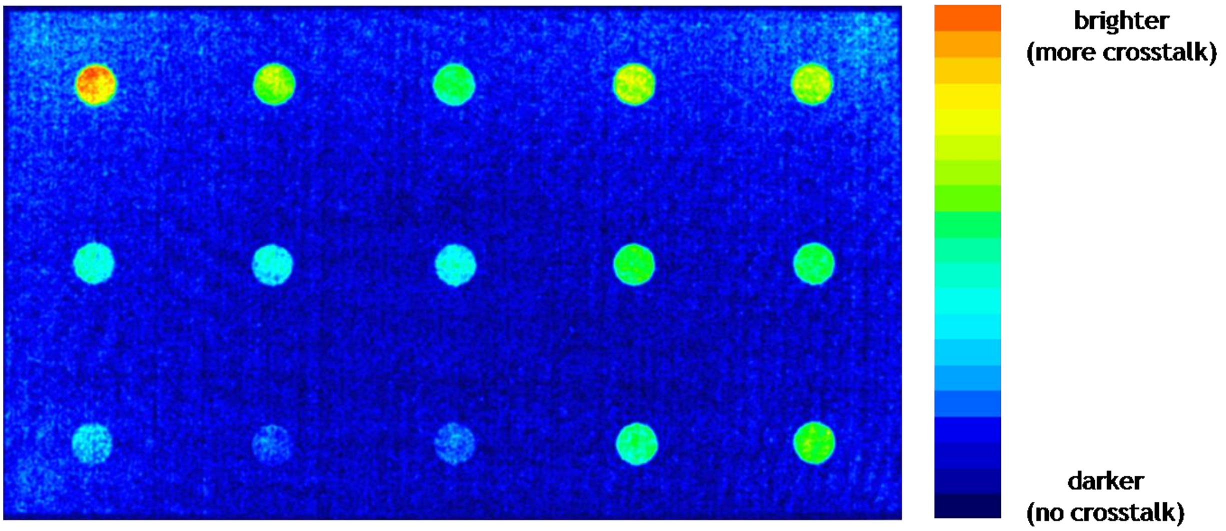

Figure 8 - Spatial variation of crosstalk (illustrated with pseudo-coloring).

4 Discussion

4.1 Angular influence

Two angular influences must be taken into account:

- As noted previously, a spatial measurement can record crosstalk variation depending on the eye gaze direction (e.g. position in the image). This gives already an angular indication of how the angular dependence of the LCS and the display angular emission are combined. In the case of LCD displays, light polarization and its interaction with the glasses polarization analyzers create specific effects altering image and crosstalk homogeneity.
- Another angular variation depends on the observer's position in front of the screen. The same effects of direction dependent light emission and of interaction between screen emission and glasses analysis will happen.

Because of the two points mentioned above, crosstalk measured at a specific angle can be dramatically more significant than a basic central measure on the screen normal axis. A single measurement at the centre of the screen is therefore not sufficient.

4.2 Influence of built-in crosstalk compensation

Anti-crosstalk or crosstalk compensation techniques are applied with the objective to decrease crosstalk perception. The basic method for anti-crosstalk is to reduce light emission in image areas where leakage from the other channel occurs. Another technique is to modify the color components of the signal in order to reduce the chromaticity of the crosstalk.

Because current 3D-TVs usually have such built-in crosstalk compensation, crosstalk (from the end-user perspective) is in fact the result of the inherent display crosstalk and the built-in mechanisms to compensate crosstalk:

- Crosstalk compensation techniques may reduce crosstalk in some scenarios but may actually generate artifacts in some other scenarios.
- Other display electronic processing may interact with anti-crosstalk mechanisms and affect its efficiency (e.g., overdrive in LCDs and power management in PDP displays)

As an illustration, a spectral measurement of a red patch image crosstalk shows colors in the blocked image (L^{LR}) (see the dotted red curve of Figure 7 showing blue and green light humps on the left side) not present in the image signal emitted for the other eye (L^{LL}) (plain red curve of Figure 7). Potentially, blue and green light was added, as a compensation, to create a grey result with the red leakage for less visibility. This chromatic correction increases the crosstalk in the corrected channels.

The points mentioned above make the evaluation of crosstalk even more difficult on 3D-TVs.

4.3 Coherence of measurements

Reproducibility of measurements is crucial to evaluate the crosstalk of a 3D display. Many issues are to be addressed to reach repeatable and reproducible measurements. The same issues can be obstacles in finding coherence between different types of measurement:

- Measurement of the weak blocked state: measurement uncertainty on the weak blocked state signal will greatly influence the crosstalk measure.

- Sensitivity of the measurement instrument: sensitivity of the measurement instruments, as well as geometry (position and angle) and spectral inconsistencies, are all sources of discrepancy between methods.
- Different spectral responses: spectral consistency is another influential factor. For example if the imaging colorimeter has built-in CIE-1931 observer spectral sensitivity, other methods should be adjusted to have spectrally the same sensitivity in order to avoid discrepancies due to the influence of color-dependent crosstalk.
- Geometry correspondence (analysis angle and position on the screen): this is very important to guarantee the same region of the screen is measured, and with the same analysis angle. Figure 9 shows a spatial acquisition identifying a 1° and a 16° field for a blocked state configuration. The difference in content between the 1° and the 16° field can affect the measurement mainly because of the non-uniformity of the crosstalk (blocked state luminance varies between 0.57 cd/m² and 1.67 cd/m² in the 16° circle). Considering the opened state as uniform (measured at 60 cd/m²), the crosstalk measure will significantly vary inside the 16° circle. It can be seen on the left part of Figure 9 that a small move of the 1° measurement spot may result in a significant change in the measure (±25% luminance variation for a ±2° move) affecting the crosstalk computation.

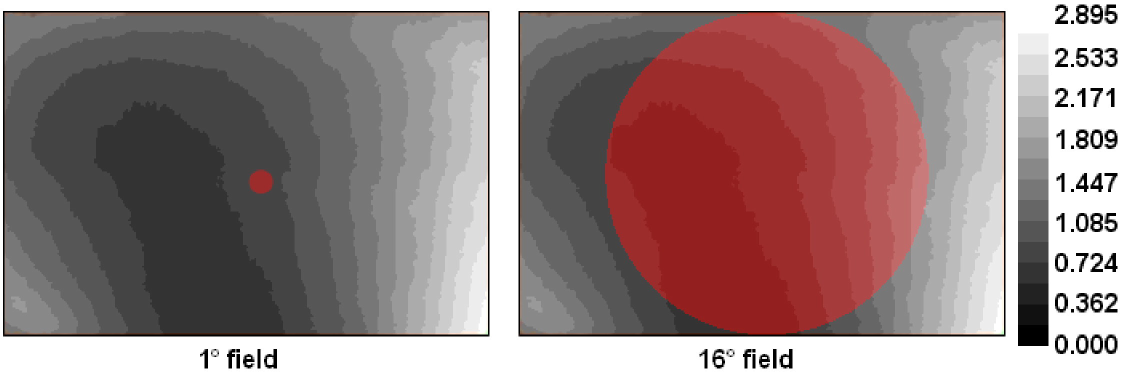

Figure 9 - 1° and 16° field observed at the centre of display.

Coherence between measurement methods can only result from rigorous experimental conditions in each case, building on the strength of each method, identifying and taking a special care of weaknesses.

5 Conclusions

Crosstalk is not necessarily only due to leakage of unintended white image/level onto intended black image/level but also to other grey-to-grey configurations (other grey-to-grey configurations may produce as perceivable/visible crosstalk).

Several types of measurement (spectral, spatial/angular, temporal) are required to meaningfully characterize and analyze crosstalk. Furthermore, many rigorous aspects in the measurement set-up must be followed in order to obtain reproducible and coherent measurements due to built-in processing mechanisms in the display that can modify the input signal depending on its characteristics. For example, it should be determined at which level(s) the measurements must be made: white on black only, or grids of small NxN patches and at which position.

Although this aspect was not covered in this contribution, the variation of crosstalk with the signal levels of each channel is another important factor to take into account.

In this contribution, we have described a number of physical measurements that, when carried out with care, can provide repeatable measures leading to a meaningful characterization of 3D display crosstalk.

6 Proposal

The selection of a 3D display for subjective quality assessment of 3D content should not be based only on the measure of crosstalk using the leakage of light signal from the open to the blocked channel, using a white image as the open channel signal and a black image as blocked channel signal but should also consider the following aspects:

1. The spatial variation of the crosstalk
2. The angular variation of the crosstalk (crosstalk off the center axis)
3. Chromatic aspects

The measurement approaches and protocols presented in this contribution can be used as a basis to define standardized measurement protocols, which can lead to a meaningful characterization of 3D display crosstalk.

Furthermore, a unified 3DTV crosstalk assessment should also be a goal. An approach to achieve such goal can be to combine several measurements, taken at different positions and angles, with different – e.g. colored – image signals. From these measurements, either an overall compound/synthetic indicator can then be built, with a weighted combination of individual crosstalk measurements/scores, or these measurements can be used with thresholds for a 'pass or fail' test on each of them. This would allow moving away from the single measure assessment of crosstalk and defining a more representative evaluation of the various usage configurations of 3D displays.

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