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HDR video past, present and future: A perspective

Alan Chalmers

WMG, University of Warwick, United Kingdon

Kurt Debattista

WMG, University of Warwick, United Kingdon

Abstract

High Dynamic Range (HDR) video has emerged from research labs around the world and entered the realm of consumer electronics. The dynamic range that a human can see in a scene with minimal eye adaption (approximately 1,000,000 : 1) is vastly greater than traditional imaging technology which can only capture about 8 f-stops (256 : 1). HDR technology, on the other hand, has the potential to capture the full range of light in a scene; even more than a human eye can see. This paper examines the field of HDR video from capture to display; past, present and future. In particular the paper looks beyond the current marketing hype around HDR, to show how HDR video in the future can and, indeed, should bring about a step change in imaging, analogous to the change from black and white to colour.

Keywords: High dynamic range imaging, HDR, HDR video

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1. Introduction

There can be a very broad range of lighting in a scene, from parts in bright sunshine to areas of dark shadow. The ratio between the darkest and brightest parts of a scene is known as its dynamic range. Figure 1 shows a sunset with a dynamic range of 10.6 f-stops. The dark area has a lighting level of 2.8 cd/m^2 (also known as nits), whilst the setting sun behind the clouds has a light level of 4,400 cd/m^2, giving the scene a dynamic range of $4400/2.8 = 1571.4 \approx 2^{1}0.6$ ie just over 10 f-stops.

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Figure 1: Captured with an ARRI Alexa camera and tone mapped for print; 10.6 f-stops of dynamic range in a sunset scene with a minimum lighting level of 2.8 ^{2} and a maximum of 4,400cm/m^2. Note detail is lost in the tone mapping process. Image courtesy of Brian Karr.

As humans can see approximately 20 f-stops of light with no noticeable eye adaption, all the detail in this scene would be visible. However, if an image of this scene was captured by a traditional, or Low Dynamic Range (LDR) (aka SDR=Standard Dynamic Range) [1] digital camera significant detail would be lost as such technology is only capable of capturing 8 f-stops. This is worse than film cameras which were capable of capturing approximately 15.5 f-stops, while as early as the 1960s a special silver halide photographic film was developed in order to capture the wide dynamic range of, for example, nuclear explosions and rocket motor flames [3, 4]. This film was capable of capturing 26.6 f-stops.

In the early 1990s, it became clear to a number of researchers that existing digital imaging techniques were inadequate to cope with the data required to store the full range of lighting available in a real world scene. This was driven primarily by computer graphics, where rapid advances in physically-based rendering techniques in the 1980s, such as ray tracing [5] and radiosity [6], had

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[1] In an attempt to standardise the definition of what constitutes HDR the MPEG adhoc committee on HDR adopted the suggestion by EU COST Action IC1005 [1]: Low Dynamic Range (LDR) is $\leq$ 10 f-stops (aka Standard Dynamic Rage (SDR)); Enhanced Dynamic Range (EDR) is $>$ 10 f-stops and $\leq$ 16 f-stops; and, High Dynamic Range (HDR) is $>$ 16 f-stops [2].

brought about the synthesis of highly realistic computer imagery. In 1991, Ward introduced a data format which was able to represent HDR pixel values to support his physically-based rendering engine, Radiance [7]. A breakthrough for capturing HDR images came with Debevec and Malik's paper in 1997 [8], which clearly demonstrated how an HDR image could be captured from a series of LDR exposures using knowledge of the camera response curve. It would still, however, be many years before the first displays capable of displaying HDR video (2004) [9], or HDR video cameras (2009) [10] would appear.

Currently, HDR video is gaining wider adoption, helped mainly through the specification of Ultra High Definition (UHD) for the broadcasting sector, ITU-R Recommendation BT.2020 [11]. Although a single standard for HDR has yet to be agreed, consensus is forming around the HDR10 [12] and HLG [13] proposals, both of which have been encapsulated in the recent ITU-R HDR-TV Recommendation BT.2100 [14]. The key question now is: *Has enough been done to ensure that HDR technology can indeed capture and later display at least all the detail that a human eye can see in any scene, and preferably even the detail that the human eye cannot see?*

2. The HDR video Pipeline

Figure 2 shows the HDR video pipeline as envisaged by cartoonist Lance Bell for EU COST Action IC1005 [1]. The 25 years since Ward published his pioneering data format for storing HDR data [7], has seen significant developments in HDR technology, albeit in step changes rather than steady progress. The development has been a classic case of *what comes first, the chicken or the egg?* Before the arrival of HDR displays, HDR images could be captured with multiple exposures, or created using computer graphics, but they could only be displayed on LDR displays. This led to a large number of tone mapping operators (TMOs) being proposed to better display the HDR images on the LDR screens [15]. With the advent of HDR displays, HDR images could finally be shown directly in HDR, but there were no video cameras capable of capturing

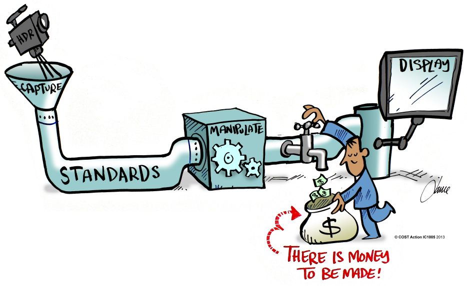

Figure 2: The HDR pipeline. Image courtesy of EU COST Action IC1005 [1].

HDR video. The multiple-exposure technique, which worked well with static scenes, resulted in ghosting artefacts when parts of the scene, or the camera, were moving.

2.1. Capture

To minimise ghosting artefacts, systems that use a multiple exposure approach to capture HDR video, such as the work by McNamee et al. [16], require sophisticated, real-time de-ghosting algorithms [17]. Other HDR video systems avoid the need for multiple exposures by using, for example, multiple sensors with the same integration time through a single lens [10]. The sensors need different sensitivities to cover the whole dynamic range of the scene which can be created by analogue-gain and/or neutral density-filters. Such an approach has the advantage that artefacts from moving objects are avoided and correct motion blur is achieved from the identical integration-time. However, matching the images from the sensors is challenging to achieve due to restrictions on sensor alignment precision. Furthermore, building cameras with multiple sensors having a larger format is difficult and the result could be physically cumbersome.

While research prototype HDR video cameras have been able to achieve 20 f-stops at 30fps, commercial HDR video cameras can currently only capture a much more modest dynamic range. A recent survey of the dynamic range of 18 commercial cameras for possible use in imaging rocket launches [18], concluded that current commercial systems were only able to capture < 18 f-stops, and thus not yet suitable to adequately image a rocket launch (> 20 f-stops).

2.2. Storage

The full range of light in a scene can be represented using 32 bit IEEE floating point single precision values for each colour channel, ie with 96 bits per pixel (bpp) [15]. LDR is typically stored using just 24 bpp, 8 bits per colour channel. The data requirements of HDR are significant. A single HDR frame of uncompressed 4K UHD resolution (3,840 × 2,160 pixels) requires approximately 95Mbytes, and a minute of data at 30fps is 167 Gbytes. Efficient data formats and compression techniques are thus essential if HDR video is to be used with existing ICT infrastructure.

Since Wards Radiance format [7], a number of other ways of representing HDR pixels have been proposed, including LogLuv encoding used in a custom HDR-version of the TIFF images [19], and OpenEXR. Developed by Industrial Light and Magic for the film industry, OpenEXR has since been released as free software [20]. Adopted by the Academy Color Encoding System (ACES) for ensuring consistent colour within the life cycle of a film [21], OpenEXR is, however, not suitable for HDR video as each frame at HD resolution requires about 8 Mbytes when compressed with lossless compression. Instead efficient video compression is required.

2.3. Compression

Compression of HDR video may be classified as one-stream or two-stream [22]. One-stream methods benefit from the higher bit-depths (≥ 10) available in modern video codecs. Compression is achieved via a transfer function that maps the input HDR video stream into a more compact representation. Meta data can be included in the resulting compressed stream to provide additional information necessary for reconstructing the HDR video signal at the display. Examples of one-stream HDR video compression include HDRv [23], adaptive LogLuv [24], PQ [25], HLG [26] and the Power Transfer Function method [27].

Two-stream methods, on the other hand, separate the single HDR video input stream into base and detail streams which are then compressed separately. One of the two streams is frequently backward compatible, allowing it to be played directly on an existing LDR player, while the other stream contains the additional information required to reconstruct the HDR video. A key advantage of two-stream methods is that they work on legacy 8-bit infrastructure, including mobile devices, as well as with more recent higher bit-depth frameworks. Examples of two-stream compression for HDR video include HDR-MPEG [28], rate distortion [29], the base and detail method [30], and optimal exposure [31]. A recent evaluation of one- and two-streams showed that one stream methods perform better, on the whole, than two-stream methods in both subjective and objective evaluations [22].

2.4. Displays

One of the earliest HDR displays was a stereoscopic viewer developed by Ward in 2002 [32], Figure 3. Comprising a bright uniform backlight connected to a set of LEEP ARV-1 stereo optics, the system provided a 120 degrees field of view in each eye. The HDR images were provided by printed transparencies which, when layered, provided a dynamic range of 10,000 : 1. This viewer was subsequently validated against real scenes and a close match found in terms of visibility and contrast [33].

The Sunnybrook Technologies SBT1.3 HDR Display was a rear-projection based dual-modulation display system. An Optoma EzPro737 DLP (Digital Light Projection) video projector was modified. The colour wheel was removed and the greyscale video was projected through an array of lenses onto the back of a 15” XGA colour Sharp LQ150X1DG0 LCD display. The system was capable of displaying HDR images with a dynamic range of more than 75,000 : 1 [34]. Future versions of Sunnybrook Technologies (which became known as Brightside in March 2005) HDR displays replaced the data projector with a backlight comprising an individually controlled array of white LEDs. These were projected through a standard LCD monitor. Each LED covered approximately 4040 pix-

Figure 3: Earliest HDR display [32] (left) and Validating HDR against reality [33] (right) .

els. This, together with software correction algorithms that took into account how the human eye perceives light scattering, provided a substantial increase in dynamic range. The DR37-P display was capable of a dynamic range of 16 f-stops [9].

In February 2007 Brightside was acquired by Dolby. Subsequent development of HDR displays was undertaken by SIM2, which in 2009 released their first HDR display, the HDR47, with a peak luminance of 4,000 cd/m^2. In 2014 SIM2 announced the HDR47ES6MB. The backlight for this display is provided by 2202 LEDs with 12 bits of brightness resolution for each LED, giving a peak brightness of 6,000 cd/m^2. The front panel is a 47 LCD TFT, High Temperature panel with full HD (1,920 × 1,080) resolution and the display is capable of a video frame rate of 60Hz. At IBC in September 2016, SIM2 together with partners, University of Warwick, TrueDR Ltd and Vicomtech-IK4, showed the world's first 10,000 cd/m^2 display. Section 3 highlights how this compares with some of the modern consumer HDR displays.

2.5. Quality Metrics

Although substantial research has been undertaken in evaluating the quality of LDR video [35, 36], the only recent wider availability of HDR video means that far less has been done with HDR video. Using LDR metrics directly with HDR video has been shown to result in a low correlation between the results of these object metrics and human studies [22]. LDR methods can be used for HDR if the metrics take into account the human visuals system's (HVS) propensity to light perception. The Perceptually Uniform (PU) encoding [37] can be used to modify traditional metrics such as PSNR and SSIM [38] to be more amiable to HDR video quality validation. Metrics designed directly for HDR, for example, the High Dynamic Range-Visible Difference Predictor (HDR-VDP) [39], and others designed directly for HDR video such as High Dynamic Range-Visual Quality Metric (HDR-VQM) [40] and Dynamic Range Independent Visual Quality Metric (DRI-VQM) [41] perform well also and, as with the PU-modified metrics, provide a good objective measure of the quality of HDR video [22].

3. The Present: Consumer HDR

From relative obscurity just three years ago, HDR has now become a widely recognised term and a first wave of televisions which claim to support HDR are appearing [42]. At the Consumer Electronics Show (CES) in January 2016, a number of leading manufacturers, including Sony, LG, Panasonic and Samsung, all showed TVs claiming to support HDR. In addition, a consortium of TV manufacturers, broadcasters and content producers, the UHD Alliance [43], was formed to promote their view of HDR. They proposed a benchmark, Ultra HD Premium, above which they were happy to certify that the platform was suitable for a "premium 4K experience". To satisfy manufacturers of both LED and OLED HDR displays, the UHD Alliance proposed two definitions of HDR [44]:

1. 1,000 cd/m^2 peak brightness and < 0.05 cd/m^2 black level (contrast ratio $20{,}000 : 1$, 14.3 f-stops) for LED TVs which are brighter but with less black levels, or
2. > 540 cd/m^2 brightness and < 0.0005 cd/m^2 black level (contrast ratio $1{,}080{,}000 : 1$, 20 f-stops) for OLED TVs which have deep blacks but much lower peak brightness.

There are currently three proposals to support consumer HDR in this first wave: HDR10 [12], HLG [26] and Dolby Vision [45]. HDR10 is based on a 10-bit PQ curve [25] which is part of SMPTE standard ST.2084 [12]. Television sets which support HDR10 are allowed by the UHD Alliance to use their Ultra HD Premium logo. Furthermore, the Consumer Technology Association (CTA), requires any television labelled as HDR-compatible to be able to decode HDR10 inputs [46]. Any metadata is static for the entire length of any content. Dolby Vision is a proprietary standard which includes a 12-bit PQ curve. The metadata for any content may vary scene by scene [46, 47]. HLG has been designed by the BBC and NHK for the television industry [26], and was standardised as ARIB STD-B67 [13]. It needs no metadata, the management of which is a major challenge in live broadcast. Both HLG and PQ are now contained in ITU-R Rec BT.2100 [14].

The first wave of consumer HDR displays are, however, unable to deliver the full potential of HDR. Despite the impressive 20 f-stops of dynamic range claimed for OLED televisions, these devices have serious limitations. To be able to actually see detail in the dark areas of the screen, the content needs to be watched in a totally dark room. In fact it is even recommended that the walls of the room are not painted white to avoid any increase in ambient light levels [48]. Even for the consumer LED HDR displays certified by the UHDA, it is recommended that, to be able to clearly see the benefits of HDR, the displays should be placed in an ambient lighting on no more than 5 cd/m^2.

A further limitation of consumer HDR displays, highlighted by the recent survey of HDTVtest [49], is that they do not provide an overall brighter image, but rather maintain the average picture level of the frames. The HDR effect is achieved by deeper black levels and a few bright highlights. In addition to the need to use these displays in dark environments so that the deeper black levels can actually be seen, it is in fact not possible to simply increase the overall brightness of the screen to get a brighter image as one would with a traditional LDR display. This is because the maximum backlight brightness is being used to provide the bright highlights. One of the contributing factors to this problem

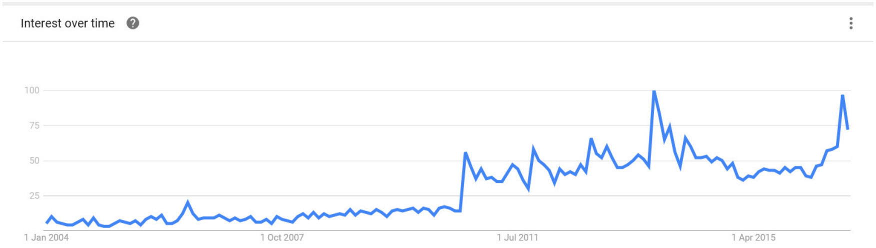

Figure 4: Searches for HDR video since 2004 (from Google trends).

is the lack of flexibility in the ST.2084 EOTF to adapt to different ambient lighting conditions because every input signal value is mapped directly to the same output luminance level on all HDR displays [12].

4. Applications

As HDR video become more widely known, so has the number of requests for more information and applications become more widespread. Figure 4 shows the trend as to how information requests about HDR video have grown since 2004. In addition there has been a significant increase in special sessions at conferences, for example, [BN11, CC14], special issues of journals, for example [50, 51] and even books dedicated to HDR video, for example [52, 53]. HDR video is now being used in applications across most fields of imaging, including: filming spacecraft [54], automotive [55], object tracking [56], etc.

4.1. Linear vs Perceptual Encoding

One issue that is now being realised is that nearly all tone mapping operators and video encoding schemes are designed to provide HDR video content for human viewers and not for computer vision applications. Perceptual encoding can exploit knowledge of the HVS, such as the fact the HVS is able to discern luminance threshold differences more clearly in darker areas than brighter ones to achieve efficient encoding [57]. However, for computer vision applications, such perceptual encoding may result in detail in the scene being missed or

Figure 5: Failure to capture all the detail in a scene with traditional imaging systems.

over-accentuated by the computer vision algorithms [44, 58, 59]. Simple linear encoding is not the answer either. Rana et al. [60] showed that although computer vision algorithms can be more effective working directly on HDR pixel values, these values first should be encoded to perceptually linear values. Further research is required to provide conclusive evidence how best to encode HDR video efficiently to provide a single compressed video stream for both human and computer requirements.

The use of HDR imaging for computer vision applications is set to increase significantly in the coming years, with more and more reliance on imaging techniques rather than humans to, for example, control autonomous cars, and increase surveillance capabilities. The consequences of a camera failing to capture and accurately analyse all the information in a scene can have tragic consequences, as shown by the fatal Tesla car accident where the on-board imaging system was unable to detect a large 18-wheel white truck and trailer against a bright sky [61]. Figure 5 shows the failure of a traditional imaging system to capture detail inside a car or outside the tunnel.

5. The Future: Fulfilling its Potential

The first wave of HDR technology can be thought of as being “display referred”. In this approach, content is graded to try getting the “best looking” image for a particular display [Wri13]. This is of course highly subjective, limited by any displays capabilities, and not necessarily a true representation of the real scene being portrayed. HDR technology has the ability to provide a one-to-one relationship between the actual dynamic range in the scene, and that which is captured and delivered to a display. While creative intent may permit the use of adapting original content, ideally the technology should have the capability of reproducing real world lighting. Thus to achieve the full potential of HDR video, it should be “scene referred”, Figure 6. The real world contains a wide range of lighting. A scene referred HDR image is one that reproduces the lighting in the actual scene. Of course, the dynamic range of the camera may not be sufficient to capture all the lighting. One advantage of a scene referred approach is that images of the same scene from different scene referred cameras should look the same. This is a key feature of the ACES workflow which is being increasingly used for managing images within motion picture and television production [21]. A challenge of scene referred content for live broadcast though is, for example, having to intercut a news reader captured in a dim studio, with content captured in a very bright environment, resulting in significant flicker [62]. The solution to this is to use knowledge of the lighting in both scenes to smooth out any flicker prior to displaying the combined content. Furthermore, to ensure an enhanced viewing experience, how the image should be displayed should also take into account the capabilities of the display device and the ambient lighting conditions under which the content is being viewed.

Defined by EU COST Action IC1005 [1], TrueHDR is a scene referred system that ensures the full range of HDR data is preserved throughout the entire pipeline from capture to display. No tone mapping occurs within the pipeline until just before display. As Figure 8 shows, with TrueHDR, an appropriate TMO (chosen dynamically from a range of TMOs) is used to tone map the received HDR video content on to the display (per scene if necessary), ensuring an enhanced viewing experience as this tone mapping takes into account, the actual characteristics of the display, the ambient lighting conditions, any creative intent, and the viewer’s own viewing preferences. These preferences can be

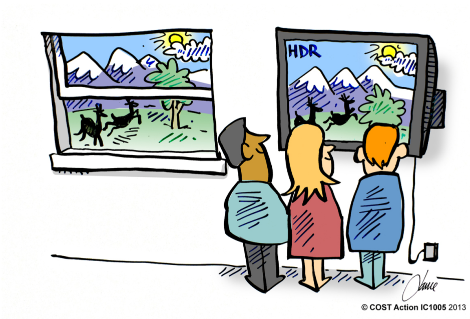

Figure 6: Scene referred data: A one-to-one relationship with a real scene. Image courtesy of EU COST Action IC1005 [1].

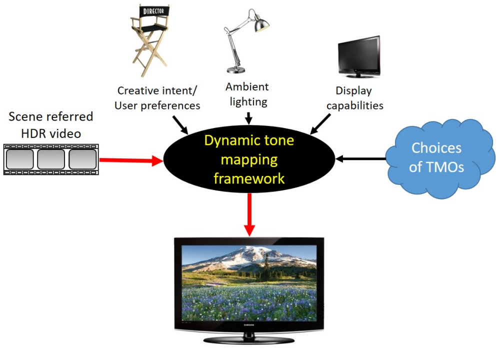

Figure 7: TrueHDR framework.

manual, such as a the viewer selecting which player he/she wishes to see clearly whatever the scene lighting conditions or automatic, such as "see ball mode", which would show, for example the golf ball clearly (in one exposure) up against the bright sky (shown in another exposure).

Although scene referred, ACES is not suitable for bit-rates used in live video [21]. One scene referred HDR video codec that is suitable for live broadcast is the Power Transfer Function (PTF) [27]. An analytical implementation of PTF has been shown to be 29 times faster than an analytical implementation PQ and over 1.4 times faster than an LUT implementation of PQ, Table 1.

	Time per frame (in ms)				Speedup	
	Analytical		Look Up Table		PTF_4	
	PTF_4	PQ	PTF_4	PQ	vs PQ	vs LUT
	2.70	69.39	3.89	3.99	25.69	1.44
	2.69	98.08	3.95	3.91	36.90	1.47

Table 1: Comparison of HDR video encoding between PQ and PTF [27].

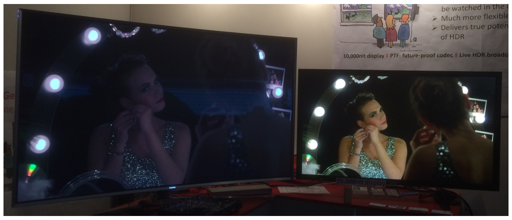

Figure 8: Comparison of displays seen at IBC 2016 (left) Samsung 1,500 cd/m^2 (right) SIM2 10,000 cd/m^2.

6. Discussion

HDR and HDR video in particular has come a very long way in just the last five years. HDR is now being used as a powerful marketing tool in the drive to sell “next generation” televisions. In traditional economics terms, the barriers that could limit widespread adoption of HDR technology are [63]:

1. **The lack of a clear benefit of HDR in a specific application:** HDR is already starting to affect every aspect of imaging from gaming, to entertainment to surveillance and autonomous vehicles. This is thus not a barrier as the benefits to these applications are clear: more immersive gaming experiences; better quality images and therefore increased sales of HDR-enabled televisions; the ability to see and track objects even in extreme lighting; and, increased safety.
2. **High costs in moving to from LDR to HDR technology:** This is currently a barrier as costs for specialised HDR equipment are high.

Low-cost consumer HDR video cameras do not yet exist, although it is possible to create HDR video using multiple exposures with off-the-shelf DSLR cameras [16], for example a Canon 5D using Magic Lantern [64]. As discussed above, consumer televisions are claiming to be HDR, however, HDR displays capable of delivering a true HDR experience with peak luminance $> 4{,}000$ cd/m^2, such as those from SIM2, are still relatively expensive. It can be expected though that consumer HDR displays will continue to improve their peak brightness as customers increasingly want to watch HDR content in conditions other than a dark room; for example Sony has announced a 4,000 cd/m^2 display [65].

3. **If some key parts in the HDR pipeline contain (expensive) proprietary IPR:** Dolby Vision is a proprietary HDR ecosystem that ensures the delivery of high-quality HDR content [45]. Fortunately for the widespread uptake of HDR video, two free alternative HDR compression schemes have been standardised, HDR10 and HLG [14], while a number of equally good methods are freely available in the academic literature [23, 24, 27]. Standardisation may be a key issue to facilitate large-scale industry adoption of HDR, however many other users, including OTT broadcasting, have no such restrictions.
4. **The lack of backward compatible solutions to ease the transition from LDR to HDR:** Backward compatibility is a major problem facing the adoption of HDR at present. The one-stream encoding methods encapsulated in ST.2100 [14] assume a 10-bit infrastructure and that the display will be HDR enabled. It is not clear yet precisely how HDR content will be shown on legacy displays which are not HDR enabled. Furthermore, although mobile devices are rapidly becoming the platform of choice to watch video content [66], until these too become 10-bit architectures, viewers will have to content with some form of image which is tone mapped at the client. An alternative is that a two-stream compression method will be needed to deliver the HDR content, perhaps in a novel architecture to take into account the actual capabilities of the devices, such

as that proposed by Melo et al. [67].

Another major factor affecting the adoption of HDR is that, despite the fact that HDR televisions are being highly marketed, HDR content is still not widely available. For example, in April 2016 Netflix offered viewers Season 1 of the Marco Polo series in 4K HDR, but required the viewers to join the Netflix 4K content streaming plan for $12 per month [68]. Amazon Prime, now offers 27 4K HDR films, but again viewers need to be customers of Amazon Prime subscription service and own an HDR 4K TV [69]. At present, viewing (the limited) HDR video content on consumer HDR televisions is impressive, but only in a dark room.

Although consumer adoption of HDR may currently be slow and there are still barriers to overcome, research and development continues apace. A 10,000 cd/m^2 SIM2 HDR display was shown within the Future Zone section of IBC in September 2016 [70], Figure 8. This demonstration can be regarded as a "game changer" for the future of HDR. The 10,000 cd/m^2 display clearly showed that HDR does not have to be watched in a dark room, perhaps even with the walls painted black. With a 10,000 cd/m^2 display you can, for example, enjoy the HDR experience within sports in the afternoon with your curtains open; and, despite previous "fear-mongering" about bright displays, you do not need sun glasses to look at a 10,000 cd/m^2 display nor do you need your own power station to power it; it has a peak power consumption of 1.5kW [71].

Existing HDR video codecs, such as HDR10, HLG and even the 12-bit PQ within Dolby Vision, only do not produce artefacts on displays with peak luminance of less than 10,000 cd/m^2. Now that a 10,000 cd/m^2 display is a reality, new codecs need to be developed. To fully exploit the future of HDR, these new video codecs need to be "scene referred"; capable of coping with the full range of light in a scene rather than a peak luminance of a display. Furthermore, such "future-proof" codecs should go beyond just HDR and take into account all components of UHD video: spatial resolution (at least 4K), higher dynamic range and frame rate, and wider colour gamut. This will provide the foundation necessary for further significant innovation in the media and creative industries, and beyond.

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References

[1] EU COST Action IC1005, HDRi: The digital capture, storage, transmission and display of real-world lighting (2015).
URL `https://www.itu.int/rec/R-REC-BT.2100`

[2] A. Luthra, E. Francois, W. Husak, Call for evidence (CfE) for HDR and WCG video coding, ISO/IEC JTC1/SC29/WG11 MPEG2014 N 15083.

[3] C. W. Wyckoff, An experimental extended response film, SPIE Newslett (1962) 16–20.

[4] C. W. Wyckoff, Silver halide photographic film having increased exposure-response characteristics, US Patent 3,450,536 (Jun. 17 1969).

[5] T. Whitted, An improved illumination model for shaded display, in: ACM SIGGRAPH Computer Graphics, Vol. 13, ACM, 1979, p. 14.

[6] C. M. Goral, K. E. Torrance, D. P. Greenberg, B. Battaile, Modeling the interaction of light between diffuse surfaces, in: ACM SIGGRAPH Computer Graphics, Vol. 18, ACM, 1984, pp. 213–222.

[7] G. Ward, Real pixels, Graphics Gems II (1991) 80–83.

[8] P. E. Debevec, J. Malik, Recovering high dynamic range radiance maps from photographs, in: ACM SIGGRAPH 2008 classes, ACM, 2008, p. 31.

[9] H. Seetzen, W. Heidrich, W. Stuerzlinger, G. Ward, L. Whitehead, M. Trentacoste, A. Ghosh, A. Vorozcovs, High dynamic range display systems, ACM Transactions on Graphics (TOG) 23 (3) (2004) 760–768.

[10] A. Chalmers, G. Bonnet, F. Banterle, P. Dubla, K. Debattista, A. Artusi, C. Moir, High dynamic range video solution, in: ACM SIGGRAPH ASIA 2009 Art Gallery & Emerging Technologies: Adaptation, ACM, 2009, pp. 71–71.

[11] M. Sugawara, S.-Y. Choi, D. Wood, Ultra-high-definition television (rec. ITU-R BT. 2020): A generational leap in the evolution of television [standards in a nutshell], IEEE Signal Processing Magazine 31 (3) (2014) 170–174.

[12] S. Standard, High dynamic range electro-optical transfer function of mastering reference displays (2014).

[13] Association of Radio Industries and Businesses (ARIB). STD-B67: Essential parameter values for the extended image dynamic range television (EIDRTV) system for programme production , howpublished = `http://web.archive.org/web/20080207010024/http://www.808multimedia.com/winnt/kernel.htm`, note = Accessed: 2010-09-30.

[14] TU-R Rec BT.2100, Image parameter values for high dynamic range television for use in production and international programme exchange (2016). URL `https://www.itu.int/rec/R-REC-BT.2100`

[15] F. Banterle, A. Artusi, K. Debattista, A. Chalmers, Advanced high dynamic range imaging: theory and practice, CRC press, 2011.

[16] J. McNamee, J. Hatchett, K. Debattista, A. Chalmers, Live hdr video streaming on commodity hardware, in: SPIE Optical Engineering+ Applications, International Society for Optics and Photonics, 2015, pp. 95990U–95990U.

[17] O. T. Tursun, A. O. Akyüz, A. Erdem, E. Erdem, The state of the art in HDR deghosting: A survey and evaluation, in: Computer Graphics Forum, Vol. 34, Wiley Online Library, 2015, pp. 683–707.

[18] B. A. Karr, A. Chalmers, K. Debattista, High dynamic range digital imaging of spacecraft.

[19] G. W. Larson, LogLuv encoding for full-gamut, high-dynamic range images, Journal of Graphics Tools 3 (1) (1998) 15–31.

[20] F. Kainz, R. Bogart, D. Hess, The OpenEXR image file format, GPU Gems: Programming Techniques, Tips and Tricks for Real-Time Graphics, R. Fernando, Ed. Pearson Higher Education.

[21] Academy of Motion Picture Arts and Sciences, Academic color encoding system (2016).
URL `http://www.oscars.org/science-technology/sci-tech-projects/aces`

[22] R. Mukherjee, K. Debattista, T. Bashford-Rogers, P. Vangorp, R. Mantiuk, M. Bessa, B. Waterfield, A. Chalmers, Objective and subjective evaluation of high dynamic range video compression, Signal Processing: Image Communication 47 (2016) 426–437.

[23] R. Mantiuk, G. Krawczyk, K. Myszkowski, H.-P. Seidel, Perception-motivated high dynamic range video encoding, ACM Trans. Graph. 23 (3) (2004) 733–741. `doi:http://doi.acm.org/10.1145/1015706.1015794`.

[24] J.-U. Garbas, H. Thoma, Temporally coherent luminance-to-luma mapping for high dynamic range video coding with H. 264/AVC, in: IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), IEEE Computer Society, 2011, pp. 829–832.

[25] S. Miller, M. Nezamabadi, S. Daly, Perceptual signal coding for more efficient usage of bit codes, SMPTE Motion Imaging Journal 122 (4) (2013) 52–59.

[26] T. Borer, A. Cotton, A display-independent high dynamic range television system, SMPTE Motion Imaging Journal 125 (4) (2016) 50–56.

[27] J. Hatchett, K. Debattista, R. Mukherjee, T. Bashford-Rogers, A. Chalmers, An evaluation of power transfer functions for HDR video compression, The Visual Computer.

[28] R. Mantiuk, A. Efremov, K. Myszkowski, H.-P. Seidel, Backward compatible high dynamic range MPEG video compression, ACM Trans. Graph. 25 (3) (2006) 713–723. `doi:http://doi.acm.org/10.1145/1141911.1141946`.

[29] C. Lee, C.-S. Kim, Rate-distortion optimized compression of high dynamic range videos, in: 16th European Signal Processing Conference (EUSIPCO 2008), 2008, pp. 461–464.

[30] F. Banterle, A. Artusi, K. Debattista, P. Ledda, A. Chalmers, G. J. Edwards, G. Bonnet, HDR video data compression devices and methods, Available at `https://register.epo.org/application?number=EP08012452&tab=main`, eP Patent App. EP20,080,012,452 (July 2008).

[31] K. Debattista, T. Bashford-Rogers, E. Selmanović, R. Mukherjee, A. Chalmers, Optimal exposure compression for high dynamic range content, The Visual Computer 31 (6-8) (2015) 1089–1099.

[32] P. Ledda, G. Ward, A. Chalmers, A wide field, high dynamic range, stereographic viewer, in: Proceedings of the 1st international conference on Computer graphics and interactive techniques in Australasia and South East Asia, ACM, 2003, pp. 237–244.

[33] P. Ledda, A. Chalmers, H. Seetzen, HDR displays: a validation against reality, in: Systems, Man and Cybernetics, 2004 IEEE International Conference on, Vol. 3, IEEE, 2004, pp. 2777–2782.

[34] H. Seetzen, L. A. Whitehead, G. Ward, 54.2: A high dynamic range display using low and high resolution modulators, in: SID Symposium Digest of Technical Papers, Vol. 34, Wiley Online Library, 2003, pp. 1450–1453.

[35] K. Sayood, et al., Statistical evaluation of image quality measures, Journal of Electronic imaging 11 (2) (2002) 206–223.

[36] H. R. Sheikh, M. F. Sabir, A. C. Bovik, A statistical evaluation of recent full reference image quality assessment algorithms, IEEE Transactions on image processing 15 (11) (2006) 3440–3451.

[37] T. O. Aydın, R. Mantiuk, H.-P. Seidel, Extending quality metrics to full luminance range images, in: Electronic Imaging 2008, International Society for Optics and Photonics, 2008, pp. 68060B–68060B.

[38] Z. Wang, A. C. Bovik, H. R. Sheikh, E. P. Simoncelli, Image quality assessment: From error visibility to structural similarity, IEEE Transactions on Image Processing 13 (4) (2004) 600–612.

[39] M. Narwaria, R. K. Mantiuk, M. P. Da Silva, P. Le Callet, HDR-VDP-2.2: a calibrated method for objective quality prediction of high-dynamic range and standard images, Journal of Electronic Imaging 24 (1) (2015) 010501–010501.

[40] M. Narwaria, M. P. Da Silva, P. Le Callet, HDR-VQM: An objective quality measure for high dynamic range video, Signal Processing: Image Communication 35 (2015) 46–60.

[41] T. O. Aydın, M. Čadík, K. Myszkowski, H.-P. Seidel, Video quality assessment for computer graphics applications, ACM Trans. Graph. 29 (6) (2010) 161:1–161:12. `doi:10.1145/1882261.1866187`.
URL `http://doi.acm.org/10.1145/1882261.1866187`

[42] Trusted Reviews, What is Ultra HD Premium? New HDR standard explained (2016).
URL `http://www.trustedreviews.com/opinions/ultra-hd-premium`

[43] UHD Alliance (2016). [link].
URL `www.uhdalliance.org`

[44] A. Chalmers, B. Karr, R. Suma, K. Debattista, Fifty shades of HDR, in: Digital Media Industry & Academic Forum (DMIAF), IEEE, 2016, pp. 53–58.

[45] Dolby, Dolby Vision: White Paper (2016).
URL `http://www.dolby.com/us/en/technologies/dolby-vision/dolby-vision-white-paper.pdf`

[46] M. Brennesholtz, HDR10 vs Dolby Vision (2016).
URL `http://www.displaydaily.com/article/152-display-daily/42427-hdr10-vs-dolby-vision`

[47] N. Pino, HDR10 vs Dolby Vision: Heres what you need to know about the HDR format war (2016).
URL `http://www.techradar.com/news/hdr10-vs-dolby-vision-heres-what-you-need-to-know-about-the-hdr-format-war`

[48] T. Schulte, HDR demystified.

[49] V. Teoh, 4K Blu-ray vs Blu-ray Reveals HDR Is Too Dim for Daytime , HDTVtest (2016).
URL `http://www.hdtvtest.co.uk/news/4k-vs-201604104279.htm`

[50] M. Mrak, C. Robert, P. Le Callet, Editorial: Special issue on advances in high dynamic range video research, Signal Processing: Image Communication 29 (2) (2014) 189–190.

[51] L. P. Santos, K. Debattista, Foreword–high dynamic range imaging, Computers & Graphics 7 (37) (2013) A11–A12.

[52] A. Chalmers, P. Campisi, P. Shirley, I. Olaizola, High dynamic range video, concepts, technologies and applications.

[53] F. Dufaux, P. Le Callet, R. Mantiuk, M. Mrak, High Dynamic Range Video: From Acquisition, to Display and Applications, Academic Press, 2016.

[54] B. Karr, A. Chalmers, K. Debattista, High dynamic range digital imaging of spacecraft, in: F. Dufaux, P. L. Callet, R. Mantiuk, M. Mrak (Eds.), High Dynamic Range Video: From Acquisition, to Display and Applications, Elsevier, 2016, Ch. 20.

[55] U. Seger, HDR imaging in automotive applications, in: F. Dufaux, P. L. Callet, R. Mantiuk, M. Mrak (Eds.), High Dynamic Range Video: From Acquisition, to Display and Applications, Elsevier, 2016, Ch. 18.

[56] N. Ladas, Y. Chyrsanthou, C. Loscos, Improving tracking accuracy using illumination neutralization and high dynamic range imaging, in: A. Chalmers, P. Campisi, P. Shirley, I. Olaziola (Eds.), High Dynamic Range Video: Concepts, Technologies and Applications, Elsevier, 2016, Ch. 11.

[57] C. Poynton, Digital video and HD: Algorithms and Interfaces, Elsevier, 2012.

[58] A. Rana, G. Valenzise, F. Dufaux, Optimizing tone mapping operators for keypoint detection under illumination changes, in: 2016 IEEE Workshop on Multimedia Signal Processing (MMSP 2016), 2016.

[59] R. Suma, G. Stavropoulou, E. K. Stathopoulou, L. van Gool, A. Georgopoulos, A. Chalmers, Evaluation of the effectiveness of HDR tone-mapping operators for photogrammetric applications, Virtual Archaeology Review 7 (15) (2016) 54–66.

[60] A. Rana, G. Valenzise, F. Dufaux, Evaluation of feature detection in HDR based imaging under changes in illumination conditions, in: Multimedia (ISM), 2015 IEEE International Symposium on, IEEE, 2015, pp. 289–294.

[61] Tesla, A tragic loss (2016).
URL `https://www.tesla.com/blog/tragic-loss`

[62] T. Borer, Personal communication.

[63] C. Moir, A. Chalmers, Factors Influencing theWidespread Uptake of HDR Video, in: A. Chalmers, P. Campisi, P. Shirley, I. Olaziola (Eds.), High Dynamic Range Video: Concepts, Technologies and Applications, Elsevier, 2016, Ch. 12.

[64] Magic Lantern (2016). [link].
URL `https://www.magiclantern.fm/`

[65] Trusted Reviews, Sony Backlight Master Drive TV (2016).
URL `http://www.trustedreviews.com/sony-backlight-master-drive-tv-review`

[66] Cisco, Global mobile data traffic forecast update, 2012-2017 (2013).
URL `http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networkingindex-vni/white_paper_c11-520862.html`

[67] M. Melo, L. Barbosa, M. Bessa, K. Debattista, A. Chalmers, Context-aware HDR video distribution for mobile devices, Multimedia Tools and Applications (2016) 1–19.

[68] S. Jukic, Netflix has quietly rolled out 4K HDR content, starting with Marco Polo Season 1, (4K news (2016).
URL `http://4k.com/news/netflix-has-quietly-rolled-out-4k-hdr-content-starting-with-marco-polo-season-1-13823/`

[69] S. Jukic, A complete list of 600 new 4K UHD titles and 27 new HDR 4K titles being released by Amazon Prime , year = 2016, url = http://4k.com/news/a-complete-list-of-600-titles-of-new-content-and-27-new-hdr-4k-titles-being-released-by-amazon-prime-12685/, note= (4K news.

[70] A. Pennington, 10,000nit display dazzles in the Future Zone (2016).
URL `http://www.tvbeurope.com/10000nit-display-dazzles-in-the-future-zone/`

[71] D. Tofolli, Personal communication.