OPENING OF THE HOLY DOOR BY POPE FRANCIS: FIRST WORLDWIDE LIVE DISTRIBUTION VIA SATELLITE OF 4K UHD PICTURES AND HDR HLG TEST

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ABSTRACT

The ceremony of the Opening of the Holy Door, celebrated by Pope Francis at the Vatican on 8 December 2015, has been the largest event produced exclusively in UltraHD 4k and distributed worldwide live via satellite in UltraHD 4k and HD. This paper describes the challenges faced by CTV (Centro Televisivo Vaticano) and its partners in the implementation of the UltraHD 4k production and distribution of the event to the entire world. Several decisions and choices had to be made in the design of the technical infrastructure, while seeking to maximize the reach of the signal, ensure the most reliable transmission, and bring into play a technology that was not entirely mature at the time of the event.

INTRODUCTION

The Centro Televisivo Vaticano (CTV) is the TV broadcasting centre of the Secretariat of Communication of the Holy See and its main goal is to contribute to spreading the universal message of the Pope through the production, distribution and archiving of TV material covering the activities of the Pope and the Vatican.

As part of its mission, CTV is the exclusive producer of live events and celebrations organised at the Vatican, which are in great demand by TV networks around the world. The CTV offers free access to broadcasters or editors wishing to rebroadcast its productions.

With a view to building future-proof libraries and distributing the best quality material, CTV started equipping its facilities with UltraHD 4k technology in 2015 and has recently announced having selected 4k as its preferred format for future productions.

When planning the production of the ceremony of the Opening of the Holy Door, CTV began contemplating an exclusive 4k production of the event and decided to involve its historical partners SONY, DBW, Globecast and Eutelsat which had already contributed to the production of the canonisation ceremonies of John XXIII and John Paul II in April 2014 and the beatification of Paul VI in October 2014.

The event of April 2014 was transmitted worldwide via satellite in HD and the event of October 2014 was one of the first CTV productions in UltraHD 4k.

To celebrate the Holy Door event and ensure the widest possible coverage of the ceremony, CTV and its partners decided to perform the first worldwide transmission via satellite in UltraHD 4k.

PRODUCTION PLANNING

Producing the ceremony implied live coverage of an approximately 4-hour event starting from the churchyard in front of St. Peter's Basilica in Rome, where the celebration mass was to be held, followed by footage inside the Basilica to cover the opening of the Holy Door and the procession of cardinals.

Camera Layout

The camera layout selected for covering the event is shown in Figure 1.

Nine cameras were placed outside the Basilica to cover the churchyard, the front of the Basilica where the Altar was placed and St. Peter's Square surrounded by the colonnade. The Camera at the centre of the colonnade was installed on a crane to provide panoramic views of the public while a second external camera was installed on top of the *Braccio di Carlomagno*, the straight colonnade at the left of the Basilica entrance to provide a stunning panoramic view of St. Peter's Square and close-ups of Pope Francis at the Altar.

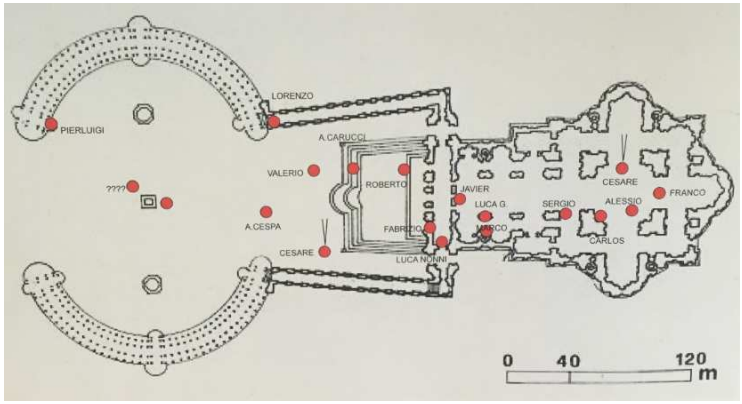

Figure 1 Camera Layout to cover the Ceremony

Eight cameras were installed inside the Basilica, with two of them immediately next to the Holy Door; one camera was mounted on a crane to provide a panoramic view of the exact moment of the opening of the Holy Door.

An additional hand-held camera mounted on a stabilizer was arranged to provide close-ups and follow Pope Francis during the celebration, providing coverage both outside and inside the Basilica.

Figure 2 – The Camera on top the *Braccio di Carlomagno*

On the date of the event, CTV's 4k production resources were centered around OB-8, the external production unit which was upgraded from HD in 2015 and equipped with 8x HDC 4300 4k cameras, a MVS-7000x video switcher and a PWS-4000 video server. To complement the required number of cameras the CTV requested thus the support of DBW Communication which proposed its external production unit OB-3 equipped with a Kahuna 4k video switcher and a PWS-4000 video Server, plus 4x HDC-4300 cameras and 6x PMW-F55 cameras.

The overall production was implemented with a total of 18x native 4k cameras (12x HDC-4300 and 6x PMW-F55), resulting in the largest native 4k production at the date of the event.

A 19th HD Beauty camera was mounted at the foot of the obelisk in the centre of the Colonnade to provide a frontal view of the Basilica. The 1080p@50 output of the camera was up-converted to UHD on the production truck.

Two cameras were equipped with wireless transmitters, the handheld camera following Pope Francis, and the crane camera at the center of the colonnade.

Due to the unavailability of wireless COFDM transmitters capable of transporting 2160@50p signals, CTV had to configure the two wireless cameras in 1080p@50 (the progressive HD format was chosen to keep the best possible quality), transmit their output via COFDM transmitters to the receiving units installed on the ground, and up-convert back to 2160p@50 their signal on the OB-VANs. Both wireless cameras were equipped with the required memory to store the entire footage in 2160p@50, in order to have their footage available in native UltraHD for archiving and off-line editing purposes.

Production and Satellite OB Vehicles

Production and transmission of the entire event was performed by outside broadcast production and satellite transmission vehicles that were parked outside of the *Braccio di Carlomagno* Colonnade.

CTV deployed two production units, OB-8 and OB-16, which were supported by OB-3, the DBW Communication production unit.

To ensure transmission to the satellite, CTV partnered with Globecast Italia which deployed 2 SNG units both equipped with 1.5 m antennas and 400 Watt SSPAs.

Figure 3 – OB Transmission and Production Vehicles at the Vatican

The overall setup of the external production was organised as shown in Figure on the next page. The 8x HDC-4300 cameras were cabled in fiber to CTV's UltraHD 4k OB-8. The remaining cameras, including radio cameras, were cabled in fiber to DBW Communications' OB-3.

BPUs and CCUs of the cameras were mounted on respective terminating OB vehicles; the output of cameras landing on the DBW OB-VAN was cabled to CTV'S OB-8 to feed the 4k MVS-7000x video mixer.

For practical reasons, the MCR and artistic management of the event were carried out from CTV's OB-16, CTV's largest unit equipped with the control panel of the video mixer and the multi-viewer.

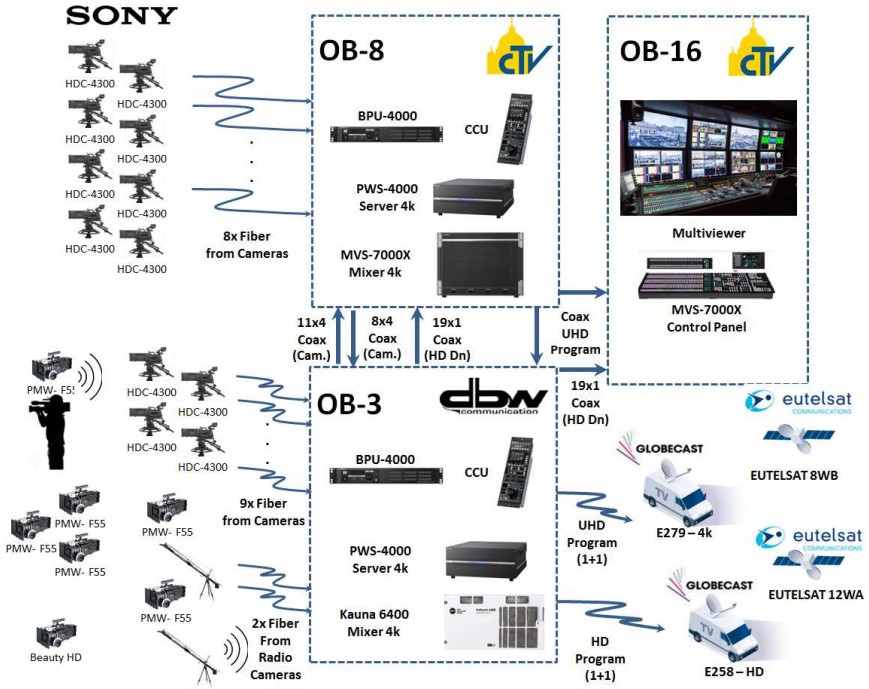

Figure 4 – Overall Layout of OB Production and Transmission

The Kahuna video mixer installed on board DBW Communication's OB-VAN, was used to perform up/down conversion of the different feeds.

As the multi-viewer installed on OB-16 could only accept 1080i@50 signals all 4k Camera preview feeds had to be down-converted to HD 1080i@50 and cabled back to OB-16 to feed the multi-viewer.

It was also discovered that one of the HEVC encoders used to compress the UltraHD 4k Program was not able to accept level-B signals, which was the only format available at the output of the MVS-7000x video mixer. It was therefore necessary to drive the Program output of the video mixer to the Kahuna to perform Level-B to Level-A conversion of the UltraHD 4k Program.

All of the camera feeds and the Program in HD and UltraHD were also recorded on two PWS-4000 servers, one installed on CTV and the second on the DBW OB-VAN.

Cabling to uplink vehicles was fully redundant as the Program feeds in UltraHD and HD were sent to encoders in 1+1 configuration.

The entire cabling between OB vehicles was implemented using coaxial 4x 3G-SDI cabling. Nearly 3 km of coaxial cable were required to ensure the signal exchanges among the vehicles in spite of a few meters distance between them.

The Holy Door Ceremony was produced by CTV in collaboration with Radio Vaticana, the multilingual radio station of the Holy See: Speakers of Radio Vaticana commented the ceremony in four different languages: Italian, Spanish, English and French.

The four audio commentaries were delivered as mono embedded audio on the HD 1080i@50 feed, while on the 2160p@50 UltraHD feed it was decided to provide a single stereo audio channel carrying the ambient sound.

The audio channels on the UltraHD Program were planned to be embedded on the first quadrant only. It was then noticed that applying audio embedding of a single quadrant of the UltraHD feed caused a limited but noticeable time delay of few frames with respect to the remaining quadrants. It was therefore necessary to apply audio embedding to all the four quadrants to maintain the time alignment of the different quadrants composing the UltraHD 4k frame.

Camera Lenses

All lenses mounted on the cameras during production were Servo Zoom lenses with various focal lengths and the possibility to be remotely controlled.

The HDC-4300 cameras with triple 2/3" sensors were equipped either with Fujinon UA80x9 BE 4k 2/3" zoom lenses - capable of a stunning 80x zoom ratio - or with Fujinon UA22x8 4k 2/3" zoom lenses. It was the first time that Fujinon delivered the new 4k lenses.

The 80x lenses were mounted on cameras designed to shoot details of the ceremony and perform close-ups of the Pope from a distance. In contrast, the cameras at the very end of the Colonnade were mainly used with short focal length to provide an overall grand angular view of the Basilica and the crowd of cardinals.

The cameras on the crane were equipped with super grand angular lenses to provide a thorough view of the crowd and the Holy Door itself. Due to the unavailability of super grand angular 4k lenses at the time of the event, CTV had to use HD lenses on such cameras.

PMW-F55 cameras (single super 35mm sensor) were equipped with different types of lenses according to their function. Lenses used were Fujinon ZK4.7x19 19-90mm T2.9 PL mount, Canon CN-E 30-300mm T2.95-3.7 L SP 4k Cinema and Canon 17-120mm T2.95-3.9 PL mount 4k Cinema.

ARTISTIC PRODUCTION AND DIRECTION OF THE EVENT

The artistic direction of the event was ensured by Stefano D'Agostini, CEO and CTO of CTV; enjoying long-lasting cooperation and sincere friendship with CTV management, filmmaker Wim Wenders was invited to attend the production and provide artistic support during the live.

Figure 5 shows Mons. Dario Edoardo Vigano', Prefect of the Holy See's Secretariat of Communications discussing with Eng. Stefano D'Agostini while visiting the MCR on OB-16 a few minutes before the ceremony; filmmaker Wim Wenders is sitting just behind them.

Figure 5 – The MCR on OB-16 few minutes before the Ceremony

FORMAT OF INTERNATIONAL FEEDS

Despite the commitment on quality and the decision to produce exclusively in UltraHD @ 2160p, it was obvious from the beginning that it would have been necessary to distribute worldwide an HD feed at 1080i as well due to the still limited capabilities of receiving and managing UltraHD 2160p feed signals from takers worldwide.

It was then decided to distribute worldwide two international feeds, the UltraHD @ 2160 and the HD @ 1080i and to get the 1080i feed from Down-conversion of the exclusive UltraHD 4k production.

Choice of International UltraHD Feed Production Format

When planning the Production it was considered whether to produce the event at 60 fps in consideration of the fact that the highest number of takers of the UltraHD feed had to be expected to be in 60 Hz regions like USA and Far East.

After careful evaluation this option was discarded as producing the event in UltraHD @ 60p would have presented a number of potential risks which suggested maintaining the production at 50p.

The first potential risk was represented by the flickering effect which may affect sequences produced at 60 Hz under source lights working at 50 Hz. Producing at 60p would have also required a frame-rate conversion to obtain the HD feed @50i for distribution to Europe implying a potential loss of quality, and would have required the firmware update of all the cameras and equipment to be used for the production.

UltraHD 4k 2160p@50 was then the signal format retained.

Choice of International UltraHD Feed Distribution Format

When choosing the UltraHD distribution feed format, it was considered whether to use a **Contribution 4:2:2** or a **Distribution 4:2:0** Format.

Despite the first UltraHD HEVC 4:2:2 contribution encoder - the NTT HHC11000 - had just been released, contribution in HEVC 4:2:2 was excluded due to the very limited availability of HEVC 4:2:2 UltraHD Contribution Decoders on the market at the time of the event.

Contribution in MPEG-4 AVC 4:2:2 “QuadHD” was also excluded as it would have required significant transmission rates - in the range of 80/90 Mbits - on top of requiring costly reception equipment (4x MPEG-4 AVC 4:2:2 HD decoders) at the receiving sites, presenting potential problems of synchronisation of the quadrants and requiring each Taker to re-encode the UltraHD feed in a distribution HEVC format to be able to exploit it.

The final decision for the UltraHD feed transmitted from the Holy See was therefore to compress the 2160p50 signal in HEVC 4:2:0 Main 10 Profile, Level 5.1. A compression bitrate of 27 Mbit was chosen as the best compromise between occupied bandwidth and visual quality: a rate small enough to allow remuxing on DTH platforms preserving the encoding quality at the source, and big enough to allow a sufficient visual quality in the event that a frame conversion and/or re-compression of the feed were required by the taker.

The international ambiance audio channel was compressed as a stereo couple in MPEG1 Layer 2 at a rate of 256 Kbps.

Choice of International HD Feed Format

The HD Program feed was obtained as a down-conversion of the UltraHD feed. The 1080i format was chosen instead of 1080p as it was decided to also provide small potential takers (equipped with less performant hardware) with the opportunity to receive and operate the signal.

A similar consideration suggested compressing the signal using 4:2:0 Chroma sampling instead of 4:2:2; the compression rate chosen was 15 Mbps CBR using MPEG-4 AVC high profile level 4.1. This would have enabled the signal transmitted from the Vatican to be received by a conventional HD set top box or integrated TV set, or be inserted as such in a Mux for distribution to final users without necessarily having to undergo decoding/re-encoding.

The 50i frame rate was chosen and to make signal reception simpler it was decided to convert the signal to 60i before transmission on satellite footprints targeting 60 Hz countries.

HEVC UltraHD and MPEG-4 HD Compression

HEVC compression of the UltraHD feed was performed on board of Globecast satellite trucks.

At the time of the event HEVC UltraHD 4k compression encoders were just being released and neither Eutelsat nor Globecast were equipped with HEVC hardware. The partners invited thus a series of manufacturers to supply their products.

NTT Electronics delivered a sample of their HCC11000 4K 50/60p H.265/HEVC encoder supporting 4:2:2 chroma sampling. The NTT encoder was used as the main encoding unit; although capable of working in 4:2:2, it was configured to work in 4:2:0 as explained above.

Thomson Video Networks provided a sample of their ViBE 4k Ultra HD encoder which was used as a main backup unit.

Ericsson (Envivio) provided a sample of their AVP-4000 encoder, which was kept as a further backup.

All encoders were configured with identical parameters (same PIDs and PSI/SI tables) to offer seamless operation in case of switching of transmission to backup units.

HD compression was performed via Ericsson AVP-2000 MPEG-4 AVC in 1+1 configuration. The four HD audio Commentaries were compressed as four audio couples in Mpeg 1 layer II at 256 Kbps per audio channel.

Figure 6 – UltraHD Monitoring on SNG

HEVC encoders were installed temporarily on the SNG truck, while it was necessary to buy an UltraHD consumer TV set that was installed on the UltraHD truck for having a

visual monitoring the UltraHD feed via reception of *Eutelsat 4K1* Channel from EUTELSAT HOTBIRD 13E.

WORLDWIDE DISTRIBUTION VIA SATELLITE

The first hop from the SNGs parked at the Vatican used satellites with European footprints.

Although the RF dimensioning of the satellite truck deployed by Globecast might have allowed operating two separate carriers for the HD and UltraHD feeds on a single antenna, it was decided to use two separate trucks respectively for the UltraHD and the HD feeds pointing to two different satellites at different orbital positions to guarantee maximum possible redundancy of the feeds.

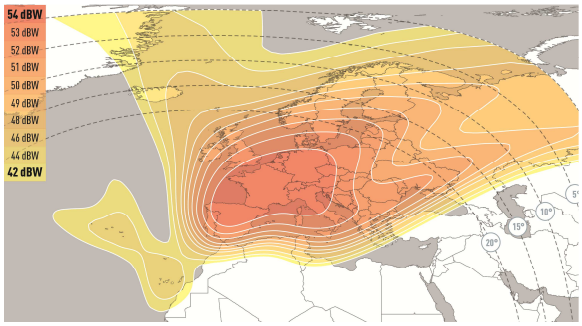

Figure 7 – E8WB Footprint

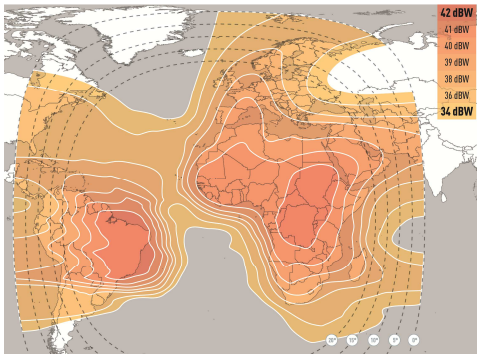

Figure 8 – E8WB C-Band

EUTELSAT 8WB was chosen to carry the UltraHD feed, while EUTELSAT12WA was used to uplink the HD feed.

To ensure the worldwide reach of UltraHD and HD feeds, Eutelsat deployed its fleet of satellites on three major neighbourhoods: EUTELSAT 8WB C-Band to cover Europe, Africa, Middle East and South America, EUTELSAT 113/117 WA C-Band to serve North and South Americas and EUTELSAT 172A C-Band to cover Asia and Oceania.

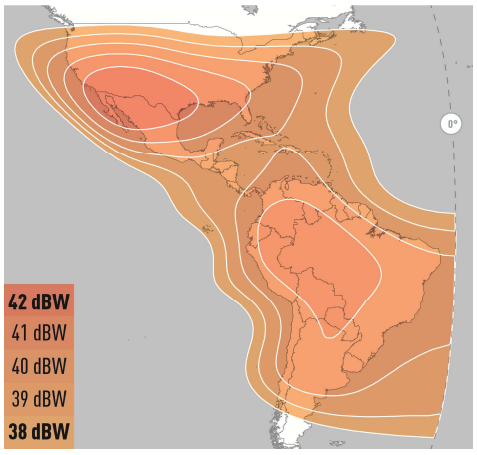

Figure 9 – E113/117 WA C-Band

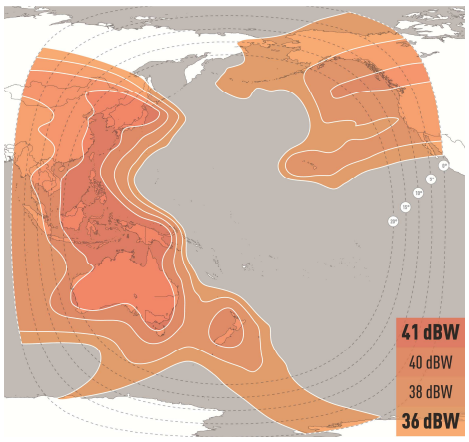

Figure 10 – E172A C-Band

Distribution of the UltraHD Feed on Eutelsat UltraHD DTH Platforms

On top of C-Band coverages, the UltraHD feed was also transmitted in DTH via Ku-band on EUTELSAT HOTBIRD 13E on the *Eutelsat 4K1* channel and on the *Fransat UltraHD* Channel on the French free-to-view platform Fransat via EUTELSAT 5WA at 5° West.

The HD feed was also included on EUTELSAT 70B at 70° East on a DTH platform operated by Eutelsat covering Far East Asia.

Teleports Operating the Turnarounds

A network of teleports was used to operate the turn-around of the signal to the different footprints under the coordination of Eutelsat staff from the Vatican.

The **Eutelsat Rambouillet Teleport** located near Paris, France, operated the turnaround to EUTELSAT 8WB C-Band and to EUTELSAT 70B Ku-band by receiving the UltraHD and HD contribution feeds respectively from EUTELSAT 8WB and EUTELSAT 12WA.

The Eutelsat Rambouillet Teleport also operated the U/L on the UltraHD DTH Platforms.

The **OVERON Teleport in Miami** operated the turnaround to Americas on EUTELSAT 113WA and EUTELSAT 117WA. Miami Teleport was fed via fiber by the OVERON Teleport in Madrid which received the UltraHD and HD feeds from the contribution satellites EUTELSAT 8WB and EUTELSAT 12WA. The HD feed was demodulated and frame converted to 1080i@60 to comply with American and Asian standards before transmission via fiber to Miami.

Figure 11 – The UltraHD Feed @ OVERON Miami MCR

The **Brewster US Teleport** close to Seattle operated the uplink of the UltraHD and HD feeds to EUTELSAT 172A C-Band by simple turnaround of the two feeds received from EUTELSAT 113/117 A.

FINAL TEST OF HDR HYBRID LOG GAMMA TRANSMISSION

The scenario for this experience reflected the desire of Pope Francis who invited the audiovisual content providers to focus the use of technology in order to enable effective communication with a worldwide audience. A key objective was to provide a more realistic visual experience to enable the audience to feel the emotion of being at the event.

The production team, recognizing the availability of a large scale 4K UHD infrastructure, also took the opportunity to carry out a 4K HDR trial during the event.

The trial consisted of three main components:

1. Shooting and Recording;
2. Signal encoding and satellite broadcasting;
3. Viewing of the images using consumer 4K TV screens.

Shooting and Recording of HDR HLG Pictures

The configuration of each camera chain was as follows:

- HDC-4300, Camera head with three 2/3-inch C-MOS sensors with a native resolution of 4096 x 2160, with a maximum frame rate of 120p in 4K.
- BPU-4000, Baseband Processor Unit, connected to the camera via a fibre transmission cable and able to provide 4K SDR, 4K HDR and HD SDR outputs, simultaneously.
- HDC-2500, Camera Control Unit, and RCP-1500, Remote Control Panel.
- BVM-X300, 30-inch Grade 1 Professional OLED Monitor, with native 4K resolution up to 4096 x 2160, and with HDR capability (HLG and ST 2084).
- PWS-4400, 4K Server with multiple I/O. Capable of recording in a variety of data rates using XAVC encoding system.

At the end of the main production, the team decided to maintain the operational infrastructure in order to implement the HDR tests with the aim of evaluating the impact of HDR on the production process, transmission and viewing. Hybrid Log Gamma (HLG) was selected to investigate its suitability for both the HDR production and a simultaneous SDR output.

For the HDR test (see Figure 12) two camera chains were set to output 3840 x 2160 resolution images at 50p with 4:2:2 10 bit sampling. Each Baseband Processor Unit was installed with pre-production firmware to provide a Hybrid Log Gamma output to facilitate the test.

Technical monitoring of the BPU output (4 x HD-SDI) was performed with a professional OLED monitor which had both HLG and ST 2084 capability.

The images were recorded on the server in 3840 x 2160, 50p, 4:2:2 using XAVC I-Frame encoding.

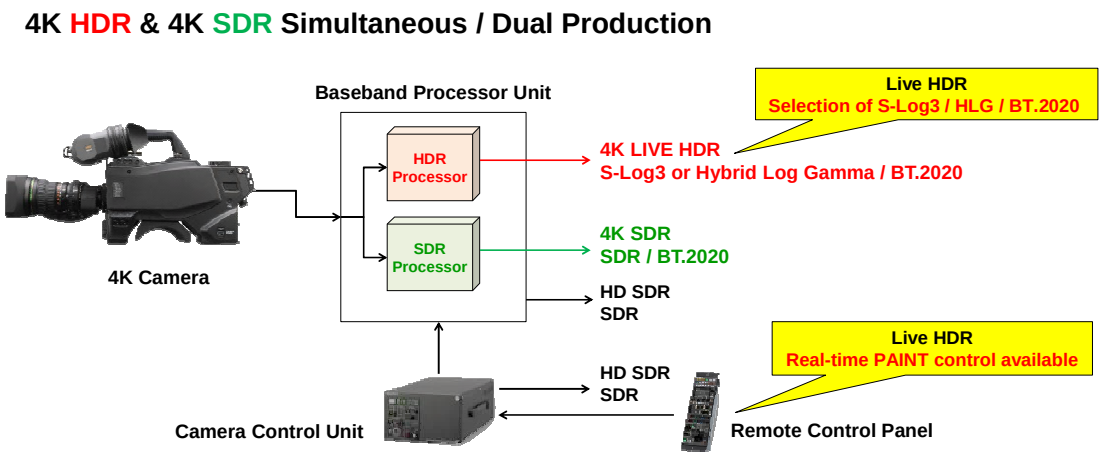

Figure 12 – Ultra HD camera chain with individual processing for HDR and SDR

A sequence of indoor and outdoor scenes was captured to test the performance of the production chain in a range of environments including sunlight and indoor lighting as shown in Figure 13.

Figure 13 – Indoor pictures acquired (HDR HLG BT.2020 on left and SDR BT.709 on right)

The production team concluded that the creation of the HDR content did not require additional equipment resource to that used for the 4K SDR production. The challenge in this initial test was in establishing a workflow to support both the creation of the HDR and SDR outputs.

Signal encoding and satellite broadcasting

The Test for HDT HLG Transmission via Satellite made use of the same infrastructure deployed for the live broadcasting of the Ceremony. While distribution of the HD feed was stopped just after the ceremony, distribution of the UltraHD pictures mapped in HLG kept running feeding the footprints and the network of partner teleports mentioned above, resulting in the first worldwide live distribution of UltraHD live pictures in HDR HLG according to the partners.

The UltraHD HDR HLG pictures produced as above were encoded in HEVC 4:2:0 Main 10 Profile, Level 5.1 via the encoders used during the Ceremony and keeping a compression bitrate of 27 Mbit. HEVC Supplemental Enhancement Information (SEI) Messages were not configured as the transmission did not require the use of any metadata.

HEVC Main10 Profile Level 5.1 using 4:2:0 colour space is recognised by the industry as the most efficient HEVC encoding Profile for the delivery of HDR/WCG pictures.

Viewing of the images using consumer 4K TV screens

An objective of the test was to compare the picture quality of the received HDR signal on both a 4K Ultra HD SDR and a 4K Ultra HD HDR 65-inch consumer TV screen. A viewing area was set up inside the Paul VI's hall to compare the images (see Figure 14 and 15).

Figure 14 – Viewing Room for comparison of images displayed in SDR and HDR

Both TVs received the DVB-S2 input via the Eutelsat Hotbird 13 satellite. The screens displayed the images via the 4K1

service from Eutelsat.

The set-up of the TV sets for this specific trial was the following:

- TV 1 - updated with non-commercially available firmware for HDR/HLG
- TV 2 - SDR, BT.709

The audience was given the opportunity for direct comparison of the two screens.

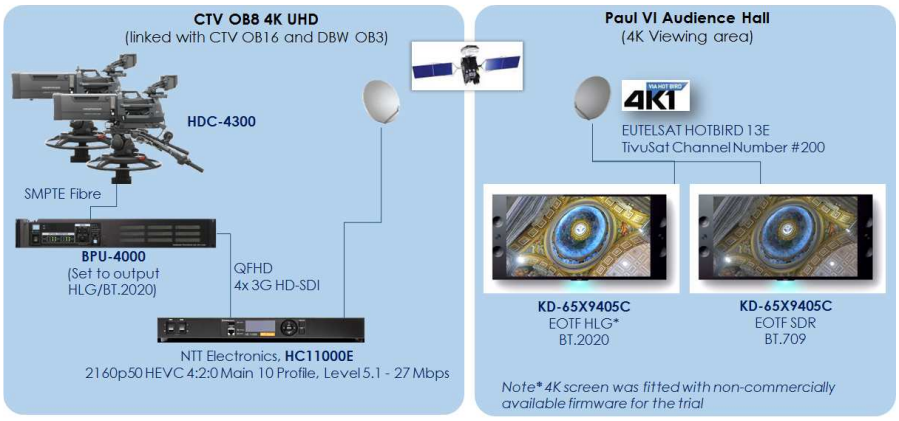

Figure 15 – HDR Production and delivery chain

Comments from the audience highlighted that the HDR display provided an impressive, closer-to-reality experience. At the same time, the SDR display produced high quality pictures without noticeable artefacts, comparable to a good quality SDR originated programme.

General outcome of the HDR HLG Test

The trial proved that the use of HDR with HLG offers a good degree of compatibility when the images are displayed on legacy SDR displays, closely matching those of SDR originated content. Additional trials in 2016 are planned to investigate HDR production workflows and distribution in more detail.

CONCLUSIONS

CTV and its partners implemented the largest UltraHD 4k live production of the Holy Door Ceremony and the first worldwide distribution of UltraHD 4k via satellite pictures.

Many different challenges had to be faced when designing the production and distribution of the UltraHD feed, mainly due to the not yet mature state of technology and shortage of HEVC compression equipment.

ACKNOWLEDGEMENTS

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