

JPEG Pleno: a standard framework for representing and signalling plenoptic modalities

Peter Schelkens^{a,b}, Zahir Y. Alpaslan^c, Touradj Ebrahimi^d, Kwan-Jung Oh^e, Fernando M. B. Pereira^f, Antonio M. G. Pinheiro^g, Ioan Tabus^h, and Zhibo Chenⁱ

^aVrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium

^bimec, Kapeldreef 75, B-3001 Leuven, Belgium

^cOstendo Technologies, 6185 Paseo del Norte, Suite 200, Carlsbad, CA, USA

^dMultimedia Signal Processing Group (EPFL), Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland

^eElectronics and Telecommunications Research Institute (ETRI), 218 Gajeong-ro, Yuseong-gu, Daejeon, 34129, Korea

^fInstituto Superior Técnico, Universidade de Lisboa - Instituto de Telecomunicações, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

^gInstituto de Telecomunicações and Universidade da Beira Interior, Av. Marques Avila e Bolama, 6200-001, Covilhã, Portugal

^hTampere University of Technology, Korkeakoulunkatu 1, Tampere, Finland

ⁱUniversity of Science and Technology China, No.443, Huangshan Road, Hefei, Anhui province, China

ABSTRACT

In recent years, we have observed the advent of plenoptic modalities such as light fields, point clouds and holography in many devices and applications. Besides plenty of technical challenges brought by these new modalities, a particular challenge is arising at the horizon, namely providing interoperability between these devices and applications, and – in addition – at a cross-modality level. Based on these observations the JPEG committee (ISO/IEC JTC1/SC29/WG1 and ITU-T SG16) has initiated a new standardization initiative – JPEG Pleno – that is intended to define an efficient framework addressing the above interoperability issues. In this paper, an overview is provided about its current status and future plans.

Keywords: JPEG, JPEG Pleno, Light Field, Point Cloud, Holography, standards, coding, visual quality assessment

1. INTRODUCTION

Enabling interoperability in image processing ecosystems has always been the core focus of the JPEG committee.¹ JPEG is a joint working group of the International Standardization Organization (ISO), the International Electrotechnical Commission (IEC) and the International Telecommunication Union (ITU). More specifically, the JPEG committee is Working Group 1 (WG1), Coding of Still Pictures, of JTC 1s subcommittee 29 (SC29), Coding of Audio, Picture, Multimedia and Hypermedia Information. The word Joint in JPEG does not refer to the joint efforts of ISO and IEC, but to the fact that most of the JPEG activities are the result of an additional collaboration with the Study Group 16 of the International Telecommunication Union (ITU).

The JPEG committee (ISO/IEC JTC1/SC29/WG1) has been responsible for the specification of many standards as illustrated in Figure 1. Its most successful image coding standard is the JPEG-1 standard (ITU-T

Further author information: (Send correspondence to Peter Schelkens)

E-mail: peter.schelkens@vub.be

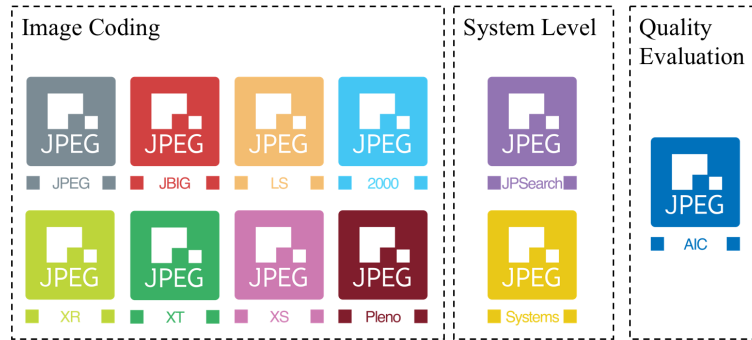


Figure 1. The JPEG committee specified standards over the last 25 years.

T.81|ISO/IEC 10918-1) defined in 1992 and it is still the most popular and impact-full image coding standard. JPEG 2000 (ITU-T T.800|ISO/IEC 15444-1 — 2000) – its successor – has been used in digital cinema, broadcasting, medical and other professional markets. Other image coding standards, include JBIG-1 (ITU-T T.82|ISO/IEC 11544 — 1993), enabling progressive bi-level image compression, JBIG-2 (ITU-T T.88|ISO/IEC 14492 — 2000), supporting lossy/lossless coding of bi-level images, JPEG LS (ITU-T T.87|ISO/IEC 14495-1 — 1998), focused on lossless and near-lossless compression of continuous-tone still images, JPEG XR (ISO/IEC 29199-2 — 2012), targeting better compression than JPEG-1 with limited complexity overhead, and JPEG XT (ISO/IEC 18477-1 — 2015), a backward compatible standard with JPEG supporting the compression of high-dynamic range images. Recently, the committee also released JPEG XS (ISO/IEC CD 21122-1 — 2018), a standard devised for low-latency lightweight image coding. It has also launched the standardization process for JPEG XL, targeting a high-end, next-generation image coding system with excellent rate-distortion performance along with features desirable for web distribution and efficient compression of high-quality images in a large spectrum of applications.

Besides image compression specifications, JPEG has also published system level standards. JPSearch (ISO/IEC 24800-x — 2011-...) is a multi-component standard supporting image search applications. JPEG Systems (ISO/IEC 19566-x — 2016-...) provides system level support for JPEG standards. An example is the JPEG 360 extension that is currently being standardized to support omnidirectional imagery. Finally, AIC (ISO/IEC 29170-x — 2015-...) provides guidelines for evaluation methodologies for image codecs. Further work on finalization or extension of many of the above standards still continue.

In recent years, the advent of plenoptic modalities was observed in many devices and applications. Besides the many technical challenges brought by these new modalities, another challenge is rising at the horizon, i.e. providing interoperability support, and in addition, at a cross-modality level as well. Based on these observations, the JPEG committee has initiated a new standardization initiative – JPEG Pleno – that is intended to provide a multi-modal framework, addressing the above interoperability issues and incorporating coding tools for light field, point cloud and holographic data.

2. JPEG PLENO FRAMEWORK

In 2015, the JPEG committee initiated the JPEG Pleno standard framework² that will facilitate capture, representation and exchange of light field, point cloud and holographic imaging.³ In its philosophy, these imaging modalities are understood to be alternative light representations all inspired by the plenoptic function, regardless of which modality was used to capture or to create whole or parts of the entire content. This mindset recognizes that conversions of - or between - different modalities are possible and often useful. The standard aims at:

- defining tools for improved compression while providing advanced functionalities at system level and;
- supporting data and metadata manipulation, editing, scalability, random access and interaction, protection of privacy and ownership rights as well as other security mechanisms.

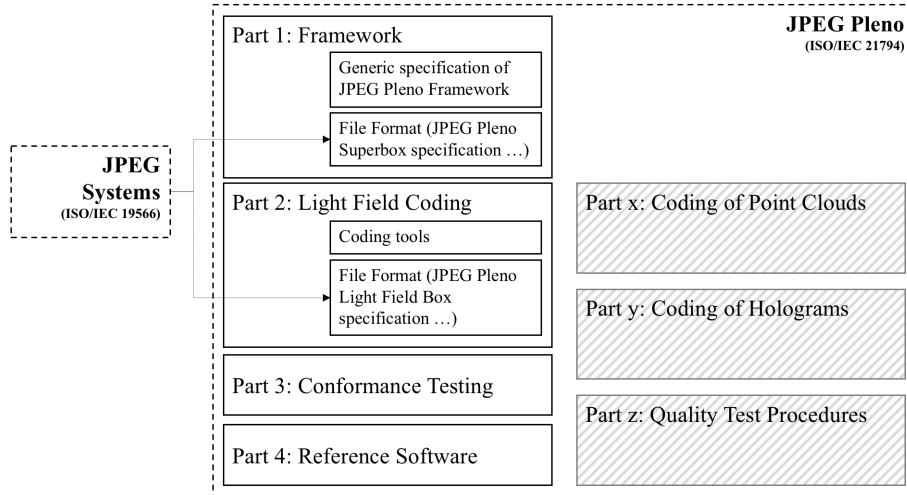


Figure 2. The JPEG Pleno framework

The JPEG Pleno standard is organized in different parts. Currently, four parts have been initiated as illustrated in Figure 2. Part 1 covers the overarching architectural specification and details the main principles of the file format. JPEG Pleno adheres to a box file format, for which the main principles are specified in JPEG Systems (ISO/IEC 19566).⁴ In this part, also the JPEG Pleno Superbox is defined that contains light field, point cloud and/or holographic content in addition to potentially complementary metadata.

Part 2 is focused on coding of light field data. Currently this standardization process has resulted in the specification of a core architecture. Also a Verification Model Software is available. Further details about the technology behind are provided in Section 4. Moreover, this part details the JPEG Pleno Light Field Box format, a box that needs to be signalled inside a JPEG Pleno Super Box. Besides configuration parameters of the light field and the encoded light field information (including depth information), this box can also contain additional calibration metadata.

Every coding standard also provides means to evaluate the conformance of third-party implementations – read independent implementations – with the standard specification. This is covered by Parts 3 and 4 of the JPEG Pleno standard framework, namely 'Conformance Testing' and 'Reference Software'. The latter is intended as an illustrative functional implementation of the standard, not maximally optimized though for computational performance. It also serves as reference for the conformance testing.

Additional parts of the standard are currently in an exploratory phase. These parts will provide support for point cloud (see Section 5) and holographic modalities (see Section 6).

In the context of the standardization process, JPEG has also published a public JPEG Pleno database² with plenoptic test data to support its efforts. This database, which is continuously updated, targets to be sufficiently heterogeneous in terms of types of plenoptic content and covering different application domains. In addition, the committee investigates the usefulness of standardizing quality evaluation procedures for plenoptic content.

3. REQUIREMENTS

Following the framework definition presented above, JPEG embarked on an effort to identify the use cases related to the three main JPEG Pleno modalities, notably light fields, point clouds and holography. These use cases are presented in the JPEG Pleno Use Cases and Requirements document⁵ organized by the imaging modality and include: i) for light fields, photography, video production, industrial and biomedical imaging, and visualization; ii) for point clouds, virtual and augmented reality, motion capture, geographical information systems, cultural heritage and large scale 3D maps; and finally, iii) for holography, (tomographic) microscopy, metrology of small objects, and macroscale holography, notably entertainment and medical.

Based on the use cases, requirements have been extracted, organized as general requirements and specific modality requirements.⁶ Regarding the general requirements, there are, naturally, the classical requirements directly associated to coding such as compression efficiency, functionality tuning, random access, scalability, editing and manipulation, low complexity, error resilience, and support for parallel and distributed processing. Moreover, there are also general requirements at the framework and system level such as on the representation model, JPEG backward and forward compatibility, JPEG Systems compatibility, privacy and security, and metadata. The JPEG Pleno Use Cases and Requirements document⁶ includes additional, specific requirements for the three main modalities, derived from the specific use cases.

Already in January 2017, JPEG launched a Call for Proposals on Light Field Coding⁵ based on the JPEG Pleno general requirements and the specific light field requirements.⁶ In July 2018, JPEG issued a JPEG Pleno Point Cloud - Use Cases and Requirements document,⁷ specifically targeting point cloud use cases and requirements, updating and refining the initially defined point cloud use cases and requirements.⁶ This document is expected to become the seed for a future Call for Proposals on Point Cloud Coding.

4. LIGHT FIELDS

4.1 Use cases

As light field imaging records images from multiple viewing angles, it enables additional functionalities in comparison to classical imaging for various use cases, such as photography, video production, industrial imaging and visualization. With one shot, a lenslet-based light field camera or a light field camera array can capture 3D information related to the scene. This brings exciting experiences to the photographer, such as acquisition angle selection or post-capture refocus. Since light field devices are able to capture a variety of viewpoints, this technology enables new visual effects in video production like virtual camera movement, relighting, depth of field adjustment and post-capture refocus. These can be used to create special effects, for instance, changing illumination of the scene, replacement of background by a virtual backdrop without need for a green screen, or correcting more effectively deficiencies during capture.

Metrology based on light field imaging may be useful for numerous industrial applications. With richer texture and depth information of the scene, a better analysis, decision and control performance can be achieved. Light field imaging benefits substantially computer vision tasks such as mapping, modeling, segmentation, localization, depth measurement, tracking, classification, object recognition and biometrics related tasks like face and palm print recognition. Therefore, light field imaging may also help robots to better understand the world. It also supports other industrial applications like non-destructive testing, 3D fluid analysis, and 3D plant and animal analysis.

For virtual and augmented reality consumers and markets, light field technology is an appealing candidate for 3D visualization. It can be integrated in different types of display, including mobile, desktop, television and head mounted devices. Moreover, it holds the promise to resolve the vergence-accommodation conflict where traditional stereo displays suffer from; on the condition though that one can achieve displays with a high spatial and angular resolution, typically requiring very small pixel pitches.⁸

As mentioned in Section 3, JPEG Pleno identified the requirements based on the above use cases.⁵ Besides the generic JPEG Pleno requirements mentioned in this section, light field-specific coding requirements have been identified for data representation and processing, including support for different types of light field representations, calibration model signalling, multi-sensor synchronization, various capturing configurations and the carriage of supplementary depth maps.

4.2 Coding architecture

The JPEG Pleno Light Field coding technology is designed to be applied to an array of angular views, or subaperture images, obtained by processing images acquired with a plenoptic camera or directly acquired by a high density array of cameras. The array of angular views is forming a set of 4D data, possessing a high redundancy, and the goal of the coding tools is to utilize this redundancy for efficient encoding of the data, subject to the requirements set up for the JPEG Pleno Light Field applications.

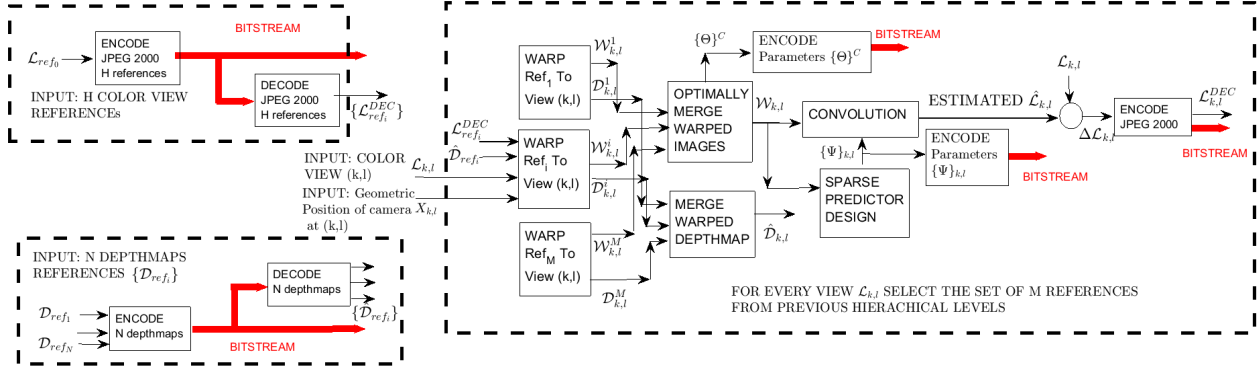


Figure 3. Illustration of JPEG Pleno Light Field encoder: Verification Model 1.0 hierarchically structures the reference views and intermediate views.^{9,10}

Since each angular view is a classical 2D image, one can utilize standard 2D image compression technology for encoding some primary set of *reference* angular views. Then, the reference views can be used to synthesize by warping and prediction all the remaining angular views, called *intermediate* views. The process of warping one angular view such that another view is partially and approximately reconstructed needs to utilize the depth map of the scene, which describes its 3D geometry. A better reconstruction of one angular view is obtained by merging the warped reconstructions of that view obtained from several neighboring angular views. By judiciously choosing the reference angular views for reconstructing a certain angular view and the 4D structure of the neighborhood in the linear predictors used for merging the warped view, one designs in practice very efficient predictors in the 4D space, so that the redundancy of the light field data is efficiently accounted for in the process of synthesizing or predicting the data. The residual data, which is the difference between the true data and the synthesized data, can be further encoded in a lossy or lossless way for improving the quality of the finally reconstructed light field data at the decoder.

The most efficient implementation of the above principles is now under investigation in the standardization process for light field images. The current version of the Verification Model, which was approved at the 80th JPEG convention in Berlin, is illustrated in Figure 3.^{9,10} The main modules are encoding (1) the reference angular views $\{\mathcal{L}_{ref_i}\}$, (2) the reference depth maps $\{\mathcal{D}_{ref_i}\}$ and (3) the prediction errors for the intermediate views $\{\Delta\mathcal{L}_{k,l}\}$, which are predicted based on the reference angular views. Besides that also the merging parameters $\{\Theta\}^C$ and the sparse predictor parameters $\{\Psi\}_{k,l}$ are signalled in the bitstream. One important feature is the hierarchical encoding of the reference views, which are grouped according to configurable layers, where a reference view from one layer can be predicted, through warping and merging, from the reference views of the preceding layers.

The scheme provides efficient coding for the test materials used in the core experiments during standardization, while in addition it also offers a number of features like forward and backward compatibility with JPEG 2000, random access to the angular views, and good parallelization properties. Through the intensive use of JPEG 2000 coding tools for reference angular views, the reference depth maps and the residual views, the scheme also inherits all attractive properties of the JPEG 2000 standard. The verification model could still undergo a few changes as a results of other core experiments with as main goal to optimize the performance of the embedded coding tools.

4.3 Quality assessment

One of the main challenges encountered during the standardization of plenoptic coding tools was in the design of objective and subjective quality assessment experiments that both in rate-distortion sense as in a functionality sense stress-test the technologies under investigation for inclusion in the standard. Hence for all JPEG Pleno related activities, significant attention has been devoted to this challenge in order to design conclusive experiments that in addition account for the always 'constrained' testing capabilities. Two particular bottlenecks for the latter are in the access to sufficient test subjects, but especially also in the large size of the test material that result

in requirements for memory-rich computational needs. The JPEG Pleno quality testing methods for light field coding are documented in detail in JPEG Pleno Light Field Common Test Conditions document .¹¹

All coding experiments utilize predetermined bitrates suitable for the light field data sets in the JPEG Pleno Database .¹² After encoding and decoding of each light field dataset, image quality is evaluated by comparing the original light field sub-aperture images to the decoded light field sub-aperture images. The main metrics for quality evaluation are $PSNR_{YCbCr}$ and $SSIM_Y$. Light field sub-aperture images are converted from RGB to YCbCr 444 in their respective bit-depth using the ITU-R BT.709-6 recommendation,¹³ before the metrics are calculated. For calculation of the $PSNR_{YCbCr}$, the $PSNR_{Cb}$ and $PSNR_{Cr}$ components are weighted 12.5% respectively while the $PSNR_Y$ component is weighted 75%. $SSIM$ is defined and calculated according to Zhou *et al.*¹⁴ Similar to PSNR, $SSIM$ calculation is also performed on light field sub-aperture images after an RGB to YCbCr 444 conversion. The PSNR and $SSIM$ results for all light field sub-aperture images are usually plotted in a 2D array to identify the spatio-angular quality issues in the light field, or presented with the Bjøntegaard metric for overall quality evaluation.

5. POINT CLOUDS

Point clouds are receiving a strong interest from the consumer market and developers. Currently there are several solutions from acquisition to display. The 'JPEG Pleno Point Cloud - Use Cases and Requirements'⁷ document, defines a set of major potential applications: 1) Rendering of content for virtual, augmented and mixed reality technologies; 2) 3D content creation; 3) Medical applications; 4) Construction and manufacturing; 5) Consumer and retail; 6) Cultural heritage; 7) Remote Sensing, GIS; 8) Autonomous vehicles, drones; and 9) Surveillance. Considering the full list of identified use cases with all specific particularities, a set of requirements was identified. In particular, the coding requirements establish a set of attributes and functionalities, like the types of data, the need for both lossless and lossy compression, and also low complexity, several types of scalability and random access.



Figure 4. Examples of University of São Paulo Point Cloud Database, which is included in the JPEG Pleno Database (JPEG PlenoDB).¹²

Despite the success of point clouds, compression technologies for such type of data are still immature. Moreover, quality evaluation methodologies are still facing reliability problems, which is a major drawback for evaluation of any compression technology. Subjective evaluation faces problems related to the point cloud representation. In a recent paper, Alexious *et al.*¹⁵ reported that subjective evaluation results are not correlated when point clouds are presented to subjects with or without surface reconstruction. However, subjective tests reveal to be very stable for surface reconstructed point clouds with the screened Poisson method,¹⁶ even when the display equipment is different. Moreover, the use of 3D display devices does not seem to change the subjective results.¹⁷ Nevertheless, Poisson reconstruction is very difficult to use with more complicated geometries, and a stable reconstruction mechanism appears difficult to reach for codec evaluation with heterogeneous content. Hence, point cloud quality evaluation is limited to the points representation with all drawbacks that might arise, which include mainly the difficult visualization when the points density is sparse. Furthermore, the most well

known metrics developed for point cloud quality evaluation tend to fail in correlating with subjective quality scores.

The JPEG committee has been developing and testing quality assessment procedures. A selection of test materials that appropriately considers the identified use cases and requirements is taking place. Point cloud geometry and their different attributes need to be appropriately represented. For that, a large database representative for several use cases has been collected and is available at JPEG PlenoDB.¹² Figure 4 shows two examples of the University of São Paulo point cloud database, collected for archaeological purposes and adopted by JPEG PlenoDB. In this case, two types of point clouds are shown: a point cloud of a simple object and a point cloud of a historical place. Considering the diversity of use cases and point cloud data, effective visualization procedures, namely displaying technologies and rendering processes are being considered and tested. Furthermore, contacts have been established with academics working on objective quality assessment for point clouds and meshes. It is also expected that a set of more reliable quality metrics will be available for the JPEG Pleno Point Cloud developments in the near future.

Considering the described developments, a Common test conditions of JPEG Pleno Point Cloud document is being prepared and will be released and analyzed in the next JPEG meeting, providing a framework for a future call for proposals together with a revised version of the previously mentioned JPEG Pleno Point Cloud - Use Cases and Requirements document.

6. HOLOGRAPHY

As opposed to the aforementioned modalities, holography adheres to a wave based-model instead of a ray-based model to describe light propagation. When light is scattered on the surface of an object, the resulting wave per surface point contains information about the amplitude – being the brightness of that point – and the phase – representing the depth position of that point. A hologram will contain information on all the points of the object and hence information about its full 3D shape. Unfortunately, classical analog or digital photographs only record light intensity and phase information is lost. However, holograms record the amplitude and phase of light through exploiting interference and diffraction characteristics while utilizing coherent light. This allows for a complete reconstruction of 3D objects.¹⁸

Main holography applications include holographic microscopy, holographic displays and holographic printing. Holographic microscopes produce holograms from which intensity and phase images can be derived. This enables for example cell refractive index tomography which facilitates 3D reconstruction of cells. Measuring the cell refractive index also allows for characterization of the medium. Examples of life science applications include monitoring the viability of cell cultures in suspensions, automating multi-well plate screening devices to measure the cell density and cell coverage of adherent cell cultures, or supporting simultaneous fluorescent and holographic cell imaging. For non-destructive testing, holographic imaging is extremely useful since it allows for high-speed video recording of nanoscale structures at nanometer precision for depth measurements.

Holographic displays realize autostereoscopic rendering without vergence-accommodation conflict. Moreover, all 3D depth cues that humans can perceive in the real world are embedded in the signal. An holographic display can be implemented in a variety of ways and hence many different solutions are currently being investigated for e.g. holographic television, table-top holographic displays and holographic head-mounted displays (HMDs). It is important to understand that holographic displays, similar to light field displays,⁸ require huge amounts of pixels to be processed. While humble for HMDs – due to the limited viewing angle and small display size, only between 10 and 100 Mpel are required – for table-top displays with 180 degree viewing angle support, one easily reaches pixel counts above 1 Tpel, while requiring pixel pitches of about 200 nm (blue light) to support these large diffraction angles. At the time of this writing, these pixel pitches are not yet available for dynamic displays. However, holographic printing can achieve these pixel pitches and provide depth cues and parallax unlike existing photographs. Holographic printing uses a laser to record captured discrete viewpoint images (holographic stereogram printing) or a wavefront (wavefront printing) into holographic material.¹⁹

The JPEG Pleno efforts in the context of holography aim at providing solutions for the compression of this data that address these above - but not limited to - use cases. For that, JPEG Pleno Holography has been collecting various holographic test data such as computer-generated holograms (CGH), microscopy/tomography



Figure 5. Numerical small aperture reconstruction of one viewpoint from a $64k \times 64k$ hologram computer-generated from the JPEG PlenoDB bi-plane point cloud with the 10 million points.

images and interferometric data. Test data can be accessed via the JPEG PlenoDB website.¹² In addition, objective/subjective quality assessment²⁰ and associated numerical reconstruction techniques for holography are being reviewed and discussed. The latter activities are very important due to the lack of existing high-end holographic displays. To bypass this bottleneck, numerical holographic reconstruction techniques are deployed that allow for displaying reconstructed holograms on e.g. light field displays or HMDs²¹ as illustrated in Figure 5.

To encourage participation and to clarify the JPEG Pleno Holography activities, recently the 'Overview of Holography 2.0'¹⁸ was released. In addition, exploration studies²² were launched to verify numerical reconstruction software and to further evaluate holographic test data.

7. CONCLUSIONS

JPEG Pleno is a new standardization initiative intended to provide a cross-modality and cross-device interoperability framework, incorporating coding tools for light fields, point clouds and holographic data, but also involving significant efforts to overcome the challenges related to objective and subjective quality assessment procedures for these types of content. In this context, the JPEG committee is seeking collaboration and input from the different actors involved in the field of plenoptic imaging to assure that defined specifications receive a broad support and adoption. More information on JPEG activities and how to get involved can be found on the JPEG Website.¹

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