Specification of Spectral-based Colour Management Protocols for ECHOES ECCCH

Deliverable 5.2

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Project Coordinator: Daniele Ferdani - CNR ISPC daniele.ferdani@cnr.it

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COLOURS Consortium

No	Short Name	Institution Name	Country
1	CNR	CONSIGLIO NAZIONALE DELLE RICERCHE	Italy
2	FhG	FRAUNHOFER GESELLSCHAFT ZUR FORDERUNG DER ANGEWANDTEN FORSCHUNG EV	Germany
3	FORTH	IDRYMA TECHNOLOGIAS KAI EREVNAS	Greece
4	NTNU	NORGES TEKNISK-NATURVITENSKAPELIGE UNIVERSITET NTNU	Norway
5	FBA	FUNDINGBOX ACCELERATOR SP ZOO	Poland
6	FBC	FUNDINGBOX COMMUNITIES SL	Spain
7	ECE	ERASMUS CENTRE FOR ENTREPRENEURSHIP BV	Netherlands
8	ZVKDS	JAVNI ZAVOD REPUBLIKE SLOVENIJE ZA VARSTVO KULTURNE DEDISCINE	Slovenia
9	BCS	Brakebush Börries	Germany
10	GMB	GALERIA MESTA BRATISLAVY	Slovakia
11	MIC	MINISTERO DELLA CULTURA	Italy

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Executive Summary

- COLOURS (Collaborative On-cloud Lab for the conservation and digital restoration of colOURed heritage collectionS, Grant Agreement No. 101233413) is a Horizon Europe Innovation Action (1 October 2025 to 30 September 2028). It develops tools and services for the documentation, simulation, conservation-restoration and visualisation of coloured cultural heritage, deploys them as a single vertical application on the European Collaborative Cloud for Cultural Heritage (ECCCH) of the sister project ECHOES, and tests them on Internal Pilots with paintings, polychrome sculptures, painted reliefs and historical colour films.
- Deliverable 5.2 (D5.2) specifies spectral-based colour management protocols as an additional, physically meaningful way of managing colour, which extends the tristimulus ICC practice of Deliverable 5.1 (D5.1, recommendations R1–R11). It explains the limits of tristimulus colour management, defines spectral colour management and its trade-offs (time, equipment, light exposure, data volume, tool support), specifies RGB and hyperspectral data collection, states for each Internal Pilot case study which protocol applies and whether spectral colour management is required, and defines the experiments that will validate the protocols on the Internal Pilots. It reports the work of Task 5.2 and the experimental design of Task 5.3.
- D5.2 makes the recommendations of D5.1 implementable. Where a pilot needs it, hyperspectral reflectance data are acquired alongside the RGB data used for 2D and 3D digitisation and visualisation. They are used to characterise and check the RGB images, to render the object under other illuminants and as a measured reference. Where spectral capture is not feasible, spectra estimated from a matched training set can be used if they are labelled as estimates.
- Three protocol tiers are defined. Protocol A is the tristimulus ICC baseline of D5.1 and is mandatory for all pilots. Protocol B is spectral-assisted RGB, with measured or estimated reference spectra. Protocol C is full spectral, with a calibrated reflectance or transmittance cube as the primary record. Spectral colour management is required for virtual varnish and overpaint removal and cleaning monitoring on paintings (case studies 1a, 1b and 1d) and for dye-fading assessment on colour films (Pilot 4). It is recommended for the painting 1c and for the polychrome sculptures, painted relief and reliquary (Pilot 2). It is not required for the XR presentation (Pilot 3), which consumes colour managed upstream.

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1. Introduction

Deliverable 5.2 (D5.2) specifies the spectral-based colour management protocols of the COLOURS project for ECHOES/ECCCH, as defined in Work Package 5 of the Grant Agreement (No. 101233413). It reports the work of Task 5.2 and the experimental design of Task 5.3 (Chapter 5) and complements the requirements of D2.1 on colour representation and on the input data of the COLOURS tools (D2.1, 2026).

It accompanies Deliverable 5.1 (D5.1), which defined general colour management protocols for digitisation and visualisation, consolidated them in eleven recommendations (R1–R11, Table 8.1 of D5.1) and stated that they will be validated on the Internal Pilots. D5.1 also stated that the spectral component would be specified here (R6, R7 and R10) and implemented in Work Package 6.

D5.1 showed that tristimulus ICC colour management remains the accepted baseline but is not sufficient for every heritage application, that calibrated hyperspectral reflectance can serve as an illuminant-independent record and as a reference for RGB images, and that practitioners photograph colour targets widely but rarely build profiles from them. D5.2 therefore presents spectral colour management as an additional way of working that is physically meaningful, with costs as well as benefits, and not as a replacement. It extends the D5.1 workflow where a pilot needs it, and Section 2.5 sets out the trade-offs.

The objectives are to (i) define spectral colour management, its trade-offs and its place in the ICC framework (Chapter 2); (ii) specify RGB and hyperspectral data collection (Chapter 3); (iii) state, for each case study of the Internal Pilots, which protocol applies and whether spectral colour management is required, recommended or not required (Chapter 4); and (iv) define the experiments with which the protocols are validated on the Internal Pilots (Chapter 5). The cloud implementation is specified in Chapter 6.

Spectral colour management means recording the object as spectral reflectance (or transmittance) and deriving colorimetric values and display RGB from it for a stated illuminant and observer, whereas tristimulus colour management converts device RGB to XYZ or CIELAB for one fixed illuminant and observer, as in D5.1. Three protocol tiers (A, B and C, Section 4.1) range from the tristimulus baseline to full spectral. For a case study, spectral colour management is called required when its objectives cannot be met or validated without calibrated spectral data, recommended when they can be met with RGB, but spectral data reduce a documented risk, and not required when spectral data would not change the result. Table 1.1 shows how the recommendations of D5.1 are carried forward.

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Table 1.1: Treatment of the D5.1 recommendations in D5.2

D5.1 item	Treatment in D5.2	Where
R1–R2 Light, board, target	Extended to hyperspectral capture, with a stable continuous source, calibrated white and dark references and a target with measured spectra.	Section 3.3, S2–S5
R3–R5 Raw, characterisation, accuracy	Retained as Protocol A; reference colours computed for the actual illuminant when spectra exist; accuracy reported as ΔE_{00} and ΔE_{76}.	Section 3.1, Chapter 5
R6–R7 Spectral data and reference	Specified, with reflectance as the primary record, colour derived once for a stated illuminant and observer, and hyperspectral reference data for RGB (Protocol B).	Sections 2.2, 3.3, 4.1
R8–R9 Photogrammetry, glossy surfaces	Retained; spectral reference areas added for polychrome 3D objects.	Sections 3.2, 4.3
R10–R11 Master, metadata	Extended to spectral masters, optional iccMAX description and spectral metadata.	Sections 2.3, 3.3, S10, S12
Validation on the Internal Pilots	Developed into five groups of experiments.	Chapter 5

2. Spectral-based Colour Management

Three protocol tiers are used throughout this deliverable and are defined in full in Section 4.1. Protocol A is tristimulus colour management based on ICC profiles, as in D5.1, in which RGB images are characterised with a colour target, and it applies to all pilots. Protocol B is spectral-assisted RGB, which is Protocol A plus reference spectra, either measured on selected areas or estimated from a matched training set, used to characterise and check the RGB images. Protocol C is full spectral colour management, in which a calibrated reflectance (or transmittance) cube is the primary record and colour is derived from it for a stated illuminant and observer.

2.1 Limits of tristimulus colour management

In CIE colorimetry the colour of an object is reduced to three tristimulus values for one illuminant and observer, so two surfaces with different reflectance spectra can match under one light and differ under another, which is called metamerism (Wyszecki & Stiles, 2000; Berns, 2019a). In a camera workflow this reduction already happens in the sensor, so an ICC input profile can only estimate colorimetric values under the capture illuminant (D5.1, Chapter 2). The estimate is exact only if the camera sensitivities are linear combinations of the colour matching functions (the Luther condition), which colour cameras generally do not satisfy (Simon Chane et al., 2013). A profile built from a target is therefore accurate mainly for materials whose spectra resemble the target patches, and less so for narrow-band pigments and dyes. It also depends on exposure, and

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polynomial models are exposure-sensitive, which root-polynomial regression was designed to remove (Finlayson et al., 2015), and the one overexposed image in Molada-Tebar et al. (2019) was the only one above about three CIELAB units.
The ICC v4 architecture adds its own limits. Its Profile Connection Space is defined for the CIE 1931 2° observer and D50 illumination, and chromatic adaptation is the only mechanism for other illuminants, which ICC notes often gives poorly aligned colour when viewing is not D50-like and cannot describe the colour shifts of fluorescent materials (ICC, 2018). For COLOURS this means that virtual relighting under museum, daylight or simulated illuminants cannot be done faithfully from tristimulus data, that metamerism cannot be predicted, and that a colour change between two conservation states can be assessed only under the capture illuminant.
These limits are felt in practice. Plutino and Simone (2021) analyse the limits of colorimetry in cultural heritage, including point-wise measurement. At the Centre de recherche et de restauration des musées de France, chart-calibrated studio photography is used and accuracy is measured using colour difference metric (45/0 geometry), while fibre-optic spectrophotometers are used where maximum accuracy and reproducibility are needed and hyperspectral cameras where spatial resolution is needed, although hyperspectral colour measurement is not yet routine because acquisition takes long (Boust & Arteaga, 2023). Tristimulus colour management is thus adequate for documenting and displaying appearance under a defined illuminant, and spectral data are needed when colour is used as evidence, compared across states or illuminants, or processed by physics-based tools. Table 2.1 compares the two approaches.

Table 2.1: Tristimulus and spectral colour management comparison

Aspect	Tristimulus (ICC v4)	Spectral
What is recorded	Three device values converted to XYZ or CIELAB for one illuminant and observer.	Reflectance (or transmittance) factor per wavelength, independent of the illuminant.
Illuminant and observer	Fixed at capture; PCS defined for D50 and the 2° observer; other illuminants by chromatic adaptation only.	applied after capture.
Metamerism	Not detectable.	Can be predicted and quantified.
Relighting	Approximate.	Physically based for diffuse, non-fluorescent surfaces and illuminants of known spectrum.
Accuracy	Depends on target, material spectra, exposure and characterisation model.	Depends on radiometric calibration, noise, geometry and reference quality.
Tool support	Uniformly implemented in operating systems, browsers and image software. (v4 ICC profiles)	ICC.2 (iccMAX) is available yet to be adopted in industry.

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Use in COLOURS	Documentation and display (Protocol A).	Evidence, monitoring, simulation and reference for RGB (Protocols B and C).

2.2 Spectral colour management

In spectral colour management the object is represented by its reflectance factor R(λ), the ratio of the light it reflects to that of a perfect reflecting diffuser under the same illumination and geometry. For a hyperspectral camera it is obtained from the object signal I(λ), the dark frame D(λ) and a calibrated white reference W(λ) of known reflectance factor ρW(λ): $R(\lambda) = (I(\lambda) - D(\lambda)) / (W(\lambda) - D(\lambda)) \times \rho W(\lambda)$. This is the radiance-to-reflectance step of Chapter 5 and Case study 1d of D5.1 (Habib et al., 2026). R(λ) describes the object under the stated geometry and not the scene lighting, so it can be combined afterwards with any illuminant. Colour is then computed on demand. For an illuminant S(λ) and observer colour matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$, the tristimulus values are $X = k \Sigma S(\lambda) R(\lambda) \bar{x}(\lambda) \Delta\lambda$, and likewise Y and Z, with $k = 100 / \Sigma S(\lambda) \bar{y}(\lambda) \Delta\lambda$ so that a perfect diffuser has Y = 100 (CIE, 2018). CIELAB values follow from XYZ and the white point of the same illuminant. As in D5.1, colour differences are reported as both ΔE_{00} and Δ_{E76}, which are not interchangeable (D5.1, Chapter 2). For exchange with D50-referenced ICC profiles the XYZ values are chromatically adapted to D50 and the adaptation is recorded (R6).

The spectral workflow of COLOURS therefore has six steps: (a) acquisition with calibration references under a known source; (b) conversion to a calibrated reflectance cube; (c) selection of illuminant and observer; (d) computation of XYZ and conversion, with chromatic adaptation where needed, to the ICC working space; (e) rendering to the display or delivery format once, at the end (R6); and (f) archiving of the cube, the transform and the metadata. It adds four capabilities: (a) illuminant-independent comparison of conservation states; (b) prediction of metamerism, for which CIE colorimetry defines indices (CIE, 2018), for example whether a retouching matched under one light mismatches under another; (c) a measured reference for validating an RGB characterisation (R7); and (d) the input of physics-based tools such as virtual varnish removal (Habib et al., 2026) and the Light Damage Estimator. Spectral data also serve pigment identification (Liang, 2012; Delaney et al., 2016; Picollo et al., 2020; Pei et al., 2023), which is material analysis and not colour management as such.

Its limits are equally clear. A reflectance factor describes diffuse, non-fluorescent reflection under one geometry. It does not describe gloss, translucency or texture (Boust & Arteaga, 2023) or fluorescence, which COLOURS keeps as separate luminescence layers (R10). On curved or glossy surfaces, it depends on the local normal and the light and view directions (Guarnera et al., 2016; Krzesłowski et al., 2012; R9). Habib, Green and Nussbaum (2023a) rendered such directional appearance of printed 2.5D surfaces through an iccMAX profile, but this has not been tested on heritage objects. The accuracy of a reflectance factor is also

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bounded by the calibration references, sensor noise and stray light, so it must be demonstrated and reported (Section 5.3).

2.3 Spectral data in the ICC framework

The ICC.2 specification (ISO 20677-1; ISO, 2019), known as iccMAX, extends ICC v4 with a spectral Profile Connection Space, profile connection conditions defined by a spectralViewingConditions tag (illuminant, observer and surround) with tags that convert to the standard D50, 2° colorimetry, programmable Calculator Elements, a bispectral (Donaldson) matrix for fluorescence, a directional viewing connection and multiplex connection spaces (ICC, 2023; ICC, 2018). Without a stated range, observer and illuminant data are assumed to span 380 to 780 nm in 5 nm steps (ICC, 2023). iccMAX is intended to be backward-compatible with v4 (ICC, 2018).
The Interoperability Conformance Specification (ICS) spectralReflectance, Part 2, restricts ISO 20677-1 to connecting multispectral reflectance data to a spectral PCS (ICC, 2021b). Colorimetry is obtained by applying the illuminant and observer of the spectralViewingConditions tag, which is the formal counterpart of the workflow in Section 2.2. Table 2.2 relates the features to COLOURS.

Table 2.2: iccMAX features and their relevance to COLOURS

iccMAX feature	Purpose	Relevance to COLOURS
Spectral PCS and spectralReflectance ICS	Connect reflectance data without early reduction to XYZ.	Archival description of hyperspectral reflectance (Protocol C).
spectralViewingConditions and PCC tags	Define the illuminant and observer of a connection and convert to D50, 2°.	Explicit illuminant and observer (S8); exchange with v4 profiles.
Calculator Elements	Programmable transforms inside the profile.	Compact spectral or characterisation transforms, including spectral estimation.
Bispectral (Donaldson) matrix	Describe fluorescence.	Possible later use; luminescence layers stay separate in COLOURS.
Directional viewing connection	Connect angle-dependent appearance.	BRDF rendering through iccMAX profiles has been shown for printed 2.5D surfaces (Habib et al., 2023a); possible link to BRDF-aware correction (R9), not tested in COLOURS.

The practical position of COLOURS follows as such: ICC v4 profiles are uniformly implemented and remain the exchange and delivery format. iccMAX is specified as an optional description of the spectral transform of an acquisition system, to

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be used where the processing chain supports it. Habib, Green and Nussbaum (2023b) implemented a polynomial spectral estimation as an ICC.2 profile with Calculator Elements, which shows that spectral processing inside a profile is feasible. Support in the colour management modules and software used by the project has not been verified and will be tested in Work Package 6.

2.4 Estimating spectra from RGB and multispectral data

Spectra can also be estimated. Imai and Berns (1998) combine a low-resolution multispectral image with a high-resolution lightness image to build a high-resolution spectral archive, close to the Specim IQ and Canon combination of COLOURS. The Centre de recherche et de restauration des musées de France obtains a 35-point reflectance curve from four filtered shots (Boust & Arteaga, 2023). In computer graphics, RGB values are lifted to plausible spectra for rendering (Jakob & Hanika, 2019). Habib, Green and Nussbaum (2023b) show that estimating reflectance from XYZ with a training set of spectrally similar materials gives low metameric mismatch under other illuminants, lower than chromatic adaptation or material adjustment transforms when the training data match the material, but the mismatch grows when the training set is a poor match. Ansari-Asl, Habib and Hardeberg (2026) compared reconstruction methods for two multispectral cameras (a spectral filter array and a filter wheel) under controlled LED light. Training-based methods (polynomial and pseudo-inverse) clearly outperformed model-based methods, selecting training samples similar to each measured colour improved the results further, and model-based methods depended on accurate sensor data and on the spectrum of the light source. They conclude that acquiring a dedicated training set for the system is highly beneficial, although their reference datasets were Munsell colour sets and not heritage pigments.

Estimated spectra are metameric reflectances, not measurements, because many spectra give the same colour. COLOURS therefore allows them only as an explicit, cheaper option (Protocol B-estimate, Section 4.1) for relighting previews and illuminant adjustment, with a training set matched to the material (for example pigment or dye reference sets; Habib et al., 2023b; Ansari-Asl et al., 2026), the validation error reported against measured spectra, and a label marking them as estimates (S13). They may be used as input to VarnishLab and the LDE for previews, as D2.1 requires these tools to accept RGB data (D2.1, 2026), but the result is labelled as estimate-based and is not used as evidence or for validation (E3)

2.5 Trade-offs of spectral colour management

Spectral colour management gives physically meaningful, illuminant-independent data, but it costs time, equipment, light exposure and skills, so it is added where

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a pilot's question depends on it and not as a default. Table 2.3 summarises the trade-offs and the cheaper options.

Table 2.3: Trade-offs of spectral colour management compared with tristimulus colour management

Aspect	Tristimulus (Protocol A)	Spectral (Protocols B and C)	Evidence
Time and equipment	Minutes per set-up; camera, white board, target.	Slower scanning; hyperspectral camera or spectrophotometer, calibrated white reference; hyperspectral colour measurement is not yet routine because acquisition takes long.	Boust & Arteaga, 2023; Pillay et al., 2019
Light exposure	Short.	Longer exposure to broadband lamps per scan; dose to be recorded (S4).	Section 3.3
Resolution and data	Full camera resolution, three channels.	Lower spatial resolution and hundreds of bands (204 for the Specim IQ), so RGB is kept for spatial detail.	Imai & Berns, 1998; Habib et al., 2026
Accuracy and reproducibility	Minimal average colour difference for chart-calibrated studio photography; limited by metamerism.	Metamerism can be assessed and data validated against references, but accuracy depends on calibration and differs between systems.	Boust & Arteaga, 2023; Pillay et al., 2020; George et al., 2017
Skills and tools	Widely supported, v4 profiles.	Specialised calibration and processing; iccMAX available, not yet adopted.	ICC, 2018; Pillay et al., 2019
Cheaper options	Not applicable.	Colour-managed RGB with spot spectra and an optical model; modified consumer camera; multispectral camera with trained spectral reconstruction; spectral estimation from a matched training set, with estimates labelled.	Berns, 2019b; Webb et al., 2018; Habib et al., 2023b; Ansari-Asl et al., 2026
Where it pays off	Documentation and display under one illuminant.	Evidence, monitoring across states, relighting and physics-based tools.	Section 2.1

2.6 The need for protocols

Spectral data do not by themselves give consistent colour. Hyperspectral cubes must be calibrated spatially and spectrally to be accurate and reproducible (Pillay et al., 2019), and round-robin tests of hyperspectral systems were organised to compare their data quality (George et al., 2017; Pillay et al., 2020). The

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practitioner survey of D5.1 points the same way. Practitioners already photograph colour targets but rarely turn them into profiles. What is missing is not tools but a short procedure that people actually follow, covering the reference materials, the calibration, how colour is derived from the data and the metadata to record. D5.2 provides this procedure as requirements S1–S13 (Table 3.2), applied through the protocol tiers of Chapter 4.

3. Data Collection

Data collection is where the protocols meet the objects, and what is not recorded correctly cannot be recovered later (D5.1, Section 6.1). This chapter specifies RGB acquisition of flat objects (3.1), RGB acquisition for 3D models (3.2) and hyperspectral acquisition (3.3). The RGB procedures follow the case studies of D5.1 and add only the spectral references that Protocols B and C need; Table 3.1 summarises the three acquisitions.

Table 3.1: Acquisition modes, typical instruments and role in the protocol tiers

Acquisition	Data	Typical instrument in COLOURS	Protocol tier
RGB, 2D (3.1)	Raw images, characterised colour, high spatial resolution	Digital camera with raw output, two oblique lights, white board and colour target (Case study 1d)	A, B, C
RGB, 3D (3.2)	Raw image sets, textured model	Camera on a fixed stand, cross-polarised lights, turntable, per-round colour target (Case study 2a)	A, B
Hyperspectral (3.3)	Calibrated reflectance cube (or transmittance)	Push-broom hyperspectral camera such as the Specim IQ; point spectrophotometer for references	B (references), C

3.1 Acquisition of RGB data for 2D/flat object

RGB images of flat originals give the spatial resolution for documentation and display and are the basis of Protocol A. In Protocols B and C the same images carry the spatial detail while spectral data provide the reference for their colour (R7). Acquisition follows R1–R3 and Case study 1d of D5.1. Two lights of the same type and known colour temperature are placed at oblique angles, the sensor plane is parallel to the painting, and a white board and multi-patch colour target are in the object plane. Images are captured raw at fixed exposure, developed identically and processed at 16 bit or higher.

The target reference values deserve attention. Chart values are normally tabulated for D50, whereas the capture illuminant is usually different, such as halogen light. When the target's reflectance spectra and the source spectrum are available, the

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reference XYZ values are computed for the actual illuminant (Section 2.2) and then adapted to D50 if a profile is built. This is the cheapest spectral-assisted step. It needs only a contact spectrophotometer on the target, which is permitted because only the object must not be touched (D5.1, Section 3.2), and it also accounts for target ageing.
After black-level subtraction, flat-field correction and demosaicing, the camera is characterised against the target (R4). At least a linear 3×3 matrix and a second-order root-polynomial model (Finlayson et al., 2015) are fitted and compared with the ICC input profile of the profiling software, because the root-polynomial terms scale with exposure. Models are validated on patches not used for fitting, and ΔE_{00} and ΔE_{76} are reported as mean and 95th percentile with illuminant and observer stated (R5). The indicative benchmarks are below about three CIELAB units (ΔE_{76}) in a rock-art study with a second-order model (Molada-Tebar et al., 2019) and an average of 2.1 ΔE_{76} for chart-calibrated studio photography (Boust & Arteaga, 2023). Acceptance limits will be set per metric from the psychovisual experiments (Section 5.3).
Large paintings, such as the 324 × 158 cm painting of case study 1a, are captured as overlapping tiles with constant light, exposure and settings, the white board and target in every tile or row, flat-field and characterisation applied per tile, and mosaicking afterwards (as for rounds in photogrammetry, R8). Lighting stability is checked by photographing the target at the start and end and reporting the colour difference between the two. In Protocols B and C the co-registered hyperspectral cube is captured in the same session and under the same lighting with the same target in view (Section 3.3), so that target and painting colour can be computed from reflectance and used to build or check the RGB characterisation (R7, experiment E1).

3.2 Acquisition of RGB data for 3D object

The proposed workflow builds on established methods for digital camera colour characterisation (Hong et al., 2001; ISO 17321-1:2012) and previously validated approaches to colour fidelity assessment in photogrammetric and scanned 3D models of cultural heritage objects (Felicísimo & Polo, 2022; Barbero-Álvarez et al., 2023).
Spectral-to-colorimetric conversion and colour-difference assessment follow established CIE recommendations and standards (like CIE 015:2018).
Rather than introducing these methods as new, Protocol B brings them together in an object-specific acquisition and validation workflow, incorporating selected spectral reflectance measurements as independent references for assessing the colour fidelity of reconstructed textures.
The proposed multi-faceted colour target is treated as an experimental extension, informed by previous research on surface-orientation-dependent colour and appearance modelling (Habib et al., 2023a).

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In photogrammetry a flat target samples colour for a single geometry and the light reaches the surface differently from shot to shot (D5.1, Sections 6.1 and 8). Case study 2a (Bratislava) is the template. It uses a fixed camera and cross-polarised light of fixed colour temperature, an object rotating on a turntable, 4 to 5 rounds per object and a ColorChecker at the start of each round (R1, R2, R8). Four requirements are added for spectral-assisted colour management. First, the target is photographed with the same polarisers as the object, because the filters change the light reaching the sensor and a characterisation made without them does not describe the object images. Second, a calibrated reference panel is kept in every set for relative radiometric normalisation, as Uccheddu et al. (2025) do with a Spectralon panel. Third, for polychrome objects, reflectance spectra are measured without contact on a few reference areas for the main pigments, gilding and bare substrate; the fibre-optic device of the Centre de recherche et de restauration des musées de France measures at 7.5 cm from the artwork (Boust & Arteaga, 2023), and flat areas can be measured with hyperspectral imaging instead (Section 3.3). Fourth, the colour of the reference areas computed from the spectra is compared with their colour in the final texture, an object-specific check that does not depend on a flat target.

The colour characterisation made for each round is applied to all images of that round before reconstruction (structure-from-motion), and the colour difference of the target patches visible in the finished model is then measured to check the result (Barbero-Álvarez et al., 2023). A flat target cannot show how the colour of a glossy or polychrome surface changes with viewing angle, so it is treated as the baseline for diffuse colour only, and a multi-faceted target will be tested to cover this (R9, experiment E4). A related method adjusts the colour measured on a flat target to predict the colour of the same printed material at a given surface slope (Habib et al., 2023a), which shows how a correction conditioned on the local normal could work. The target has at least three facets at different known angles, spanning the range of surface orientations, and the angles are recorded. If a scanner supplies the colour, it is characterised in the same way, because an ICC profile built from a target reduced colour error in scanned textures (Felicísimo & Polo, 2022).

Luminescence layers (UVL, VIL) are registered to the same mesh so that all textures share one UV layout (Uccheddu et al., 2025) but are not treated as colour data (R10). Es Sebar et al. (2023) register visible, UV-reflected, UV-luminescence and false-colour images on one model. Such approaches use a few imaging modalities and not calibrated spectral cubes, which is why Protocol B for 3D objects relies on reference points and small hyperspectral reference areas and not on full-surface hyperspectral capture.

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3.3 Acquisition of Hyperspectral data

Hyperspectral and multispectral cameras record many narrow bands per pixel, and the data become reflectance only after a defined calibration chain. Typical heritage systems are push-broom cameras scanning a painting on an easel or on a motorised rotating tripod and, in the project, the handheld Specim IQ with 204 bands from 397.32 to 1003.58 nm at 3.09 nm intervals is used (Habib et al., 2026). Imaging spectroscopy extends into the short-wave infrared for pigment mapping (Delaney et al., 2016; Picollo et al., 2020). Point reflectance measurements with a fibre-optic spectrophotometer give independent references (Boust & Arteaga, 2023). Modified consumer cameras with a characterised spectral response are a lower-cost option for spectral and 3D imaging (Webb et al., 2018).

Acquisition and calibration

The procedure follows Pillay et al. (2019) and Case study 1d (Habib et al., 2026). For the set-up, the light is stabilised and spectrally continuous (halogen or broadband LED), the geometry is fixed and recorded, and mixed lighting is avoided (R1); exposure is limited and recorded for fragile objects because the light dose matters for the photodegradation estimated by the Light Damage Estimator. For the references, a calibrated white reference of known reflectance factor (a PTFE target of the Spectralon type) is placed in the object plane together with a verification target with measured spectra that is not used for calibration; a secondary white board may be used for convenience if it is calibrated against the primary reference, as in Case study 1d. For the settings, the integration time is chosen so that the brightest reference stays below the detector's linear limit, which manufacturers recommend as around 80 percent or less, and a dark frame is captured at the same integration time; because a bright 99 percent reference wastes dynamic range on dark paintings, references of different reflectance can be used (Pillay et al., 2019). The calibration then consists of dark subtraction, flat-fielding, conversion to reflectance factor (Section 2.2), band selection and geometric registration and, for scans in sections, mosaicking (Pillay et al., 2019; Liang, 2012). For validation, the spectral root-mean-square difference and the colour differences of the verification target are computed against its measured spectra, as in Habib et al. (2026). The cube is then registered to the RGB image and the residual misregistration is reported, and any fusion of the two data sets (Imai & Berns, 1998) is labelled as derived (S6). Transmission imaging for colour films uses the same chain, with the open gate as white reference and the transmittance factor in place of the reflectance factor (Section 4.5).

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Requirements

Table 3.2 consolidates the requirements as S1–S13, numbered to continue R1–R11 of D5.1. Must means that the data cannot be called spectrally calibrated in COLOURS without it; Should means recommended practice that can be relaxed with the reason recorded. The tier column states where it applies.

Table 3.2: Specification requirements for spectral colour management

No.	Requirement	Priority	Basis	Tier
S1	Record calibrated reflectance (or transmittance) factor as the primary spectral data, covering at least 400–700 nm with sampling no coarser than 10 nm (5 nm preferred); state sampling and spectral resolution.	Must	Sections 2.2, 3.3; ICC, 2023	C
S2	Apply the full calibration chain (dark, flat-field, reflectance with a calibrated white, band selection, registration); keep the signal below the detector's linear limit; use several references for dark objects where possible.	Must	Pillay et al., 2019; Habib et al., 2026	C
S3	Use a calibrated white reference and a dark reference and record the geometry for which the reference values apply. Use a verification target with measured spectra that is not used for calibration.	Must (white, dark); Should (verification target)	Sections 3.1, 3.3; Pillay et al., 2019	B, C
S4	Use a stable, spectrally continuous source of known type and colour temperature in a fixed geometry, without mixed lighting. Measure its spectrum and record the light exposure.	Must (source); Should (spectrum, exposure)	R1; Deborah et al., 2026	B, C
S5	Record the illumination and viewing geometry and reduce specular reflection (oblique light or polarisation). Reflectance on curved or glossy surfaces is valid only for the recorded geometry.	Must	Section 3.2; Guarnera et al., 2016	B, C
S6	Co-register spectral data to the RGB images of the session and report the residual misregistration. Declare any resampling or fusion; derived spectra are labelled.	Should (Must where RGB is characterised from spectra)	R7; Imai & Berns, 1998	B, C
S7	Validate spectral accuracy on the verification target (spectral RMSD, ΔE_{00} and ΔE_{76} for a stated illuminant and observer) with the uncertainty of S11.	Should (Must before use as evidence)	Chapter 5; Habib et al., 2026; Sharma et al., 2005	B, C
S8	State illuminant (spectrum), observer (CIE 1931 2° by default), integration range and	Must	R6; CIE, 2018; ICC, 2022	B, C

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	interval, white point and the chromatic adaptation used for D50-referenced ICC profiles.			
S9	Convert to display colour once, at the end, with a documented rendering; flag out-of-gamut colours and never use the rendered image as analysis input.	Must	R6, R10	A, B, C
S10	Archive the reflectance cube as master with its derived colorimetric ICC profile. Describe the spectral transform as an iccMAX profile where tools allow; delivery never depends on it.	Must (cube); Should (iccMAX)	R10; ICC, 2021b; Khronos Group, 2021	C
S11	Report repeatability and reproducibility and the expanded uncertainty of reflectance and colour difference; treat a colour change as real only if it exceeds the combined uncertainty.	Should (Must for change monitoring)	Section 5.3; JCGM, 2008; Pillay et al., 2020	B, C
S12	Record instrument, spectral range, sampling and resolution; source and geometry; reference materials and certificates; settings; dark and white frames; software versions; profiles; accuracy results; exposure dose; and link them to the image metadata of R11.	Must	R11; Deborah et al., 2026; Section 6.5	A, B, C
S13	Label estimated spectra as estimates, with the training set and the validation error against measured spectra, and do not use them as evidence.	Must when estimates are used	Section 2.4; Habib et al., 2023b	B-estimate

S1–S13 apply to reflectance on objects whose surface is close to planar relative to the measuring geometry and to the reference areas of 3D objects. They do not remove the angular dependence of reflectance on full 3D objects (experiment E4).

4. Colour Management recommendations based on case studies included in each Pilot

This chapter applies Chapters 2 and 3 to the Internal Pilots, listed in Table 4.1 below according to the final Internal Pilot list of WP10 (see the note below the table). For each pilot it states the colour management issues, the protocol tier and whether spectral colour management is required, recommended or not required. Case studies 1d and 2a of D5.1 (the Düsseldorf painting, one of the paintings of case study 1d, and the Bratislava statuary) are used as the starting point for the matching pilot objects.

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Table 4.1: Description of Internal Pilots and their case studies

Pilot No.	Pilot Title	Case Studies	Object Type
1.	*Conservation & Restoration of historic painting & Testing of Predictive Simulation and Visualization Tools*	1a. Adoration of the Holy Cross	Easel painting
		1b. Depiction of the War with the Ottomans	Easel painting
		1c. Six Dukes of Jülich-Kleve-Berg	Painting
		1d. Series of paintings *"Monitoring progressive surface cleaning and varnish removal of paintings by means of HSI"*	Painting(s)
2.	*Virtual restoration, Reconstruction of original appearance of Polychrome 3D Objects*	2a/b. J.A. Eglauer wooden polychrome sculptures	Polychrome wooden sculptures
		2c. Bas-relief from the tomb of Sethi	Painted bas relief
		2d. Reliquiary Diptych of Christina von Stommeln	Mobile altar
3.	*Enhancing Public Engagement with Cultural Heritage through XR applications*	3a. J.A. Eglauer wooden polychrome sculptures	Polychrome wooden sculptures
		3b. Bas-relief from the tomb of Sethi	Painted bas relief
		3c. Reliquiary Diptych of Christina von Stommeln	Mobile altar
4.	*Koshofer collection selected film frames: Testing and Refining Advanced Restoration Tools*	4a. Colour Films collection	Films

Note: Pilot numbering follows the final Internal Pilot list of WP10. Correspondence with the pilots of the Grant Agreement (Part B): case study 1a = GA Pilot 1; case study 1b = GA Pilot 2; Pilot 2 (2a/b) = GA Pilot 3; Pilot 3 = GA Pilot 4; Pilot 4 = GA Pilot 5. Case studies 1c, 1d, 2c, 2d, 3b and 3c were added by the consortium; the Grant Agreement presents its pilot examples as illustrative and open to revision.

4.1 Protocol tiers and decision criteria

Three cumulative tiers are defined (Table 4.2); a team applies the lowest tier that answers the pilot question. Protocol C can be applied to selected areas of a larger object, called hyperspectral reference areas, which are captured with hyperspectral imaging; the remainder of the object follows Protocol B, and the spectra of these areas serve as the reference for the rest (R7).

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Table 4.2: Protocol tiers and minimum practical requirements

Tier	Content	Minimum kit and steps	Main outputs
A	Tristimulus ICC baseline (R1–R5, R8, R10, R11 of D5.1).	Stable light, white board, one colour target, camera with raw output, profiling software. Capture board and target each session, develop raw identically, characterise, report ΔE_{00} and ΔE_{76}, record metadata.	Characterised 16-bit master with profile; sRGB delivery version; accuracy report.
B	Spectral-assisted RGB, which is Protocol A plus S3–S9 and measured reference spectra.	A plus a contact spectrophotometer for the target and a non-contact spectrophotometer or hyperspectral imaging system for reference areas. Compute target colour for the actual illuminant; check the RGB characterisation and texture colour on the reference areas.	As A, plus reference spectra and colour of reference areas under stated illuminants.
B-estimate	Protocol B with spectra estimated from a training set matched to the material (S13), for RGB or few-band multispectral cameras.	A plus a training set of spectrally similar materials, which gives lower errors than a generic set (Habib et al., 2023b; Ansari-Asl et al., 2026). Estimate, report the validation error, label as estimates; use for relighting previews, not as evidence.	As A, plus labelled estimated spectra.
C	Full spectral, which is Protocol B plus S1, S2, S10 and S11.	Hyperspectral camera, calibrated white and verification target, stable continuous light. Full chain of Section 3.3, cube archived as master, uncertainty reported.	Reflectance or transmittance cube; derived colorimetry; validation report.

The tier follows from six questions (Table 4.3). Spectral colour management is required when question 1 or 2 is answered yes and spectral capture is feasible (Protocol C, possibly for selected areas only), recommended when question 3 or 4 is yes or when feasibility limits capture to references (Protocol B), and not required when only question 6 is yes.

Table 4.3: Decision criteria for the protocol tier

No.	Question	If yes
1	Is colour used as measurement or evidence (monitoring change, validating a simulation) and not only to show appearance?	Required (C)
2	Must a result of the pilot or of a COLOURS tool (VarnishLab, Light Damage Estimator, Neg2Pos) be validated quantitatively on reflectance or transmittance?	Required (C)
3	Is metameric risk high (original and overpaint, dyes, narrow-band absorbers)?	References needed (B or C)

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4	Must the appearance be shown or compared under other illuminants?	References needed (B or C)
5	Can calibrated spectral data be captured given the size, geometry, surface and handling?	If no, limit to references (B)
6	Is the task only presentation of colour managed upstream?	Not required (A)

4.2 Pilot 1: Conservation and restoration of historic paintings, testing of predictive simulation and visualisation tools

Pilot 1 tests simulation and visualisation tools on four paintings. Case study 1a, Adoration of the Holy Cross (324 × 158 cm, attributed to Matteo Ingoli), is in very poor condition with unstable layers, heavy overpainting, non-original varnish and a changed format, and asks whether non-original varnish can be separated from the original and whether the appearance after removing non-original layers can be simulated (Grant Agreement, Part B). Case study 1b, Depiction of the War with the Ottomans (Antonio Calza, 98 × 147 cm), has been restored and has before-and-after images and documentation, so simulations can be compared with the real result. Case study 1c (Six Dukes of Jülich-Kleve-Berg) and 1d (a series of paintings with progressive cleaning monitored by hyperspectral imaging) complete the pilot.

The virtual varnish removal of Habib et al. (2026) works on reflectance, separating interface and body reflection and removing the wavelength-independent interface contribution (Trumpy et al., 2015). Currently, the model has been tested on hyperspectral data. It will also be adapted to handle RGB data where only the dark and light areas of the painting will be reflectances captured with a spectrophotometer or estimated for the physics-based model (D2.1, 2026). Overpaint and original paint, or a retouching and its surroundings, can match under one light and differ under another, which tristimulus data cannot show (Simon Chane et al., 2013). The large format of 1a makes uniform light and consistent calibration difficult, and any comparison between states needs a difference larger than the measurement uncertainty (S11).

For 1a, spectral colour management is required, Protocol C on hyperspectral reference areas chosen with the conservators to cover original paint, overpaint and varnish states, and Protocol B over the whole painting, with a full-surface mosaic as an extension (Pillay et al., 2019). For 1b it is required for a quantitative validation of VarnishLab, since the comparison needs calibrated spectra of the state before treatment, which cannot be acquired retrospectively; if none exist, the case follows Protocol B for the present state, legacy images are used with their limits stated, and VarnishLab is validated on 1a and 1d. For 1c, Protocol B is provisionally recommended until the holder confirms the condition, treatment and equipment. For 1d it is required (Protocol C at every cleaning stage), with fixed set-up, registration marks, a white reference and verification target per session,

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and differences interpreted against the expanded uncertainty. Acceptance is by experiments E1 to E3 (Chapter 5).

4.3 Pilot 2: Virtual restoration and reconstruction of the original appearance of polychrome 3D objects

Pilot 2 concerns the wooden polychrome sculptures by J.A. Eglauer (2a/b) from the former main altar of the Jesuit Church in Bratislava, with varying preservation and fragments of original polychromy (Grant Agreement, Part B), the painted bas-relief from the tomb of Sethi (2c) and the Reliquary Diptych of Christina von Stommeln, a mobile altar (2d). The Eglauer sculptures are the objects of Case study 2a (D5.1), so Protocol A is already being applied to them.
Issues are glossy, polished and gilded surfaces (R9) and the mixture of original polychromy, overpaint and restoration. The original appearance cannot be measured, so a reconstruction is an interpretation. Berns (2019b) describes a practical way where colour-managed RGB images, small-aperture spectrophotometry of the object, an optical model of colorant mixing and a database of artists' materials are used to adjust segmented areas, and the result is an informed approximation that cannot be verified, with an error that depends on the colour range inside each segment. Reconstructed colours must therefore be tied to measured spectra of surviving paint and documented as paradata with their uncertainty.
Protocol B is specified for the 3D objects while Protocol A over the whole object and measured reference spectra (S3–S8) on areas of surviving polychromy, overpaint, gilding and substrate. They give an object-specific check of texture colour, a basis for reconstructed colours defined as reflectance and a measure of how well the characterisation holds for the object's pigments. For 2c, the near-planar relief allows Protocol C on the relief or panels; for 2d the painted panels can be captured as hyperspectral reference areas, while gilded and metallic parts are documented as appearance under a defined geometry and not as reflectance factor. Spectral colour management is recommended for the digitisation and required for the reference areas from which original colours are reconstructed.
Full-surface spectral capture of 3D objects is not specified. On a non-planar surface the reflectance factor depends on the local normal and on the light and view directions, so the flat white reference of Section 3.3 holds only near the reference plane. Published multispectral 3D workflows use few bands or modalities, for example six bands in Uccheddu et al. (2025) and a few registered modalities in Es Sebar et al. (2023), and hyperspectral textures have been used for colour management in virtual reality scenes of flat plates, whereas other geometries need photogrammetry (Díaz-Barrancas et al., 2020). Geometry-aware radiometric correction is left to future work. Acceptance is by experiment E4.

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4.4 Pilot 3: Enhancing public engagement through XR applications

Pilot 3 uses the ATON framework to create extended reality applications, namely mixed reality that overlays reconstructed sections on unrestored parts of the polychrome sculptures, mobile access to diagnostic data layers, and virtual reality exploration of the objects in their original context (Grant Agreement, Part B). The case studies listed in the pilot table are the Eglauer sculptures (3a), the Sethi bas-relief (3b) and the reliquiary (3c), that is the objects of Pilot 2 in a presentation context.

The colour management issues of this pilot lie in delivery and display, not in acquisition. The delivery chain is limited by glTF, which fixes the base-colour textures as sRGB with BT.709 primaries and ignores embedded ICC profiles (Section 6.5 of D5.1), so that colour management must be done upstream and documented as in R10. The displays of mobile devices and head-mounted displays differ in primaries, white point, transfer function and peak luminance, and the observer is in an uncontrolled environment. In see-through mixed reality, the displayed colour is added to the light of the physical object and of the room, so that absolute colour accuracy cannot be guaranteed and the assessment is relative; headsets that show a camera image on an opaque display do not have this additive limitation.

Protocol A, with a display characterisation, applies. Spectral colour management is not required for the XR delivery, because the XR runtime consumes display-referred RGB (question 6 of Table 4.3). The pilot depends on Pilot 2 for the colour content. The reconstructed colours defined as reflectance in Pilot 2 are rendered once, for a stated illuminant and the display white point (R6, S9), into the master texture from which the sRGB glTF delivery version is derived (R10). If the application offers several lighting scenarios, a texture per illuminant is generated upstream, or the lighting is handled in RGB and its approximation of the spectral product, which can differ for saturated pigments under strongly coloured light, is documented. The XR measures are: the colorimetric characterisation of each class of display (primaries, white point, transfer function and peak luminance, measured with a colorimeter or spectroradiometer where possible); the flagging of colours outside the sRGB gamut (R10); and the psychovisual experiment in the three viewing conditions, a controlled laboratory display, AR/VR viewing, and uncontrolled computer display viewing, with the methodology and viewing conditions following the relevant standards (ITU-R, 2023; ISO, 2009; CIE, 2011).

4.5 Pilot 4: Colour film frames of the Koshofer collection

Pilot 4 tests restoration tools on selected frames of the Koshofer collection, an archive of colour film technology from the late 19th century to the 1980s including hand-coloured and tinted films, additive and mimetic processes such as Kinemacolor and Gasparcolor, and chromogenic monopack film, whose main problem is dye fading (Grant Agreement, Part B). The tools involved are the Light

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Damage Estimator, doLCE 2.0 for lenticular film and Neg2Pos for negative film (Grant Agreement, Part B; D5.1, Table 6.1). The case study is 4a, Colour Films collection; its frames are still to be confirmed with the film experts, so the decisions below are provisional.

Film frames are transmissive, so colour is formed by dyes or silver deposits and depends on the spectrum of the viewing or projection light. Scanner responsivities can be too wide for a direct colorimetric characterisation. Berns and Shyu (1995) therefore related scanner values to dye concentrations through a spectral model of the film and calculated spectral transmittance, reaching an average CIELAB error below 1 on the media used for the characterisation and below about 2 on spectrally similar independent media. Pringle et al. (1995) proposed archiving the analytical dye densities once per film and the dye concentrations per pixel, estimated from as few as three bands, with filter bandwidths up to about 60 nm acceptable when the dye density curves are known, and a global linear transform to reverse fading; they note that their sample was small and the treatment of fading incomplete. Both studies used modern transparencies, so their transfer to historic processes is to be tested. Neg2Pos lists scanner profile, spectral capture bands, optical filtration and calibration-target integration as expected features, none yet implemented (D5.1, Table 6.1). The Light Damage Estimator is documented for reflectance of paintings, and the model of Siozos et al. (2025) was validated on two pigment systems and three light sources, so its use on film needs a transmittance input and its own validation. Frames are small, so macro-optics and control of stray light at the frame border are needed.

Spectral colour management is required for Pilot 4 (questions 1, 2 and 3 of Table 4.3). Protocol C is applied in transmission with the chain of Section 3.3. This needs a stable, spectrally continuous, diffuse backlight, the open gate as white reference, a dark frame, reference filters or density steps with measured transmittance as verification target, and low, recorded exposure because light fades dyes. Colour is computed for a stated projection or viewing illuminant and observer (S8), and point transmittance measurements give independent references. Where full spectral cubes are not feasible, a dye-density route with analytical densities known for the film type is the practical alternative, to be validated against measured transmittance (experiment E2). Because the spectralReflectance specification covers reflectance (ICC, 2021b), the transform of a film scanner is documented in a separate file stored with the scan data, together with a derived colorimetric profile, unless an iccMAX specification for transmittance is available (S10).

4.6 Summary of protocols and spectral colour management for the Internal Pilots

Table 4.4 gives the tier and the decision for each case study. Protocol A is the floor for all pilots. Spectral colour management is required where the pilot question is answered on reflectance or transmittance (1a, 1b, 1d and 4a), recommended as spectral-assisted RGB for the painting 1c and the polychrome 3D objects (2a/b,

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2c, 2d) because pigment information supports reconstruction while full-surface 3D spectral capture is not specified, and not required for the XR presentation (3a, 3b, 3c), which consumes colour managed upstream. Protocol A will be applied to the acquisitions depending on the pilot's case studies, the reference measurements of S3–S8 for Protocol B or the whole of S1–S13 for Protocol C will be added, colour for display will be rendered once at the end, and the master with its metadata will be archived. Some decisions are provisional, because details of the objects are still to be confirmed, and will be revised after the pilots are deployed (D10.1).

Table 4.4: Protocol tier and spectral colour management requirement for each case study

Case study	Object	Protocol Tier	Spectral colour management	Main reason
1a	Painting, overpainted	C on reference areas, B overall	Required	Varnish and overpaint simulation on reflectance; metameric risk
1b	Restored painting	C if before-state spectra exist, else B	Required for quantitative validation	Comparison of simulation with real restoration
1c	Painting	B	Recommended	Overpaint and pigment information
1d	Series of paintings, cleaning monitored by HSI	C	Required	Change detection on reflectance
2a/b	Polychrome wooden sculptures	B	Recommended; required for reference areas	Evidence for original colour; angular dependence
2c	Painted bas-relief	B, C where relief permits	Recommended	Near-planar surface allows hyperspectral capture of areas
2d	Reliquiary diptych	B, C on flat panels	Recommended	Painted panels plus gilded parts
3a, 3b, 3c	XR presentation of Pilot 2 objects	A with display characterisation	Not required	Colour managed upstream; glTF is sRGB
4a	Colour film frames	C in transmission (dye-density route as alternative)	Required	Dye-based colour; scanner bandwidths; fading is spectral

5. Experimental Design and validation requirements

This chapter is the output of Task 5.3 at M12: it designs the experiments, including the psychovisual experiments, with which the protocols are validated. The experiments have not yet been carried out except for E1 which is carried out for case study 1d and the results are shown in D5.1, Section 8.1 under Case study 1d. The rest require the Internal Pilot datasets, which the Grant Agreement schedules in WP10 from M12; they will be implemented and tested between M13 and M24 and reported in D10.2 (M24)

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It defines the experiments with which the protocols are validated on the Internal Pilots. They develop the validation planned in D5.1, in which stakeholders assess colour and appearance consistency, into five groups of experiments (Table 5.1) that ask whether the characterised RGB workflow is more accurate than white balance alone and within the limit set by observers, whether hyperspectral reference data improve it, whether the spectral chain is accurate, repeatable and reproducible, and whether the spectral applications (virtual cleaning, spectral references for 3D objects, transmittance scanning of films) are valid. Colour differences are reported as both ΔE_{00} and ΔE_{76}, which are not interchangeable (D5.1, Chapter 2), so limits are set for each. Where no reliable basis exists, limits are not fixed in advance but they are derived from the psychovisual experiments (Section 5.3) and from baseline measurements, and until then results are reported against 1 benchmark, an error below about three CIELAB units (ΔE_{76}) in a controlled characterisation (Molada-Tebar et al., 2019).

Table 5.1: Experiments and acceptance criteria

ID	Objective	Case studies	Metrics	Acceptance
E1	RGB characterisation of flat objects by white balance, 3×3 matrix, root-polynomial regression and ICC profile, with and without hyperspectral reference (R5, R7).	1a, 1c, 1d	ΔE_{00} and ΔE_{76} (mean, median, 95th percentile, maximum) on independent patches and painting areas.	Better than white balance alone; hyperspectral-based equal or better than chart-based; limits from the psychovisual experiments.
E2	Spectral accuracy of the calibration chain, for the reflectance of paintings and the transmittance of films.	1a, 1d, 4a	Spectral RMSD per band, ΔE_{00} and ΔE_{76} on a verification target; repeatability of repeated scans.	Baseline first; limit from the baseline expanded uncertainty.
E3	Virtual cleaning against physically cleaned areas, and repeatability across cleaning stages.	1d	ΔE_{00}, ΔE_{76} and spectral RMSD; stage-to-stage differences against expanded uncertainty.	Within the E2 and observer-based limits on at least two paintings; changes reported only above uncertainty.
E4	3D colour, tested through per-round characterisation, a multi-faceted target and spectral reference areas compared with the texture (R8, R9).	2a/b, 2c, 2d	ΔE_{00} and ΔE_{76} of visible target patches, angle-dependent error, error at reference areas.	Better than white balance alone; smaller angle-dependent error; Protocol B smaller error than A.
E5	Delivery chain and displays, from the master to glTF sRGB and from	2a/b, 3a, 3b, 3c	Master-to-delivery colour difference, out-of-gamut share, effect	Out-of-gamut colours flagged; limits from the

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	displayed to intended colour.		of embedded profiles, displayed colour of test patches, psychovisual ratings.	psychovisual experiments.

5.1 Colour accuracy experiments on flat objects e.g. paintings

The flat-object experiments use the paintings of Pilot 1 and the Case study 1d set-up, in which RGB and hyperspectral data are captured together with the same target. E1 develops each session's raw images identically and characterises the camera by four methods (white balance, linear matrix, second-order root-polynomial regression (Finlayson et al., 2015) and the ICC profile of the profiling software) and, in Protocol B or C, also from the colour computed from hyperspectral reflectance under the measured illuminant. Target patches are split into fitting and validation sets, the validation should ideally use painting areas measured with a spectrophotometer, and methods are compared on the same patches by paired differences.
E2 measures the spectral accuracy of the chain on a verification target not used for calibration (S3, S7); the spectral difference per band reveals bias in particular ranges, and its baseline sets the limits of E3. E3 repeats the validation of virtual varnish removal of Habib et al. (2026) on at least two paintings, comparing virtually and physically cleaned areas, and measures at each cleaning stage of 1d the repeatability of the sessions so that stage-to-stage differences are reported only above the expanded uncertainty of Section 5.3.

5.2 Colour accuracy experiments on 3D objects e.g. sculptures

The 3D experiments use the Eglauer sculptures, the Sethi bas-relief and the reliquary. E4 applies the per-round characterisation to all images of each round before structure-from-motion and measures the colour difference of the target patches visible in the textured model (Barbero-Álvarez et al., 2023), which quantifies the blending step. It also photographs a multi-faceted target of the same reference colours at known orientations and compares the angle-dependent error under the flat-target correction with that under a correction conditioned on the local normal and the light and view directions, propagated over the mesh or point cloud (Goesele et al., 2004; Sitnik et al., 2011; Pepe et al., 2017; Guarnera et al., 2016), and compares the colour computed from the spectra of each reference area with the texture colour under Protocol A and Protocol B.
E5 follows the delivery chain. The master is converted to the glTF sRGB version, the colour difference and the share of pixels outside the sRGB gamut are reported, and a check confirms that an embedded ICC profile does not change the displayed colour in the viewers used (Khronos Group, 2021). It also measures the displayed colour of test patches on each display class used in the pilots and forms the physical part of the psychovisual validation.

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5.3 Robustness, uncertainty, and repeatability analysis

Colour and spectral measurements always contain some doubt, so the results of the experiments in Table 5.1 are reported together with their uncertainty, following the Guide to the expression of uncertainty in measurement (JCGM, 2008). In practice this means knowing how repeatable a measurement is, how much it changes between users and instruments, and how sensitive it is to the conditions that vary in real work. This puts requirements S7 and S11 of Table 3.2 into practice, and Table 5.2 lists the minimum requirements.

To estimate the uncertainty, the verification target (a colour chart with known spectra, S3) is captured repeatedly and the spread of the results is recorded, which covers noise, lamp drift and positioning. This spread is combined with the uncertainty given in the certificates of the white reference and the target, and with an allowance for other known effects such as tilt of the reference, stray light and misregistration between hyperspectral and RGB data. The combined value is multiplied by 2 to give the expanded uncertainty, the range within which the true value is expected to lie with about 95 percent confidence (JCGM, 2008). A difference between two measurements, for example between two cleaning stages of a painting, is reported as a real change only if it is larger than this expanded uncertainty. Smaller differences are reported as not distinguishable from measurement scatter.

Table 5.2: Minimum practical requirements for uncertainty, repeatability and reproducibility

Requirement	What to do	Minimum
Uncertainty of a measurement	Capture the verification target repeatedly, combine the spread with the certificate values and known effects, and report the expanded uncertainty (coverage factor 2).	Every spectral result in Protocol C and every comparison between states.
Repeatability	One operator, instrument and set-up, with the reference repositioned between captures, over more than one day.	At least ten captures of the verification target.
Reproducibility	The same target and procedure with a second operator and, where possible, a second instrument or institution.	At least two operators; a circulated target for checks between institutions.
Robustness	Change one condition at a time (exposure, colour temperature of the source, lamp warm-up, reference tilt, mixed light) and record the effect on colour difference and spectral error.	The conditions that differ most between the pilots.
Reporting rule	Report a difference as real only if it is larger than the expanded uncertainty, and state ΔE_{00} and ΔE_{76} with illuminant and observer.	All comparisons between states, cleaning stages and methods.

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Acceptance limit	Derive the limit from the psychovisual ratings of stakeholders under the three viewing conditions.	Before the final acceptance thresholds are set.

Repeatability is checked by one operator capturing the verification target at least ten times, repositioning the reference each time and spreading the captures over at least two days. Reproducibility is checked by a second operator, and where possible a second instrument or institution, capturing the same target with the same procedure. The partners can circulate one verification target and one white reference for this, as in the round-robin tests of hyperspectral systems (George et al., 2017; Pillay et al., 2020). Robustness is checked by changing one condition at a time that varies in practice, for example the exposure by one stop, the colour temperature of the source, the warm-up time of the lamp, the tilt of the reference or the presence of mixed light and noting how much the colour difference and the spectral error change. The results show where tolerances must be specified and which requirements of Chapter 3 need particular care.
The psychovisual experiments set the limit that links a numerical error to what stakeholders accept. Restorers, conservators and curators of the Internal Pilots, with screened colour vision, compare the original with the reproduction in the three viewing conditions of Task 5.3: a controlled laboratory display with standard illumination, A VR/AR viewing and an uncontrolled computer display, following the standards for subjective assessment and for colour differences in images (ITU-R, 2023; CIE, 2011) and the viewing conditions of ISO (2009) for the controlled condition. The share of reproductions rated acceptable in each condition is reported with confidence intervals, and its relation to ΔE_{00} and ΔE_{76} sets the limits used in Table 5.1.

6. Cloud Implementation, interoperability, and data management

The COLOURS tools, including those that produce or consume colour-managed data, will be made available to users through the European Collaborative Cloud for Cultural Heritage (ECCCH), which is being built by the sister project ECHOES. This chapter gives a high-level summary of how COLOURS integrates with ECCCH. The interoperability requirements are specified in COLOURS D7.1 "Interoperability Requirements Analysis". The integration and testing methodology is specified in COLOURS D7.2 "Integration and Test Plan".

6.1 COLOURS as a Vertical Application

All COLOURS tools and services are deployed together as a single Vertical Application (VA) in the ECCCH Application Layer. The core of the VA is the COLOURS Platform, which evolves from the PERCEIVE Platform. It provides a unified web front-end, a common Platform API for data transfer and storage, and

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a worker-based execution environment where processing tools run as orchestrated jobs. Tools with their own web interface, such as the ATON-based Collaborative Simulation Environment, use the same authentication and data services. Individual tools have no direct interface with ECCCH. They exchange data, metadata and paradata through the Colour Knowledge Repository (CKR), via the Platform API.

6.2 Integration with ECCCH

Only two paths cross the boundary between the COLOURS VA and ECCCH:

- **Authentication and authorisation.** Users log in through the ECHOES Authentication and Authorisation Infrastructure (AAI), which the COLOURS Platform uses as its upstream identity provider. Identity and entitlements are managed centrally by the AAI, and the COLOURS roles and permissions are derived from them. COLOURS does not keep a separate user directory.
- **Semantic publication.** Curated, public CKR records are mapped to the Heritage Digital Twin Ontology (HDTO). They are published into the ECCCH Knowledge Base through the Knowledge Base Management System (KBMS) APIs.

Everything else is internal to the VA and is not exposed to ECCCH, including the message bus, the workers and the internal storage. These paths are registered with the ECHOES Integration Task Force as three Integration Units: COLOURS Platform × AAI, CKR × Knowledge Base and CKR × HDTO. All three target Level 2 (Strategic) integration and follow the ECHOES six-step integration process in successive integration cycles (see D7.1).

The ECHOES documentation reviewed in October 2026 refers to IIIF for image access and lists glTF among the formats for 3D models (Kowalska et al., 2026), and its engineering handbook asks providers to keep the colour profile and colour space as technical metadata and to record colour conversions (ECHOES, 2026). None of these documents, including Kowalska & Pawlikowski, 2026; Cignoni et al., 2026; Andújar et al., 2026, specifies colour-managed delivery or display: colour on ECCCH currently relies on device and browser defaults. The requirements below address this for the COLOURS Vertical Application; those concerning ECCCH itself will be submitted to the ECHOES Integration Task Force.

6.3 Data management

The CKR is the central repository of the VA and its interoperability node towards ECCCH. Tool outputs, together with their metadata and paradata, are stored in the CKR through the Platform API. Recording provenance and paradata ensures that any result, including colour-managed data, can be traced back to its input data and to the processing and settings that produced it. The CKR keeps its own editorial lifecycle, with drafts, curator review and optional embargo. Drafts are never synchronised with ECCCH. Only published, public records describing physical

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objects become Heritage Digital Twins in the ECCCH Knowledge Base. Related records, such as analytical data, simulation results and the colour-management protocols of this deliverable, enrich the digital twin of the object they refer to. Large datasets remain on COLOURS storage and are referenced from the published records through stable public URLs.

6.4 Implementation, testing and deployment

The integration is carried out in three stages:

- **WP8 (M13–M24):** semantic adaptationo f the COLOURS HDTs (T8.1); AAI integration; and adaptation of the Platform API. This work is planned in D8.1 "Deployment Plan".The mapping of CKR records onto the HDTO, including the colour-management metadata defined in this deliverable, is implemented under Task 3.4 and documented in D3.3 (M18), as set out in D7.1.
- **Testing:** integration tests follow the plan in D7.2.
- **WP9 (M25–M33):** deployment and validation of the VA in ECCCH (D9.1 "Cloud Deployment").

ECCCH is still under active development, so the integration approach will be reviewed at each ECHOES integration cycle.

6.5 Colour management requirements for data in the cloud

For colour-managed data to open correctly wherever they are accessed, the cloud must hold, for every acquisition, a complete colour data package and keep it intact. The package contains the unaltered raw files and the raw-development settings used (R3 of D5.1); the characterised 16-bit master image or EXR texture, with an embedded ICC profile or a stated colour encoding and transfer function; the delivery derivatives (sRGB, 8 bit) with the documented transform that produced them (R10); the ICC input profile or characterisation model, the target reference values and the accuracy report (R4, R5); the reference captures needed to repeat the derivation, that is white board, dark frame and colour target images; and the metadata and paradata of R11 and S12, namely illuminant, geometry, camera or instrument, settings, software versions and processing log. For Protocols B and C the package also holds the calibrated reflectance (or transmittance) cube in an open, documented format with its wavelength list, the white and dark reference data, the verification results, the illuminant spectrum and, if produced, the iccMAX profile (S10). Luminescence layers (UVL, VIL) are stored as separate layers, and every file carries a role (raw, master, derivative, reference, spectral, profile) and a flag that states whether the data are scene-referred or output-referred and whether any spectra are estimated and not measured (Section 2.4). A short manifest, stored as a CKR record, lists the files of the package, their roles, versions and checksums, so that the files are retrieved and interpreted together. At present the CKR has no field dedicated to ICC profiles,

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colour space or acquisition targets (Table 6.1 of D5.1), so these fields must be added in the CKR mapping planned in WP8 (Section 6.4). This is also needed because most practitioners do not retain the metadata and paradata that make imagery usable in the long term (Deborah et al., 2026).

The platform must then preserve and correctly pass on what it receives. Masters, raw files and profiles are stored without re-encoding, bit-depth reduction or removal of embedded profiles or metadata and are protected by checksums. Derivatives, such as thumbnails, web images and glTF textures, are generated by a documented and versioned colour-managed conversion, tagged with their colour space, and linked to their master. Untagged images are treated as sRGB by browsers, so every image served carries an explicit tag, and glTF textures are delivered as sRGB with the master kept separately because glTF viewers ignore embedded ICC profiles (Khronos Group, 2021; ICC, 2022). The tools use the same information. VarnishLab and the Light Damage Estimator require both RGB and reflectance packages, including the white and dark references and wavelengths, and refuse or warn if these are missing. They store rendered sRGB results with a flag that marks them as visualisation only (R6). ATON and MuLaX read the sRGB derivatives and show luminescence layers separately. Each tool validates the colour metadata on ingestion and reports what is missing. Data without colour management information, such as legacy images or uploads from external users, are accepted but marked as colour status unknown, are shown under the sRGB assumption, and are not used for any colour accuracy claim.

The platform does not control the display of the user and does not know whether it is calibrated. What it can guarantee is that the data are correctly described and unambiguous, so that a colour-managed browser converts the tagged image to the profile of the display of the user, normally the profile that the operating system provides, and that any remaining difference is due to the display and not to the data. For quantitative work the platform therefore reports values computed from the data, such as CIELAB values, ΔE_{00} and reflectance spectra, which do not depend on the screen, and states the illuminant and observer used. For visual work it shows the colour status of the data and recommends calibrated display and controlled viewing for colour-critical tasks. The uncontrolled computer display is one of the three viewing conditions to be evaluated, so the effect of an uncalibrated display on the acceptance of colour is measured instead of assumed.

This deliverable provides the specification and the procedures to be followed for colour management based on case studies and tools how the protocols are validated. The prototype that implements these protocols in the COLOURS Vertical Application on ECCCH is not part of this deliverable. It will be delivered in Task 6.1 and reported in D6.1. There are two reasons. First, the acceptance limits and the choice between the options within the protocols, such as the characterisation method, depend on the experiments E1–E5 of Chapter 5, which use the Internal Pilot datasets scheduled in WP10 from M12 and are reported in D10.2 (M24). Second, ECCCH is under active development, and the integration is carried out in

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the WP8 and WP9 cycles (Section 6.4). The main elements of the protocols have, however, already been tested in prototype form on case study 1d. Experiment E1 was carried out with a code implementation that characterises the RGB camera and colour-manages the RGB image with hyperspectral reflectance of the colour chart as the reference, with the results reported in Section 8.1 of D5.1, and the VarnishLab prototype, which performs virtual varnish removal on hyperspectral reflectance, has been tested on the hyperspectral data of the same case study (Habib et al., 2026). These implementations are the starting point for the work in Tasks 6.1 and 6.3.

7. Conclusions and future work

This deliverable specifies spectral-based colour management protocols as an additional, physically meaningful way of managing colour that extends the protocols of D5.1. Tristimulus colour management remains the baseline (Protocol A), but it records colour for one illuminant and observer, cannot predict metamerism and cannot support illuminant-independent comparison, which paint, varnish and dye studies need. Spectral colour management treats calibrated reflectance (or transmittance) as the primary record and derives colour from it for a stated illuminant and observer. It costs time, equipment, light exposure and skills, so it is added where a pilot's question depends on it, and cheaper options (reference spectra with RGB, modified consumer cameras, estimated spectra labelled as estimates) are specified with their limits. Requirements S1–S13 rank what *must* and *should* be done, and Table 4.2 gives the minimum kit and steps per protocol tier.

Spectral colour management is required for the paintings where varnish and overpaint removal are simulated or cleaning is monitored (1a, 1b with the condition on before-state spectra, 1d) and for the colour films (4a); recommended as spectral-assisted RGB for the painting 1c and the polychrome 3D objects (2a/b, 2c, 2d); and not required for the XR presentation (3a, 3b, 3c) provided that the colour it receives is managed upstream. Full-surface spectral capture of 3D objects is not specified because reflectance on non-planar or glossy surfaces depends on the lighting and viewing geometry.

The protocols rest on one painting, one statuary collection and the literature, and the experiments of Chapter 5 have not all been carried out except for E1 that has been tested on case study 1d discussed in D5.1 Section 8.1. The numerical limits depend on the psychovisual experiments and the baselines of E2. Support for iccMAX in the colour management modules and software of the project has not been verified, the Light Damage Estimator and Neg2Pos have to be adapted and validated for transmittance, the transfer of the film studies to historic processes is untested. Future work will carry out the experiments, set the limits and revise S1–S13, define the data and metadata the tools need, test iccMAX where tools allow, and address geometry-aware calibration of hyperspectral data on 3D surfaces, and an iccMAX use case for transmittance.

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