



European Laser Research Infrastructures serving Science and Industry

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WP 4

Cross-Facility Services

D4.3 - Standardized performance assessment

**Commonly agreed shared protocols for performance assessment,
routine quality check and automated acquisition in at least 3 different
research fields**

Lead Beneficiary: Politecnico di Milano (POLIMI)

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Table of Contents

About Lasers4EU	1
1 Introduction and objectives.....	2
2 Diffuse Correlation Spectroscopy	4
2.1 – Scope.....	4
2.2 Methodology	5
2.3 Definitions	7
2.4 Protocol	7
2.4.1 Accuracy	7
2.4.2 Linearity	8
2.4.3 Precision	9
3 Transient Absorption Spectroscopy	12
3.1 Scope	13
3.2 Methodology	13
3.3 Definitions and reporting conventions.....	13
3.4 Protocol	14
3.4.1 Performance properties	14
3.4.2 General measurement procedure	14
3.4.3 Minimum reporting requirements.....	15
3.4.4 Reference compound selection	16
3.4.5 Literature benchmark conditions	16
3.5 Reference compound implementations.....	17
3.5.1 ZnTPP Zinc tetraphenylporphyrin.....	17
3.5.2 DCM 4 dicyanomethylene 2 methyl 6 p dimethylaminostyryl 4H pyran...	18
3.5.3 IR 125.....	18
3.5.4 Cresyl violet	19
3.6 Interpretation of results	19
3.7 Implementation status and next steps.....	19
4 Characterisation of Ultrafast Pulses	20

4.1 Composition of the Working Group	20
4.2 Pulse characterisation methods	21
4.2.1 Survey of methods	21
4.2.2 Methods used by the Working Group	23
4.3 Assessment of ultrashort pulse measurement.....	24
4.3.1 Assessment of electro-optical methods.....	24
4.3.2 Assessment of optical autocorrelations.....	25
<i>Fourier relationship</i>	25
<i>Autocorrelation deconvolution</i>	26
<i>Preparation of the instrument</i>	26
<i>How far from FTL?</i>	27
<i>Assessment of the autocorrelation by adding dispersion</i>	28
4.3.3 Assessment of third-order cross-correlators with high dynamic range/ laser pulse contrast.....	32
4.3.4 Definition of the temporal intensity contrast.....	33
4.3.5 Assessment of real and ghost pulses	34
<i>Conclusion</i>	36
4.3.6 Assessment of spectro-temporal field reconstruction	36
4.4 Conclusion: how and when to assess pulse measurements	38
5 Conclusion	41

List of figures

Figure 1 - Agenda of the Workshop on Performance Assessment and Standardization	3
Figure 2 - Principles of DCS and SCOS and the corresponding blood-flow-related measurands.....	5
Figure 3 - Example of a liquid-phantom implementation in which the effective diffusion coefficient is varied by changing viscosity or glycerol concentration. The implementation is illustrative; the protocol is defined by the FOMs above.....	8
Figure 4 - Examples of linearity plots using temperature or pumps to change the measured effective flow	9
Figure 5 - Example of a liquid-phantom implementation in which the effective diffusion coefficient is	

varied by changing viscosity or glycerol concentration. The implementation is illustrative; the protocol is defined by the FOMs above.....	10
Figure 6 - Reproducibility over probe repositioning. Need for a non-degradable phantom stable over days/ months/ years.....	11
Figure 7 - Chemical structure of zinc tetraphenylporphyrin ZnTPP	17
Figure 8 - Chemical structure of DCM	18
Figure 9 - Chemical structure of IR 125.....	18
Figure 10 - Chemical structure of cresyl violet.....	19
Figure 11 - Survey of optical pulse characterisation methods.....	21
Figure 12 - Survey of optical pulse characterisation methods used by the Working Group.....	24
Figure 13 - Key relationships for ultrafast pulses (a) Fourier relationship (b) deconvolution of autocorrelation (c) deconvolution factors assuming a pulse shape.....	25
Figure 14 - Example of checklist before assessment of a measurement by autocorrelators	26
Figure 15 - Example of three different methods to estimate the difference between the real pulse and the FTL	28
Figure 16 - Final pulse duration stretched by the insertion of a fused silica plate of different thicknesses at 800 nm as a function of the initial pulse duration; e is expressed in mm in the inset formula at 800 nm	29
Figure 17 - Assessment of the autocorrelation measurement by added material dispersion.....	29
Figure 18 - Thickness of fused silica required at 800 nm to observe a significant relative variation of the initial pulse duration after propagation.....	30
Figure 19 - Example of the pulse duration changes as a function of the compressor stage displacement around the optimal position	31
Figure 20 - Assessment of the autocorrelation measurement by added compressor dispersion.....	31
Figure 21 -Temporal intensity contrast of the JETi40 laser system.....	33
Figure 22 - Generation of artificial post-pulses using a 2 mm thick BK7 plate.....	34
Figure 23 - Influence of the B-integral in the amplifier chain on the generation of real pre-pulses from post-pulses	35
Figure 24 - Assessment of short pulse duration measurement: How?	39
Figure 25 - Assessment of short pulse duration: When?	40

List of tables

Table 1 - Members and activity of the 3 subgroups (coordinators in bold)	2
Table 2 - Core quantities used for system-level DCS/SCOS performance assessment.....	7
Table 3 - Summary of the proposed system-level DCS/SCOS performance-assessment protocol...	11
Table 4 - Laser facility profiles of the Working Group	21
Table 5 - Assessment of photodiode-based optical pulse measurements.....	25

Disclaimer

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About Lasers4EU

Lasers4EU incorporates the major laser research infrastructures, in a large number of European member states, into a comprehensive virtual distributed laser research infrastructure that offers to a broad user community, from academia and industry, access to an exceptional portfolio of technical and scientific capabilities. This unique set of instruments together with the specific scientific expertise at the host facilities allows Lasers4EU users to carry out high-level research in an extremely wide range of high-impact topics in life sciences, materials nano-processing, etc.

Laser technology has experienced remarkable advances and breakthroughs in the last 60 years and is now a key innovation driver for highly diversified societal applications and products, thereby substantially contributing to economic growth and to solving challenges in the areas of health, environment and energy. Through its strategic approach, Lasers4EU aims to strengthen Europe's leading position and competitiveness. It facilitates long-term coordination of the laser research activities within the European Research Area and provides concerted and efficient services to scientific, industrial and medical researchers. The main objectives of Lasers4EU are to:

- provide coordinated access to high-quality services based on a coherent and comprehensive consortium of 27 leading European laser installations offering to users from academia and from industry cutting-edge performances at the forefront of the laser technologies,
- structure the European landscape of laser Research Infrastructure through enhanced access, extended geographical coverage, novel science diplomacy activities, improved synergies with other European networks and projects,
- increase European human resources in the field of laser science by implementing training activities towards researchers from new domains of science and technology and from geographical regions where laser communities are still less developed.

1 Introduction and objectives

The objective of Task 4.4 is to enhance the quality of services provided to users by developing guidelines and good practices for assessing instrument performance and operation. During the initial phase, a workshop and survey mapped existing procedures for performance assessment, routine quality checks and automated data acquisition across Lasers4EU facilities. The analysis, considering differences in facility size and scientific field, supported the identification of common features and the selection of three homogeneous subgroups to develop joint protocols/guidelines: (1) Diffuse Correlation Spectroscopy; (2) Transient Absorption Spectroscopy; and (3) Characterisation of Ultrashort Pulses.

The three subgroups worked through a series of online meetings to define their scope, exchange experience and develop joint approaches to performance assessment.

Table 1 - Members and activity of the 3 subgroups (coordinators in bold)

Subgroup	Participants	Institutions	Meetings
Diffuse Correlation Spectroscopy	Lorenzo Cortese, Antonio Pifferi, Aboma Merdasa	ICFO, Politecnico di Milano (CUSBO), Lund Laser Centre	26/02/2026 23/03/2026 22/05/2026
Transient Absorption Spectroscopy	Andrea Lapini, Fàbio Schaberle, Mattia Russo, Antonio Pifferi	LENS, Politecnico di Milano (CUSBO), University of Coimbra (CLL)	25/02/2026 06/03/2026 25/03/2026 01/04/2026 24/04/2026
Characterisation of Ultrashort Pulses	Alexander Sävert, Stéphane Petit, Alexandra Bran, Andrea Lapini, Antonio Pifferi, David Garzella, Felix Ritzkowsky, Lenard Vamos, Michal Cervenak, Mihai Muresan, Raphaël Clady, Rytis Butkus	Helmholtz-Institute Jena, CELIA, INFLPR (CETAL), LENS, Politecnico di Milano (CUSBO), CEA, DESY, ICFO, PALS, HiLASE Centre, LP3, VULRC	17/02/2026 01/04/2026 28/04/2026 25/06/2026

The results of this work were presented and discussed at a dedicated Workshop on Performance Assessment and Standardisation, held in Prague on 26 May 2026 during a four-day Lasers4EU and Laserlab-Europe event. The workshop brought together participants from different scientific fields and professional roles, providing additional input to the approaches developed by the subgroups.

Workshop on “Standardised performance assessment in Lasers4EU”

26 May 2026

HiLASE Centre & ELI-Beamlines

Dolní Břežany, Czechia

<https://elibeams.webex.com/elibeams/j.php?MTID=m073919bf494e209d396f44e1b0599330>

Agenda

14:30 – 14:40: Introduction; aim of the task and of the workshop

14:40 – 15:10: Cluster 1 – **Standardised performance assessment for Diffuse Correlation**

Spectroscopy, Lorenzo Cortese (ICFO)

15:10 – 15:40: Cluster 2 - **Standardised performance assessment for Transient**

Absorption, Andrea Lapini (LENS)

15:40 – 16:10: Cluster 3 - **Standardised performance assessment for Characterisation of**

Ultrashort Pulses, Alexander Sävert (HI Jena) & Stéphane Petit (CELIA)

16:10 – 16:30: General discussion and next actions, Antonio Pifferi (CUSBO)

Figure 1 - Agenda of the Workshop on Performance Assessment and Standardization

Following the workshop, the subgroups finalised the proposed protocols, which are presented in the following sections.

Future activities may focus on: (1) testing the protocols through joint experiments and assessing their possible application in user access; (2) extending participation beyond the Lasers4EU consortium; and (3) disseminating the results through publications, tutorials or other open-access materials.

The three protocols differ in structure and level of detail, reflecting the specific technical requirements and practices of the respective subfields.

2 Diffuse Correlation Spectroscopy

2.1 – Scope

Diffuse Correlation Spectroscopy (DCS) is a laser-speckle technique for non-invasive assessment of microvascular blood-flow dynamics in highly scattering media such as biological tissue. Coherent light propagating through tissue undergoes multiple scattering and produces a speckle pattern whose temporal evolution depends on the motion of the scatterers. In tissue, the dominant dynamic contribution is associated with moving red blood cells; faster motion therefore produces faster speckle fluctuations and faster decorrelation of the detected signal.¹

In conventional DCS, these fluctuations are detected with single-photon-sensitive detectors and analysed through the normalised intensity autocorrelation function

$$g_2(\rho, \tau) = \frac{\langle I(\rho, t)I(\rho, t + \tau) \rangle}{\langle I(\rho, t) \rangle^2},$$

where ρ is the source-detector separation and τ is the correlation delay time. The decay of g_2 is related to the temporal field autocorrelation and, through an appropriate light-transport model, to an effective dynamic parameter conventionally reported as the Brownian diffusion coefficient D_B or as a Blood Flow Index BFI. These quantities provide the system-level measurand considered in the present protocol.

A closely related approach is Speckle Contrast Optical Spectroscopy (SCOS), where a CMOS camera records spatial speckle patterns. The primary observable is the speckle contrast,

$$K^2 = \frac{\sigma_I^2}{\langle I \rangle^2},$$

which decreases when the speckle pattern changes more rapidly during the camera exposure. After suitable modelling and detector-noise correction, SCOS can also provide a blood-flow-related quantity comparable to DCS.²

¹ L. Cortese *et al.*, “Recipes for diffuse correlation spectroscopy instrument design using commonly utilized hardware based on targets for signal-to-noise ratio and precision,” *Biomedical Optics Express* 12, 3265 (2021)

² C.P. Valdes *et al.*, “Speckle contrast optical spectroscopy, a non-invasive, diffuse optical method for measuring microvascular blood flow in tissue,” *Biomedical Optics Express* 5, 2769 (2014)

DCS & SCOS

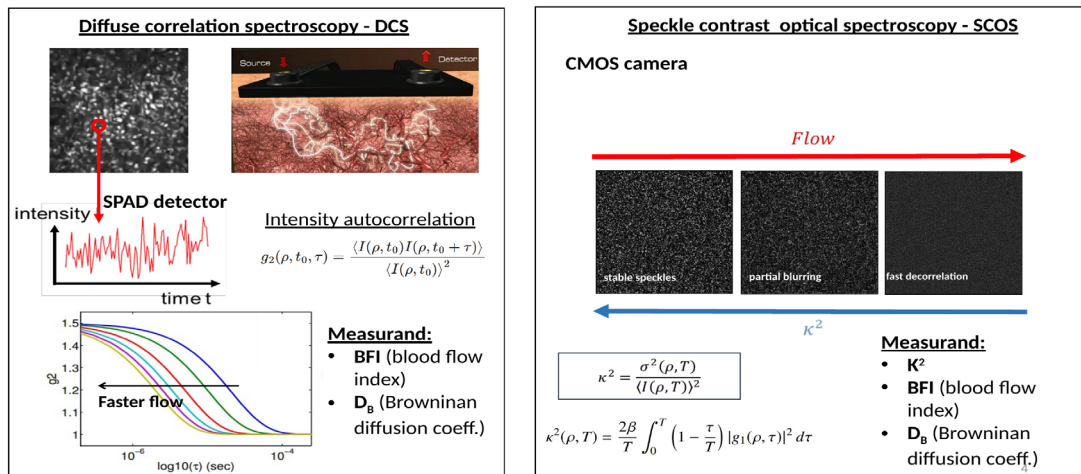


Figure 2 - Principles of DCS and SCOS and the corresponding blood-flow-related measurands

The proposed framework is designed for the primary laser-speckle technologies used or emerging for tissue blood-flow monitoring. This includes conventional DCS and SCOS as well as time-domain and interferometric variants where the same type of output measurand is available. The immediate focus is on complete instruments rather than individual components.

DCS has been applied for more than two decades across a broad range of biomedical applications, including adult and neonatal cerebral monitoring, intensive care, functional brain measurements, exercise and muscle physiology, cancer monitoring and preclinical research. While the diversity of instruments and implementations has increased substantially, commonly agreed multi-laboratory procedures for assessing device performance are still limited. The objective of this section is therefore to define a shared, system-level framework for comparing instruments in terms of their ability to measure and detect blood-flow-related changes under controlled conditions.

2.2 Methodology

The methodology follows the general performance-assessment philosophy established in diffuse optics, in particular by the MEDPHOT protocol³ and subsequent multi-laboratory initiatives such as the BitMap exercise⁴ [Lanka 2022]. The central principle is to assess the complete device as a measurement system and to describe its performance through figures of merit that are as close as possible to the quantity relevant for the intended application.

Accordingly, the instrument is treated as a black box. The primary objective is not to characterise

³ A. Pifferi *et al.*, "Performance assessment of photon migration instruments: the MEDPHOT protocol," *Applied Optics* 44, 2104 (2005)

⁴ P. Lanka *et al.*, "Multi-laboratory performance assessment of diffuse optics instruments: the BitMap exercise," *J. Biomedical Optics* 27, 074716 (2022)

the laser, detector, correlator or camera separately, but to assess the performance of the complete system in its intended operating configuration. Whenever possible, testing should therefore use the instrument’s own probe, acquisition settings and analysis chain. Component-level testing remains valuable for system development but is outside the primary scope of the present protocol.

A second methodological principle is the distinction between the protocol and its implementation. The protocol defines the property to be assessed, the measurand and the corresponding figure of merit. These elements should remain stable and technology-independent. The implementation defines how the test is performed in practice, including the phantom, test bench, acquisition sequence and controlled variables. Different implementations may therefore be acceptable if they quantify the same performance property in a reproducible way.

At the present stage, phantom-based measurements are considered the most suitable approach for harmonisation. Phantoms should reproduce the relevant optical and dynamic properties of tissue and, where possible, allow independent variation of absorption coefficient μ_a , reduced scattering coefficient μ_s' and dynamic parameter D_B . Liquid phantoms are particularly useful because their dynamic properties can be adjusted in a controlled manner. For suspended spherical scatterers undergoing Brownian motion, a useful reference relation is the Stokes-Einstein equation,

$$D_B^{\text{ref}} = \frac{k_B T}{6\pi\eta r},$$

where T is absolute temperature, η is the dynamic viscosity and r is the scatterer radius. This relation supports implementations in which D_B is varied through temperature or viscosity. Other approaches may use controlled flow, mechanical modulation or electronically generated decorrelation.⁵

For meaningful comparison across facilities, the test report should include the acquisition parameters that can affect the result, including wavelength, source-detector separation, integration time or exposure time, photon count rate or camera signal level, phantom optical properties, environmental temperature and the main analysis settings. The longer-term objective is to converge towards reproducible or transferable phantoms, shared test procedures and multi-laboratory comparison exercises. In-vivo validation and industrial standardisation can follow once the device-level protocol and its implementations have reached sufficient maturity.

⁵ L. Cortese *et al.*, “Liquid phantoms for near-infrared and diffuse correlation spectroscopies with tunable optical and dynamic properties,” *Biomedical Optics Express* 9, 2068 (2018)

2.3 Definitions

For the purposes of this protocol, the following quantities are defined.

Table 2 - Core quantities used for system-level DCS/SCOS performance assessment

Quantity	Symbol	Definition / role in the protocol
Intensity autocorrelation	$g_2(\rho, \tau)$	Normalised temporal intensity defined in previous section; primary DCS observable
Coherence factor	β	Instrument-dependent factor relating intensity and field correlation through the Siegert relation, $g_2 = 1 + \beta g_1 ^2$
Brownian diffusion coefficient	D_B	Effective dynamic parameter derived from the correlation decay. In the standard Brownian model, $\langle \Delta r^2(\tau) \rangle = 6D_B \tau$
Blood Flow Index	BFI	Blood-flow-related output of the instrument. In many DCS models, $BFI = \alpha D_B$ where α is the fraction of dynamically scattering events
Speckle contrast	K	SCOS observable defined in previous section, decreases with increasing speckle decorrelation rate
Figure of merit	FOM	Numerical quantity summarizing the outcome of one performance test

The preferred measurand for the protocol is the final blood-flow-related quantity reported by the system, i.e., BFI or D_B . This ensures that the assessment remains relevant to the intended application while avoiding dependence on a specific detector technology or signal-processing architecture. Where an instrument reports a different but directly related quantity, the corresponding relationship or conversion should be documented.^{1,2}

For the definitions below, let x denote the reported blood-flow measurand, with $x = \text{BFI}$ or $x = D_B$, and let $\bar{x}$ and σ_x denote the sample mean and standard deviation obtained from repeated measurements under the stated test conditions.

2.4 Protocol

The initial protocol comprises five core performance properties: **accuracy**, **linearity**, **precision**, **stability** and **reproducibility**. Temporal resolution is included as an additional derived characteristic. The mathematical definition of each FOM is fixed by the protocol, whereas the specific phantom and procedure are part of the implementation.

2.4.1 Accuracy

Accuracy quantifies the agreement between the measured value and a known reference value. For

a reference x_{ref} , absolute and relative errors are defined as

$$\varepsilon_{\text{abs}} = \bar{x} - x_{\text{ref}}, \quad \varepsilon_{\text{rel}} = \frac{\bar{x} - x_{\text{ref}}}{x_{\text{ref}}}.$$

Absolute accuracy therefore requires a calibrated or otherwise well-characterised dynamic reference. This remains one of the main open issues for DCS/SCOS standardisation. The preferred long-term solution is a stable and reproducible phantom whose dynamic properties can be assigned with sufficiently low uncertainty. Until such a reference is available, the protocol should distinguish clearly between absolute accuracy and the ability to follow controlled relative changes (i.e., “trend accuracy” - see section 2.4.2).

When accuracy is measured, the uncertainty of the reference value and the relevant operating conditions shall be reported. Since estimator bias can depend on signal level and correlation decay rate, measurements should preferably cover representative count rates, exposure conditions and optical properties.

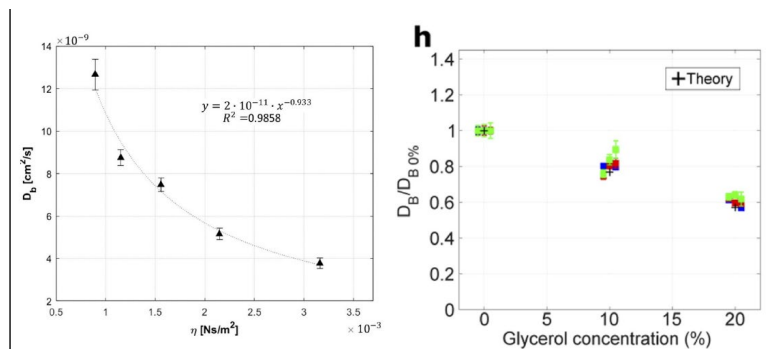


Figure 3 - Example of a liquid-phantom implementation in which the effective diffusion coefficient is varied by changing viscosity or glycerol concentration.^{5, 6} The implementation is illustrative; the protocol is defined by the FOMs above

2.4.2 Linearity

Linearity, also referred to as trend accuracy, evaluates whether controlled changes in the phantom dynamics are correctly reproduced by the measured x . For a series of reference states, a linear model may be fitted as

$$\bar{x} = a + b x_{\text{ref}},$$

with the slope b , intercept a and coefficient of determination R^2 reported as FOMs. An ideal response gives $b = 1$, $a = 0$ and $R^2 = 1$.

This test can be implemented without requiring a fully traceable absolute reference for every

⁶ C. Amendola *et al.*, “A Compact Multi-Distance DCS and Time Domain NIRS Hybrid System for Hemodynamic and Metabolic Measurements”, *Sensors* 21, 870 (2021)

measurement point, provided that the sequence of dynamic states is known and reproducible. Suitable implementations include variation of liquid-phantom viscosity, controlled temperature changes, or forced motion. The use of glycerol-water mixtures is a practical example for changing viscosity and therefore the expected D_B .

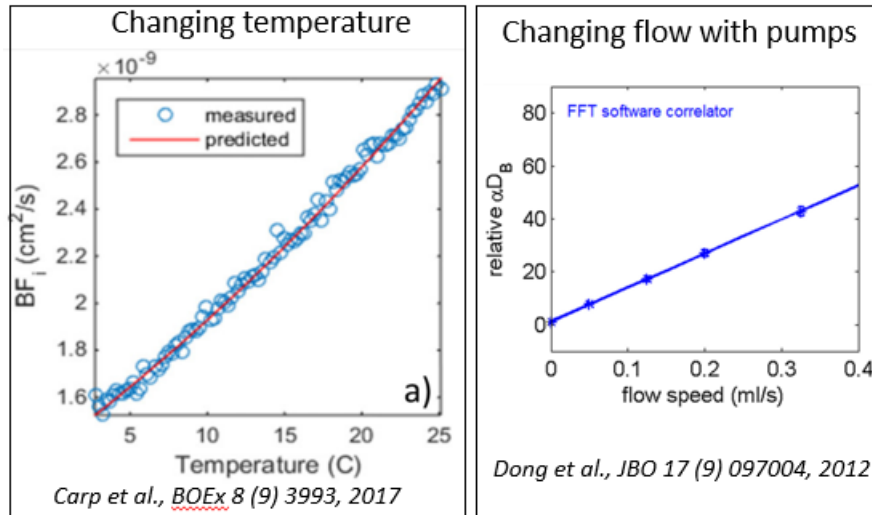


Figure 4 - Examples of linearity plots using temperature or pumps to change the measured effective flow⁷

2.4.3 Precision

Precision describes the dispersion of repeated measurements performed under nominally unchanged conditions. The recommended FOM is the coefficient of variation

$$CV_x = \frac{\varepsilon_x}{\bar{x}}.$$

Precision should be evaluated for acquisition conditions representative of the intended use. In particular, CV_x can depend strongly on photon count rate or camera signal level, integration time, absorption, scattering and the characteristic decorrelation rate. For this reason, the test report should always specify these parameters. When relevant, precision should be measured as a function of integration time and signal level rather than quoted as a single instrument-independent number.

2.4.4 Stability

Stability describes the ability of the complete system to maintain a constant result while measuring an unchanged sample over time. For a time series $x(t)$, the relative deviation from the mean may

⁷ S. Carp *et al.*, “Combined multi-distance frequency domain and diffuse correlation spectroscopy system with simultaneous data acquisition and real-time analysis”, Biomedical Optics Express 8, 3993 (2017); J. Dong *et al.*, “Diffuse correlation spectroscopy with a fast Fourier transform-based software autocorrelator” J. Biomedical Optics 17, 097004 (2012)

be expressed as

$$\delta_x(t) = \frac{x(t) - \bar{x}}{\bar{x}}.$$

The FOM may be reported as the maximum absolute deviation $\max_t |\delta_x(t)|$, together with the duration of the test, or as a normalized drift rate obtained from a linear fit versus time. A stable phantom and controlled environmental conditions are required so that changes of the test object do not dominate the measured drift. Temperature should be monitored whenever liquid phantoms are used.

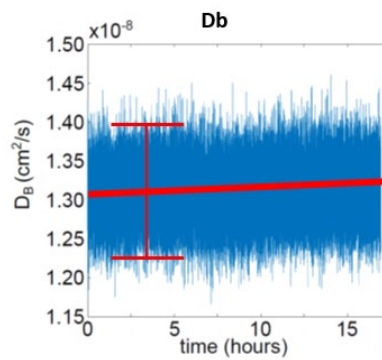


Figure 5 - Example of a liquid-phantom implementation in which the effective diffusion coefficient is varied by changing viscosity or glycerol concentration. The implementation is illustrative; the protocol is defined by the FOMs above

2.4.5 Reproducibility

Reproducibility assesses agreement between independent measurement sessions. Relevant changes between sessions may include probe removal and repositioning, instrument restart, operator change, or repetition on different days. If $\bar{x}_j$ is the mean value obtained in session j , a suitable FOM is

$$CV_{\text{sess}} = \frac{\sigma(\bar{x}_j)}{\bar{x}_j}.$$

The protocol should state which factors were changed between sessions. Long-term reproducibility tests require a sufficiently stable, preferably non-degradable, reference phantom. For clinical configurations, probe repositioning is particularly relevant because it reflects a routine source of variability in repeated measurements.

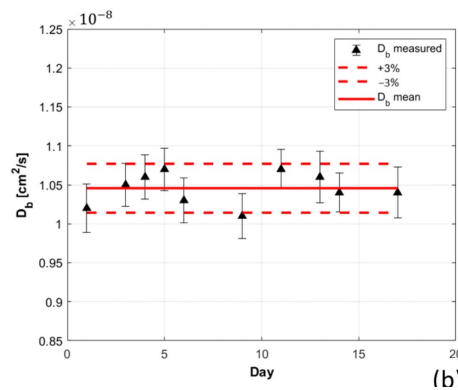


Figure 6 - Reproducibility over probe repositioning. Need for a non-degradable phantom stable over days/ months/ years

2.4.6 Temporal resolution and future extensions

Temporal resolution should be defined at the level of the measurable blood-flow change rather than solely from the detector or correlator settings. A practical definition is the minimum integration time $T_{\min}$ required to achieve a predefined precision threshold $CV_{\max}$:

$$T_{\min} = \min\{T: CV_x(T) \leq CV_{\max}\}.$$

This definition links temporal resolution directly to the ability of the complete instrument to resolve a change in BFI or D_B .

Spatial sensitivity, including depth and lateral response, is considered a later extension because it requires inhomogeneous or layered phantoms and a more specific definition of the target measurand. In-vivo tests, such as arterial cuff, probe-pressure or head-of-bed protocols, are likewise outside the present core protocol because they introduce additional physiological, ethical and biostatistical variability. Component-level testing may also be developed separately for source, detection and processing subsystems.

Table 3 - Summary of the proposed system-level DCS/SCOS performance-assessment protocol

Test	Recommended FOM	Indicative implementation / reporting
Accuracy	$\varepsilon_{\text{abs}}, \varepsilon_{\text{rel}}$	Calibrated reference phantom; report reference uncertainty and acquisition conditions
Linearity	a, b, R^2 from $\bar{x} = a + bx_{\text{ref}}$	Multiple controlled dynamic states; e.g. viscosity or temperature variation
Precision	$CV_x = \sigma_x / \bar{x}$	Repeated measurements; report versus integration time and signal level where relevant

Test	Recommended FOM	Indicative implementation / reporting
Stability	$\max \delta_x(t) $ and/or drift rate	Continuous or repeated measurement of a stable phantom over a defined interval
Reproducibility	CV_{sess}	Independent sessions, including probe repositioning and/or different days
Temporal resolution	T_{min} for a defined CV_{max}	Determine precision as a function of integration time under representative conditions

The framework is intentionally limited to quantities for which a common system-level definition can already be established. Further development should focus on harmonising test implementations, conducting multi-laboratory comparisons using common or equivalent phantoms, and subsequently validating the approach under application-relevant conditions. This staged approach is consistent with performance-assessment methodologies established in diffuse optics and provides a practical path towards future standardisation.

2.4.7 Implementation status and next steps

This deliverable fixes the core system-level tests and their FOMs while leaving the experimental implementation sufficiently flexible to accommodate different DCS and SCOS architectures. The next phase should select one or more practical phantom implementations and define the range of μ_a , μ_s' and dynamic conditions to be covered, together with the environmental and acquisition parameters that must be reported. This exercise could be extended to other institutions beyond the Lasers4EU project, following the solid contacts established by ICFO. Each participating team should then apply the same protocol using the instrument configuration adopted in routine operation. This further evolution goes beyond the scope of the Lasers4EU project. Conversely, the protocol will be tested during user access, to assess the usability of the practical implementation for routine access procedures.

3 Transient Absorption Spectroscopy

This protocol provides a harmonised framework for evaluating the performance and reliability of transient absorption (TA) spectrometers through measurements of selected reference compounds. It defines the properties to be assessed, the experimental information to be reported, and literature-based benchmark responses. It is intended as a guidance document for cross-facility comparisons and routine quality checks; it does not constitute an analytical reference standard and does not yet

prescribe universal pass/fail thresholds.

3.1 Scope

Transient absorption spectroscopy measures pump-induced changes in sample transmission or absorbance as a function of probe wavelength (or wavenumber) and pump-probe delay. This addresses complete optical TA instruments operating from femtoseconds to nanoseconds, including visible/near-infrared broadband detection and, where applicable, mid-infrared probing.

The purpose is to determine whether an instrument can recover established spectral signatures and kinetic components under documented conditions. The proposed reference set spans complementary tests of temporal response, spectral coverage and calibration, signal quality, long-delay acquisition and, for sufficiently short pulses, coherent vibrational responses. The protocol is aimed primarily at routine performance assessments.

3.2 Methodology

The instrument is assessed as a complete measurement system in the configuration used for experiments. Wherever possible, the reference sample should be measured with the facility's routine acquisition and analysis chain, while all settings that materially affect the result are recorded.

The protocol distinguishes between the performance property and its implementation. The performance property is the capability being tested, such as the recovery of a sub-picosecond rise, a known excited-state lifetime or a coherent oscillation. The implementation comprises the selected compound, solvent, cell, excitation wavelength, probe range, pump fluence, acquisition sequence and analysis model. Alternative implementations are acceptable when they test the same property and are fully documented.

The values reported below are literature benchmarks measured under specific experimental conditions. Agreement should be judged together with instrument response, spectral window, excitation density, sample condition and fitting uncertainty. A single literature lifetime must not be treated as an instrument-independent certified value.

3.3 Definitions and reporting conventions

Term	Definition and Role
Transient absorbance ΔA	Pump-induced change in absorbance. The sign convention and calculation used by the acquisition software shall be stated

Term	Definition and Role
Instrument response function IRF	Effective temporal response of the complete pump-probe measurement, including pulse durations, timing jitter and crossing geometry
Optical density OD	Static absorbance at the pump wavelength for the stated optical path length
Kinetic component τ_i	Time constant returned by a stated kinetic model. Rise and decay components shall be identified explicitly
Amplitude A_i	Signed or unsigned contribution associated with τ_i at a stated probe coordinate or in a stated global model. Amplitudes are not transferable unless the convention is specified
Long-lived component	Population component that persists into the late portion of the measured time window. Its value is meaningful only when the delay range adequately constrains the fit
Reference response	Literature-reported spectral or kinetic feature used as a benchmark, not a certified acceptance value

3.4 Protocol

3.4.1 Performance properties

Property	Assessment	Suggested reference
Temporal response	Recovery of the fastest resolvable rise or decay after convolution with the measured IRF	DCM in ACN-d3; IR-125; cresyl violet for very short-pulse systems
Kinetic fidelity	Recovery of published intermediate and long-lived time constants using an explicitly stated fit model	ZnTPP, DCM and IR-125
Spectral fidelity	Correct position, sign and shape of ground-state bleach, stimulated emission and excited-state absorption within the available probe range	ZnTPP and cresyl violet in the visible; DCM in the mid-IR
Sensitivity and precision	Signal-to-noise ratio and dispersion across repeated scans at a stated delay and probe coordinate	Any selected reference sample
Long-delay capability	Ability to constrain a component approaching the upper limit of the available delay window	ZnTPP, DCM, IR-125 or cresyl violet, as compatible with the instrument
Coherent response	Optional recovery of reproducible oscillatory residuals and their Fourier frequencies after population-background removal	Cresyl violet for suitably broadband, short-pulse instruments

3.4.2 General measurement procedure

1. Select at least one reference compound compatible with the pump wavelength, probe range and accessible delay window. Use more than one compound when distinct performance properties must be tested.

2. Prepare the sample using the solvent, concentration or optical density, path length and circulation conditions specified for the selected implementation. Record the compound identity, supplier or batch, solvent grade, preparation date and temperature.
3. Record the instrument configuration: pump and probe wavelength ranges, pulse durations or measured IRF, repetition rate, pump pulse energy and spot size, estimated fluence, polarisation geometry, delay range and sampling, detector, referencing scheme and acquisition averages.
4. Measure the static absorption spectrum before and after acquisition. Adjust the concentration or path length to obtain the target OD without introducing aggregation, reabsorption or excessive pump attenuation.
5. Acquire pump-on and pump-off data using the routine facility workflow. Check the solvent/cell response, coherent artefacts near time zero, scattered pump light, chirp correction and detector saturation.
6. Repeat the measurement sufficiently to estimate precision. At a minimum, retain independent scans rather than only the final average.
7. Process the data using documented corrections. Report any wavelength-dependent time-zero correction, spectral smoothing, baseline subtraction, outlier rejection or decomposition method.
8. Extract benchmark observables using a model appropriate to the data and convolved with the IRF where needed. Report fit ranges, parameter uncertainties and residuals; do not force the number or sign of components solely to reproduce a literature table.
9. Compare the measured spectral signatures and kinetic parameters with the selected reference response. Explain deviations in relation to solvent, excitation conditions, IRF, spectral window, delay range, fluence or sample degradation.

3.4.3 Minimum reporting requirements

Category	Information to report
Sample	Compound and form; solvent; concentration and/or OD; path length; cell/window material; flow or translation; temperature; preparation and stability checks
Pump	Centre wavelength and bandwidth; pulse duration; repetition rate; pulse energy; spot size; fluence; polarisation; modulation scheme
Probe and detection	Spectral range and resolution; detector; probe/reference geometry; integration time; averages; shot-to-shot or sequential acquisition

Category	Information to report
Timing	Delay range and step sizes; time-zero method; IRF determination; group-velocity-dispersion correction
Analysis	Definition of ΔA ; preprocessing; fit or global-analysis model; convolution; probe coordinates or spectral ranges; uncertainty and residuals
Outcome	Recovered spectral signatures; time constants and amplitudes with conventions; SNR or repeatability metric; comparison with literature; deviations and likely causes

3.4.4 Reference compound selection

Compound	Medium	Pump	Probe benchmark	Primary use
ZnTPP	Benzene or CH ₂ Cl ₂	397 nm	Visible; example at 656 nm	Picosecond relaxation and nanosecond S1 lifetime
DCM	DMSO-d ₆ or ACN-d ₃	400 nm	Mid-IR, 1440-1620 cm ⁻¹ ; example at 1495 cm ⁻¹	Sub-ps/ps rise components and long-lived S1 population
IR-125	Ethylene glycol	425 nm	Example at 850 nm	Fast rise and hundreds-of-ps decay
Cresyl violet	Methanol or ethanol	Within the visible absorption band; record exact value	Visible broadband response	Spectral fidelity and optional coherent-wavepacket test

3.4.5 Literature benchmark conditions

System	Sample condition	Reported benchmark dynamics	Ref
ZnTPP / benzene	1 mm cell; OD ₃₉₇ = 0.55; C about 0.22 mM	About 1.5 ps and 12 ps components; S1 lifetime about 1700 ps	⁸
ZnTPP / CH ₂ Cl ₂	1 mm cell; OD ₃₉₇ = 1.10	About 2.1 ps and 38 ps components; the source table does not report a long-lived value	⁸
DCM / DMSO-d ₆	C about 0.1 mM; 0.1 mm flow cell with CaF ₂ windows	Rise components about 2.6 ps and 34 ps; S1 lifetime about 1500 ps	⁹
DCM / ACN-d ₃	C about 0.1 mM; 0.1 mm flow cell with CaF ₂ windows	Rise components about 0.54 ps and 7.9 ps; S1 lifetime about 1130 ps	⁹
IR-125 / ethylene glycol	C = 0.5 mM; 70 μ m free jet	Rise about 1.2 ps; S1 lifetime about 460 ps	¹⁰

⁸ H.Z. Yu *et al.*, “Ultrafast dynamics of porphyrins in the condensed phase II Zinc tetraphenylporphyrin”, J. Physical Chemistry A 106, 9845 (2002)

⁹ A.J. Van Tassle *et al.*, “Investigation of the excited state structure of DCM via ultrafast electronic pump vibrational probe”, J. Physical Chemistry B 110, 18989 (2006)

¹⁰ S.H. Ashworth *et al.*, “Vibronic excitations of large molecules in solution studied by two-color pump-probe experiments on the 20 fs time scale”, J. Chemical Physics 104, c5761 (1996)

System	Sample condition	Reported benchmark dynamics	Ref
Cresyl violet / alcohol	Original draft: C = 0.12 mM; exact solvent, path length, pump wavelength and OD to be fixed	Original draft lists about 1.9 ps and 3500 ps; verify the selected literature source and measurement conditions before inter-laboratory use	¹¹

Note: Numerical amplitudes from the original summary table are not reproduced because their meaning depends on the probe coordinate, normalisation and kinetic model. They may be retained only when these conventions are defined.

3.5 Reference compound implementations

3.5.1 ZnTPP Zinc tetraphenylporphyrin

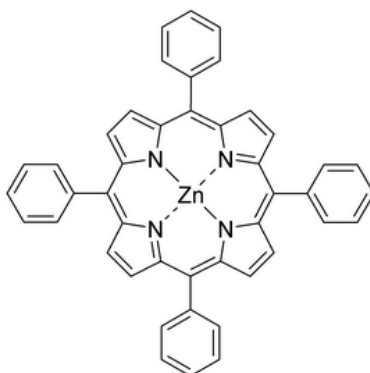


Figure 7 - Chemical structure of zinc tetraphenylporphyrin ZnTPP

Reference measurements were reported in benzene with 397 nm excitation and visible probing. A 1 mm cell with OD = 0.55 at 397 nm corresponded to a concentration of approximately 0.22 m/m. Measurements in dichloromethane used the same excitation and probe region, a 1 mm cell and OD = 1.10 at 397 nm⁸.

ZnTPP provides a useful test of picosecond relaxation and long-delay acquisition. The reported response includes an ultrafast S₂-related component of about 1.5 ps, vibrational relaxation of about 12 ps in benzene and 38 ps in dichloromethane, and an S₁ lifetime of about 1.7 ns in benzene⁸. The fitted response should be compared only after accounting for the instrument response and available delay range.

¹¹ J. Brazard *et al.*, "Accurate convergence of transient-absorption spectra using pulsed lasers", Review of Scientific Instruments 86, 053106 (2015); L.A. Bizimana *et al.*, "Resolving molecular vibronic structure using high-sensitivity two-dimensional electronic spectroscopy", J. Chemical Physics 143, 164203 (2015); J. Brazard *et al.*, "Experimental detection of branching at a conical intersection in a highly fluorescent molecule", J. Physical Chemistry Letters 7, 14 (2016); S. Speiser and N. Shakkour, "Photoquenching parameters for commonly used laser dyes", Applied Physics B 38, 191 (1985)

3.5.2 DCM 4 dicyanomethylene 2 methyl 6 p dimethylaminostyryl 4H pyran

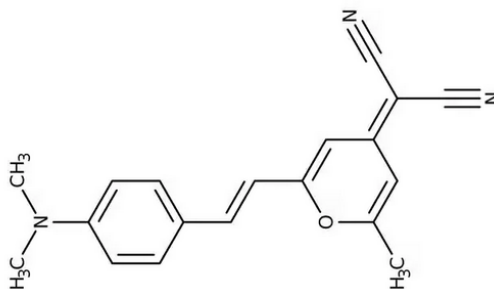


Figure 8 - Chemical structure of DCM

Mid-infrared TA measurements were reported from 1440 to 1620 cm^{-1} for DCM in DMSO- d_6 and ACN- d_3 at approximately 0.1 m/m. Excitation was at 400 nm and the example kinetic trace was probed at 1495 cm^{-1} . The sample was circulated through a 0.1 mm flow cell with 2 mm CaF_2 windows⁹.

In DMSO- d_6 , rise components of about 2.6 and 34 ps were reported; in ACN- d_3 , the corresponding values were about 0.54 and 7.9 ps. The reported S1 lifetimes were about 1500 ps and 1130 ps, respectively⁹. DCM therefore tests both early-time response and the recovery of solvent-dependent picosecond dynamics.

3.5.3 IR 125

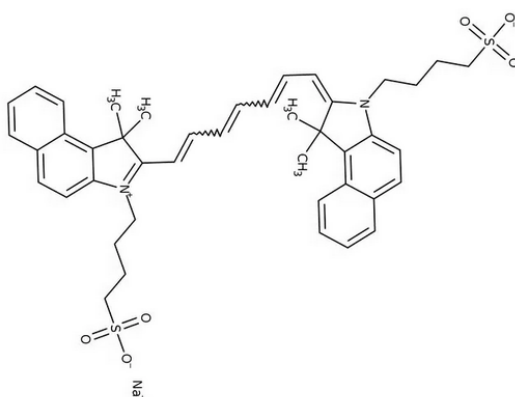


Figure 9 - Chemical structure of IR 125

The reported implementation used a 425 nm pump, detection at 850 nm and IR-125 in ethylene glycol at 0.5 m/m. A 70 μm free jet was used. The kinetic response showed a rise of about 1.2 ps and an S1 lifetime of about 460 ps¹⁰. If a cuvette or flow cell replaces the free jet, the altered geometry and optical path must be reported and the result treated as a modified implementation.

3.5.4 Cresyl violet

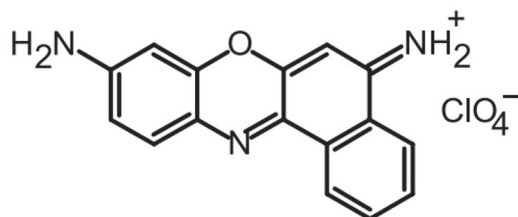


Figure 10 - Chemical structure of cresyl violet

Cresyl violet has a strong visible absorption band near 590-600 nm and a structured ultrafast response. It can be used to inspect the recovery of ground-state bleach, stimulated emission and excited-state absorption across a broadband visible probe. For sufficiently short and stable pulses, oscillatory residuals can provide an additional qualitative test of pulse compression, chirp correction and timing stability.

For standardisation, the implementation must specify the salt or chemical form, solvent, exact excitation wavelength, OD, path length, pump fluence and spectral window. The broad 500-750 nm pump entry in the original draft is not sufficiently specific for a reproducible benchmark. In addition, the assignment and numerical benchmark of the 1.9 ps and 3.5 ns components should be tied to one clearly identified experimental study before the compound is used for quantitative inter-facility comparison.

3.6 Interpretation of results

A performance assessment should report measured values with their associated uncertainties and classify the comparison as consistent, partially consistent or inconsistent with the selected reference implementation. Until multi-laboratory tolerances are established, this classification should be supported by the observed spectral agreement, fit residuals, repeatability and known differences, in experimental conditions rather than by an arbitrary percentage threshold.

A discrepancy does not by itself identifies an instrumental fault. Before concluding that performance is inadequate, the operator should examine sample degradation or aggregation, excitation fluence, solvent quality and oxygenation, cell geometry, pump-probe overlap, the IRF, group-velocity-dispersion correction, probe/reference stability, detector nonlinearity, spectral calibration and the adequacy of the delay window and kinetic model.

3.7 Implementation status and next steps

The present draft defines a common reporting structure and a reference-compound panel but does not yet establish certified materials, shared sample-preparation batches or universal acceptance

limits. The next implementation phase should 1/ select a minimal core test for visible TA and, separately, for mid-infrared TA, 2/ fix one reproducible preparation and acquisition recipe for each, and 3/ conduct a tentative round-robin measurement across participating facilities.

4 Characterisation of Ultrafast Pulses

Determining the duration and temporal profile of ultrashort pulses is essential in ultrafast science. For instance, in time resolved pump-probe spectroscopy, the observation of ultrashort events can be influenced by the temporal shape of the laser pulses. More fundamentally, as it triggers many phenomena in optics and, especially, in nonlinear optics and in intense-field/high-intensity physics, the first parameter that the experimentalist wants to access is the pulse duration: is my probe shorter than my pump? What is the peak power of my radiation? What is the laser intensity on my target? Subsequently, a more precise knowledge of the temporal shape may be necessary or even essential for the needs of the experiment or the interpretation of the results.

To answer these questions, many techniques have been developed over the past 50 years, since the picosecond pulses broke through the femtosecond barrier in the 1980s and continued beyond to the attosecond scale. Whether through direct measurements, time-domain methods, or spectral-domain approaches, many methods have been explored and, decades later, some of them have emerged as common tools for experimentalists.

The objectives of this Working Group are twofold: first, to provide an overview of the pulse-characterisation methods currently used by Lasers4EU access-providing facilities; and second, to develop guidelines and recommendations for assessing the quality and reliability of ultrashort-pulse measurements.

4.1 Composition of the Working Group

The Working Group comprises 12 researchers and laser scientists involved in laser development, laser operation and ultrafast physics, representing 12 laser laboratories across Europe that provide access to Lasers4EU users. As shown in Table 4, 73% of the working-group members use short- and ultrashort-pulse Ti systems as their primary drivers, while 55% use high-power rare earth based laser technologies. Secondary sources include parametric amplification, extending spectral coverage from the UV to the mid-IR, and high harmonic generation, providing access to the UV and attosecond regimes. This broad range of short-pulse sources directly influences the methods used to measure and characterise pulse duration.

Table 4 - Laser facility profiles of the Working Group

Fundamental laser and secondary sources	% of the facilities
Ti:sapphire	73%
Rare earth based (Ytterbium, thulium, etc)	55%
OPCPA	18%
OPA from UV to MID-IR	45%
High Harmonic generation	45%

4.2 Pulse characterisation methods

4.2.1 Survey of methods

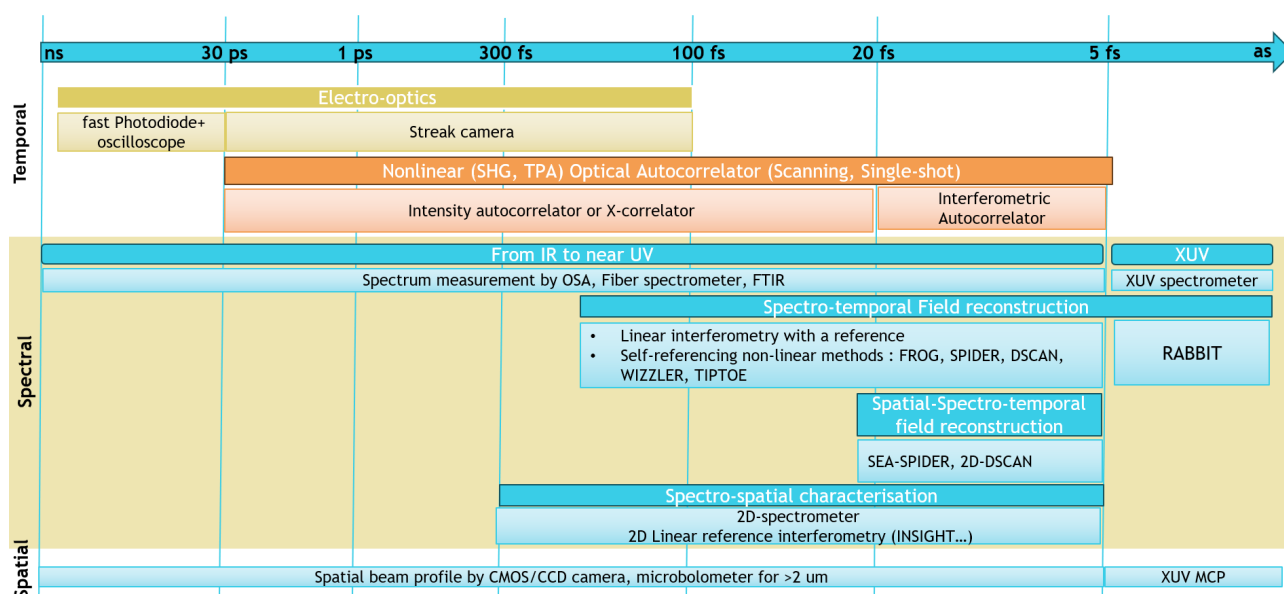


Figure 11 - Survey of optical pulse characterisation methods

Determining the temporal shape and pulse duration strongly depends on the timescale of the pulses themselves. For long pulses, electro-optics devices like photodiodes or streak cameras are suitable. For nanosecond pulses, a photodiode associated with an oscilloscope is the most convenient and powerful method for measuring both the shape and duration of the pulse. As discussed later, certain precautions must be taken especially when approaching the limits in terms of the bandwidth of the photodiode and the oscilloscope. Limited by the electronic response time of the devices, optical pulses as short as 30 ps can be measured by photodiodes. However, photodiodes are commonly used in ultrafast facilities in order to measure nanosecond or ASE contrast, as well as the stretched pulse duration in CPA systems.

When pulses become shorter, the electronic response time, limited to tenths of a picosecond, required the use of methods based on nonlinear optics, such as second-harmonic generation (SHG). These methods are extensively used from the picosecond to the femtosecond scale, and are even adapted to the attosecond regime. By delaying two replicas of the pulse and mixing them through a nonlinear effect, one can access the autocorrelation profile of the pulse. As shown later, under specific assumptions, one can deduce the pulse duration. The most commonly used nonlinear effect is second-harmonic generation; however, for some wavelengths, especially in the UV or the mid-IR where SHG crystals may suffer from one-photon absorption, two-photon absorption in transparent materials can be used. Finally, autocorrelators can be single-shot devices (for which one acquisition provides the full autocorrelation in a single laser shot) or scanning autocorrelators (for which a moving mirror scans the delay between the replicas). For pulses longer than 10-20 fs, background-free autocorrelators are mostly used whereas shorter pulses require the use of interferometric autocorrelators.

However, when pulses become increasingly short, their temporal structure is heavily governed by the spectral phase, i.e., how the spectral components composing the short pulse are delayed in time. Therefore, the characterisation of the pulse is no longer solely a question of time-domain measurement but also extends into the spectral domain. Measuring the fundamental spectrum is therefore essential. Depending on the operating wavelength, the facilities use Fabry-Perot-based Optical Spectrum Analysers (OSAs), grating-based fibre-coupled spectrometers (visible-IR or XUV) or Fourier-Transform Infrared interferometers (FTIR). This measurement provides information exclusively about the minimum pulse duration that can be achieved by the given spectral content.

For a more precise measurement of the optical field, the spectral or the temporal phase must also be determined. Over the years, a range of spectral-temporal field-reconstruction techniques have therefore been developed, from linear interferometric methods using a well-characterised reference pulse to self-referenced approaches based on nonlinear optics. Common techniques include FROG¹², SPIDER¹³, D-SCAN¹⁴, WIZZLER¹⁵ or TIPTOE¹⁶, each acronym reflecting the rigorous physics behind it. For its optical simplicity (basically an autocorrelator with a spectrometer), FROG (Frequency Resolved Optical Gating) is the most widely used device, even if the phase retrieval algorithm can occasionally be ambiguous. Conversely, SPIDER (Spectral Phase Interferometry for

¹² R. Trebino and D. J. Kane, "Using phase retrieval to measure the intensity and phase of ultrashort pulses: frequency-resolved optical gating", J. Optical Society of America A 10, 1101 (1993)

¹³ C. Iaconis and I.A. Walmsley, "Spectral phase interferometry for direct electric-field reconstruction of ultrashort optical pulses", Optics Letters 23, 792 (1998)

¹⁴ M. Miranda *et al.*, "Characterization of broadband few-cycle laser pulses with the d-scan technique", Optics Express 20, 18732 (2012)

¹⁵ T. Oksenhendler *et al.*, "Self-referenced spectral interferometry", Applied Physics B 99, 7 (2010)

¹⁶ S.B. Park *et al.*, "Direct sampling of a light wave in air", Optica 5, 402 (2018)

Direct Electric-field Reconstruction) features a more complex optical setup but benefits from a phase retrieval method based on simple spectral interferences. D-SCAN (Dispersive Scan) is another method based on the deformation of the second-harmonic spectrum of the pulse while changing the dispersion of the pulse. WIZZLER is based on spectral linear interferometry between the pulse and a reference created by cross-polarized wave generation (XPW) in a nonlinear crystal. These methods generally rely on phase-matched nonlinear crystals, which can become challenging for broadly tunable sources, such as OPAs, or at wavelengths approaching the UV, where suitable nonlinear materials may be limited.

To address this issue, the more recently developed TIPTOE method uses the ionization of air, which is intrinsically a non-phase-matching process. By collecting the electric charges created by the pulse and a delayed multiphoton-absorbed pulse, TIPTOE acts as an interferometric cross-correlation where the fringes in the cross-correlated signal provide direct access to the spectral phase. Over the years, all these methods have demonstrated their robustness and reliability.

At very short pulse durations, particularly under tight focusing conditions, spatio-temporal coupling effects can strongly affect the real pulse duration at the focus. As in the spectral domain, measuring the spatial beam distribution and the beam quality factor M2 can only provide basic information about the best beam size one can expect at the focus. For a more precise measurement, spectro-spatial methods, for which the distribution of the spectrum over the spatial beam profile is measured, are used. This can be achieved using 2D spectrometers (with one dimension for the spectrum and the other one for the spatial dimension) or via spectro-spatial interferometers (such as INSIGHT). By coupling this method with the spectral phase measurement described above, one can then estimate the spatio-temporal distortion of the pulse. Ultimately, the definitive approach for measuring real spatio-temporal distortions is to combine spatial measurements with spectral phase measurements into a single diagnostic. This can be achieved, for instance, by spatially resolving the spectral interference given by a SPIDER (SEA-SPIDER) on a camera or by combining a 2D spectrometer with a D-SCAN. In this way, a complete spatio-spectro-temporal characterisation of the ultrashort pulsed laser beam can be achieved, granting access to a complete measurement of the electric field in space and time. In practice, however, performing this level of characterisation directly at the interaction point remains technically demanding.

4.2.2 Methods used by the Working Group

Among the methods described above, the Working Group predominantly uses autocorrelators and complete field-reconstruction techniques. Most autocorrelators are scanning devices, while third-order autocorrelators are also used for picosecond-range measurements and for assessing amplified spontaneous emission (ASE) contrast in high-intensity laser systems.

Among the field-reconstruction techniques, FROG is the most widely used, followed by WIZZLER. d-scan and TIPTOE are less common, while SPIDER is used comparatively rarely within the Working Group.

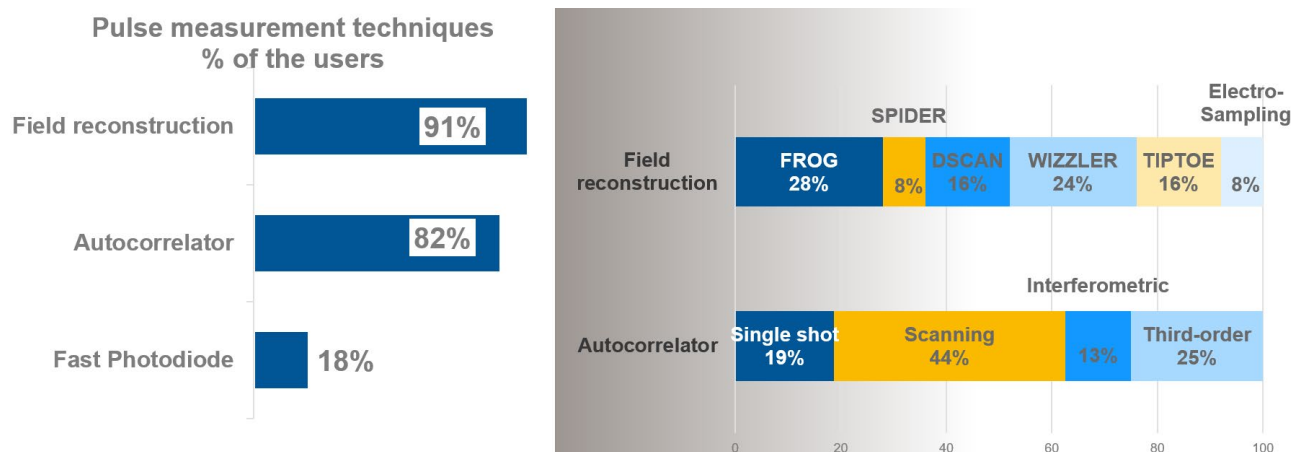


Figure 12 - Survey of optical pulse characterisation methods used by the Working Group

4.3 Assessment of ultrashort pulse measurement

Pulse characterisation can be performed using either commercial instruments or custom-built devices. In both cases, the reliability of the measurement must be critically assessed. Relevant questions include whether the measured result is physically consistent, which factors may introduce errors or bias, whether comparable procedures are used by other laboratories, and whether common assessment practices can be established.

The aim of this section is therefore to provide practical guidelines and propose methods for evaluating the reliability and consistency of ultrashort-pulse measurements.

4.3.1 Assessment of electro-optical methods

For pulses longer than approximately 30 ps, pulse duration can be measured using a photodiode coupled to an oscilloscope. The rise time of the photodiode should be shorter than the expected pulse duration, while the oscilloscope must provide sufficient electronic bandwidth to resolve the detected signal accurately. If the bandwidth of the oscilloscope is too narrow, the measured electronic signal will be limited by the response of the device. For instance, for 1 ns pulses, a photodiode with a maximum 100 ps rise time should be combined with an oscilloscope of at least 1 GHz. As a practical example, for a pulse duration of around 1 ns, a photodiode with a rise time of no more than 100 ps should be combined with an oscilloscope providing a bandwidth of at least 1 GHz.

Table 5 - Assessment of photodiode-based optical pulse measurements

Measurement	Question(s)	Checklist
Long pulse duration measurement (> 30 ps)	- Is the frequency bandwidth response of detector and oscilloscope compatible with the expected pulse duration?	- Check 10-90 % rise and fall time of the measured pulse - Compare to the total bandwidth of the oscilloscope and the photodiode
Pulse duration in highly stretched CPA	- Does the stretched pulse waveform map with the spectrum?	- Measure the optical spectrum - Compare with temporal shape, both must be identical
Nanosecond and sub-ns ASE and pre-pulse contrast measurement	- Is the measured background higher than the noise of the oscilloscope? - Is the photodiode not saturated for the pre-pulses?	- Check the noise level of the oscilloscope - Compare the attenuation of the measured peaks by inserting a known neutral density

4.3.2 Assessment of optical autocorrelations

Ultrashort pulses are the result of the constructive interference of many waves of different frequencies locked in phase in the time domain. The broader the spectrum, the shorter the time window where the interference is constructive and, consequently, the shorter the pulse.

(a) Fourier relationship

$$\Delta t_{FWHM} \Delta \nu_{FWHM} \geq K$$

(b) Autocorrelation deconvolution

$$\Delta t_{AC\ FWHM} = \Delta t_{FWHM} A$$

(c) Factors K and A depending on the pulse shape

Shape	K	A
Gaussian	0.441	1.44
Sech ²	0.315	1.55
Rectangle	0.892	1

Figure 13 - Key relationships for ultrafast pulses (a) Fourier relationship (b) deconvolution of autocorrelation (c) deconvolution factors assuming a pulse shape

Fourier relationship

Short and ultrashort pulses are governed by the Fourier relationship [Fig. 13 (a)], which links pulse duration to spectral bandwidth. This relationship leads to the following considerations:

- When the relationship holds as an equality, the pulse duration is then the shortest allowed by the spectral content. The pulses duration is then limited by the Fourier transformation and the pulses are referred to as Fourier-Transformed-Limited (FTL). In this case, all spectral components are temporally in phase and the spectral group velocity dispersion is zero.
- When the relation is an inequality, the pulses are not as short as they could be. The spectral components are delayed relative to each other, reflecting the presence of a non-zero group velocity dispersion, which affects the temporal shape of the pulse.
- This relationship depends on a factor K [Fig.13(c)] that changes with the temporal shape of the

pulse. Compared to a Gaussian shape, sech^2 is the temporal shape that yields the shortest pulse for the same spectral content. When the measurement is assessed, special care must be taken regarding this assumption, as sech^2 is sometimes used inadequately for giving the best shortest pulse.

The use of this relationship constitutes the first step in assessing pulse duration measurements.

Autocorrelation deconvolution

When the autocorrelation (AC) is measured, a symmetric bell shape is obtained with a width larger than the pulse duration. A linear relationship between the autocorrelation width and the pulse width is shown in Fig.13(b). As with the Fourier relationship, the deconvolution factor A depends on the assumed pulse shape. Once again, the sech^2 pulse shape has the smallest deconvolution factor $\backslash(A)$, which can lead to its inappropriate use when deriving the shortest possible pulse duration.

Preparation of the instrument

As with any measurement instrument, an autocorrelator must be correctly operated and aligned to ensure reliable results. Several key parameters should therefore be verified before accepting a measurement. Figure 14 provides an example checklist that can be used for this purpose.

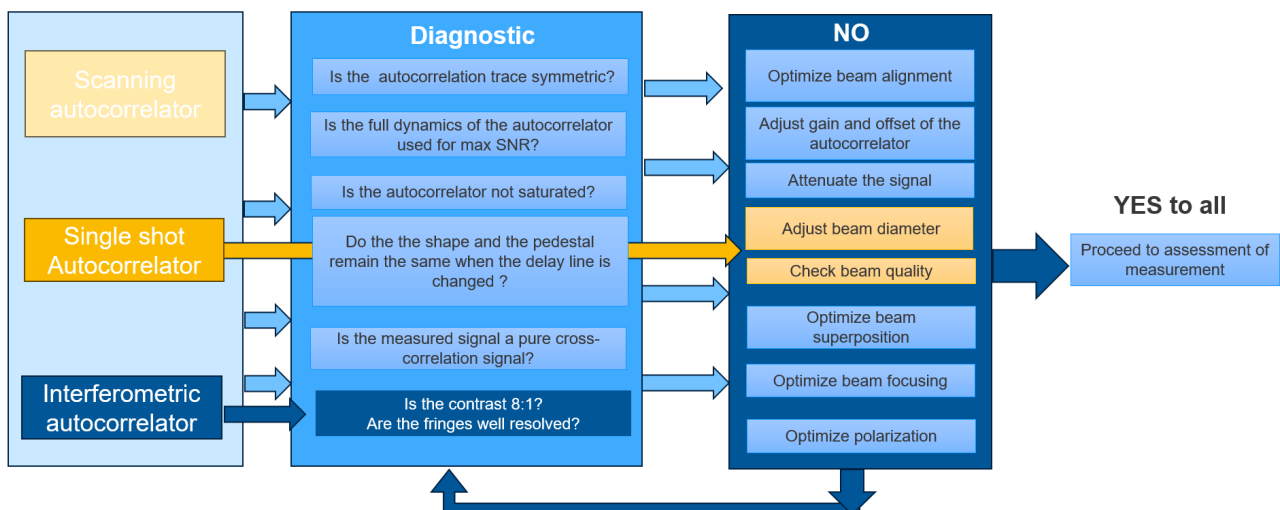


Figure 14 - Example of checklist before assessment of a measurement by autocorrelators

Some parameters are common to all autocorrelators, while others are specific to particular configurations, such as fringe analysis for interferometric autocorrelators or spatial beam quality for single-shot devices. Key parameters to verify include detector saturation, which can broaden the measured autocorrelation trace, the effective dynamic range and the symmetry of the trace.

If any of these criteria is not satisfied, the instrument should be readjusted and realigned before the

measurement is accepted. Otherwise, the reliability of the result cannot be assured.

How far from FTL?

Once the autocorrelator has been properly prepared and the measurement completed, the next step is to assess whether the result is physically consistent and how closely the measured pulse duration approaches the Fourier-transform limit (FTL). Figure 15 presents three methods for performing this assessment, ranging from a basic consistency check to a more advanced analysis:

- **Basic:** the autocorrelation and spectrum are independently measured. From the FWHM (Full Width at Half Maximum) of the AC and the spectrum, the Fourier relationship and the autocorrelation deconvolution relationship give access to two pulse widths that can then be compared. The ratio between these pulse widths gives directly the deviation from the FTL. However, as both relationships depend strongly on the assumption on the pulse shape, the autocorrelation must be numerically fitted by a Gaussian or Sech autocorrelation function in order to use the right K and A factors.
- **Advanced:** when the spectrum deviates significantly from a Gaussian-like function, the Fourier-transform-limited pulse may differ strongly from a Gaussian pulse. In this case, the Fourier transform of the spectrum will give exactly the temporal shape of the pulse limited by the spectrum. The corresponding autocorrelation can then be computed and compared to the measured autocorrelation.
- **More advanced:** a method derived from the D-SCAN method can reveal if the pulse is far from the Fourier limit. Experimentally, the fundamental pulse is frequency doubled in a nonlinear crystal and the second harmonic spectrum is recorded. Concurrently, starting from the fundamental spectrum, the FTL second-harmonic spectrum can be computed. This computed spectrum reflects the broadest SHG spectrum that can be obtained with an FTL spectrum. If some chirp is present, the experimental SHG spectrum will be narrower or even structured.

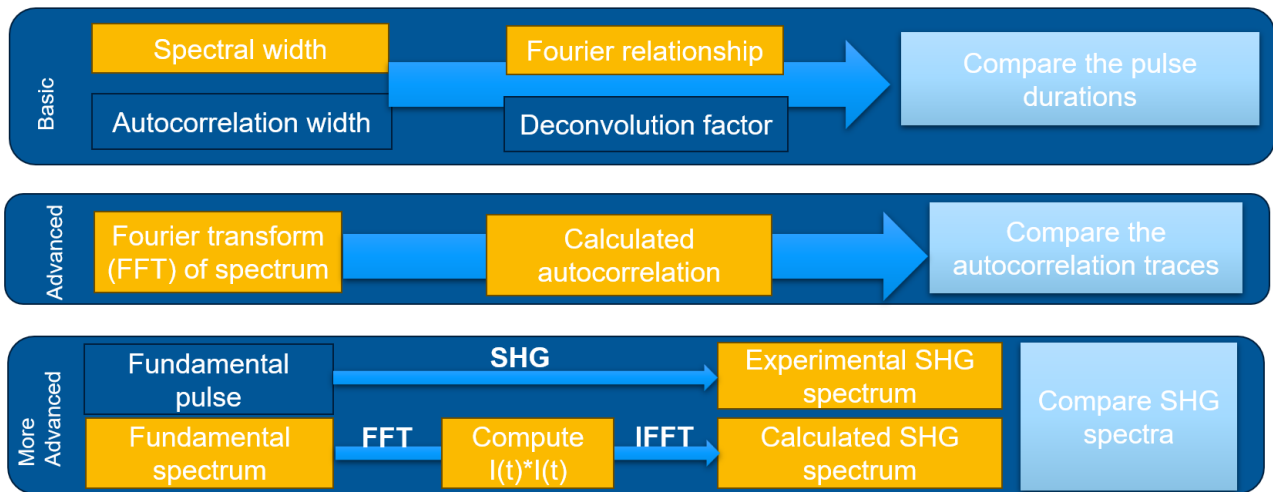


Figure 15 - Example of three different methods to estimate the difference between the real pulse and the FTL

All these methods give qualitative information on how far from the FTL limit the pulses are. If the measured pulses are close to the FTL, then the assessment of the autocorrelation measurement can be carried out with confidence. Otherwise, the presence of a chirp in the pulse can change the results, especially when the assessment is performed, as described in the next section, by adding a known dispersion, which means that the analysis must be made with special care. If the difference from the FTL seems to be too large, complete field reconstruction methods should be used.

Assessment of the autocorrelation by adding dispersion

When a laser pulse passes through a dispersive transparent material, such as a fused silica substrate of thickness (e), the dispersion of the group velocity index spreads the spectral components in time. The pulse is then stretched in time and the final pulse duration can be determined by:

$$\tau_{Stretched} = \tau_{FTL} \sqrt{1 + \left[\frac{2.77 \beta^{(2)} e}{\tau_{FTL}^2} \right]^2}$$

with τ_{FTL} the initial FTL pulse duration (FWHM), $\tau_{Stretched}$ the stretched pulse duration and $\beta^{(2)}$ the dispersion coefficient of the dispersive material of thickness e . The dispersion coefficient depends on the central wavelength: for fused silica $\beta^{(2)}=36 \text{ fs}^2/\text{mm}$ at 800 nm and $19 \text{ fs}^2/\text{mm}$ at 1030 nm. From the equation above, the duration of the pulse stretched by the dispersion can be computed as a function of the initial FTL pulse duration for different thicknesses of fused silica as shown in Figure 16 at 800 nm.

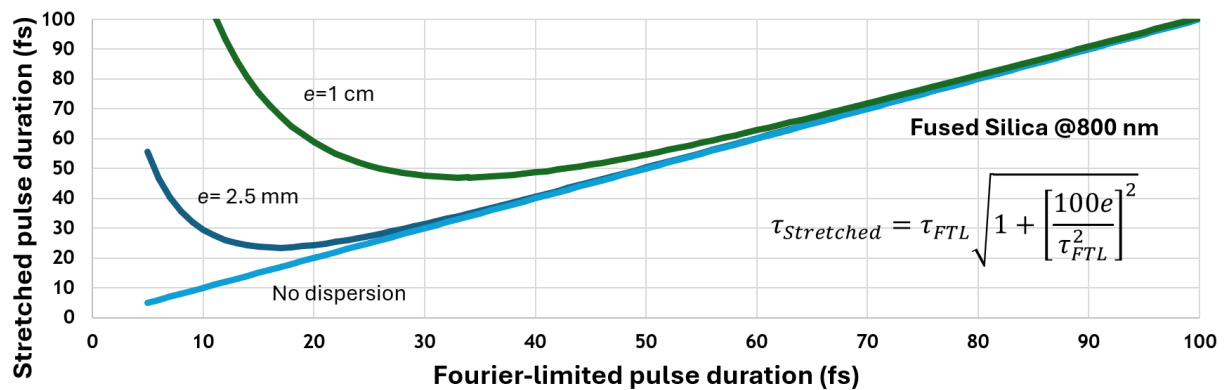


Figure 16 - Final pulse duration stretched by the insertion of a fused silica plate of different thicknesses at 800 nm as a function of the initial pulse duration; e is expressed in mm in the inset formula at 800 nm

As shown above, one can notice that dispersion has a greater impact on shorter pulses. Since shorter pulses possess a much broader spectral content, the group velocity dispersion induced by the glass plate has a stronger influence on their temporal spreading. This means that the assessment of the autocorrelation measurement is much easier to achieve with very short pulses than with long ones, as a very thin piece of glass has a strong impact on the ultrashort pulse. In contrast, for long pulses (longer than 50 fs at 800 nm), dispersion has a very small effect when using a reasonable fused silica glass thickness of less than 1cm. For longer pulses, highly dispersive devices must be used.

The assessment of the autocorrelation measurement can then be carried out as shown in Figure 17.

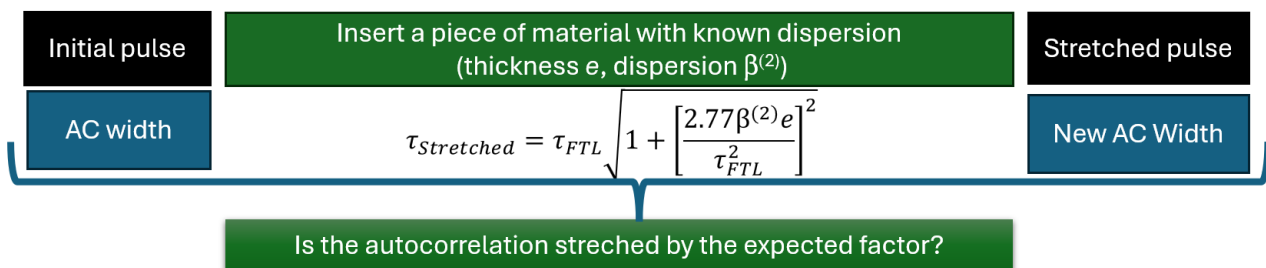


Figure 17 - Assessment of the autocorrelation measurement by added material dispersion

- The autocorrelation of the near-FTL pulse is measured.
- A piece of transparent material of given thickness e and dispersion $\beta^{(2)}$ is inserted in the beam.
- The new autocorrelation is recorded.
- The stretching factor can be calculated and compared to the experimental result.

As shown above, this method relies on the dispersion introduced by the glass, the effect of which may be small depending on the initial FTL pulse duration. To produce a measurable change in pulse duration after propagation through the material, the glass thickness—and, more generally, the product $\beta^{(2)}e$ – must be properly chosen. In Figure 18, we show, for instance, the fused silica

thickness required to observe significant changes at 800 nm. For a 20 fs pulse, 2 mm of fused silica will increase the pulse duration by 10% while 4.5 mm and 7 mm will respectively stretch the pulse by 50 % and 100 %. At this wavelength, 1cm of glass increases the pulse duration up to 50 fs, which is at the limit of the validity of the assessment. Special care must also be taken, especially in the IR, regarding the zero-dispersion wavelength. The influence of dispersion decreases while approaching the zero-dispersion wavelength, requiring thicker material.

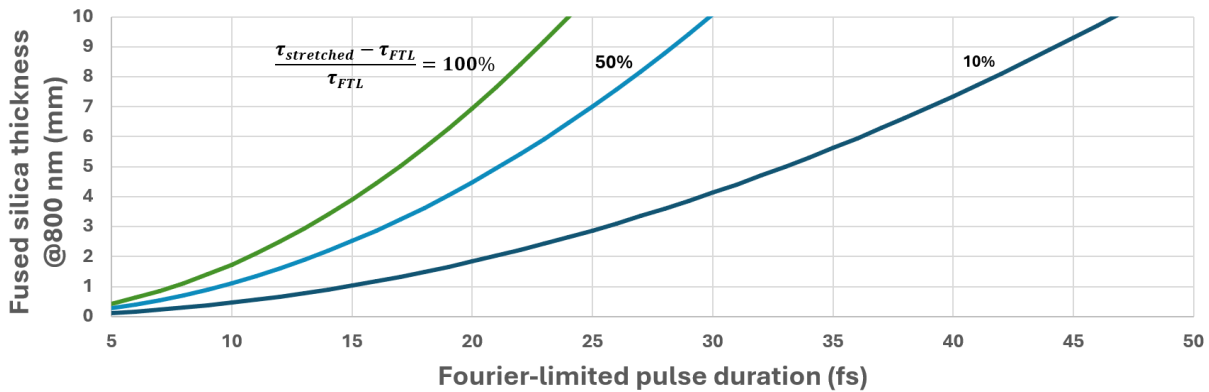


Figure 18 - Thickness of fused silica required at 800 nm to observe a significant relative variation of the initial pulse duration after propagation

Once the procedure is carried out, the results must be compared.

- If the result is in agreement with the theory, then the measurement is validated and the results can be trusted.
- Otherwise, it does not necessarily mean that the measurement is wrong. If the pulse is significantly non-FTL or if a strong variation in the spectral phase (due to the B-integral for instance) is suspected, the dispersion brought by the piece of glass will be added to these nonlinear phases, which could shape the pulse in time in an unexpected way. In that case, the assessment is no longer valid and a characterisation by complete field reconstruction methods is advised.

As shown above, pulses longer than 50 fs at 800 nm are not very sensitive to the dispersion brought by 1cm of fused silica. For longer pulses, highly dispersive devices must be used, such as the compressor of the CPA laser system itself.

As illustrated in Figure 19, since the second-order dispersion term brought by a Treacy compressor varies linearly with the distance between the gratings, the theoretical pulse duration around the shortest value varies linearly when the distance between the gratings is varying. This behaviour applies to near FTL pulses with all spectral components travelling nearly together. The pulse duration is then symmetrically changed around this position.

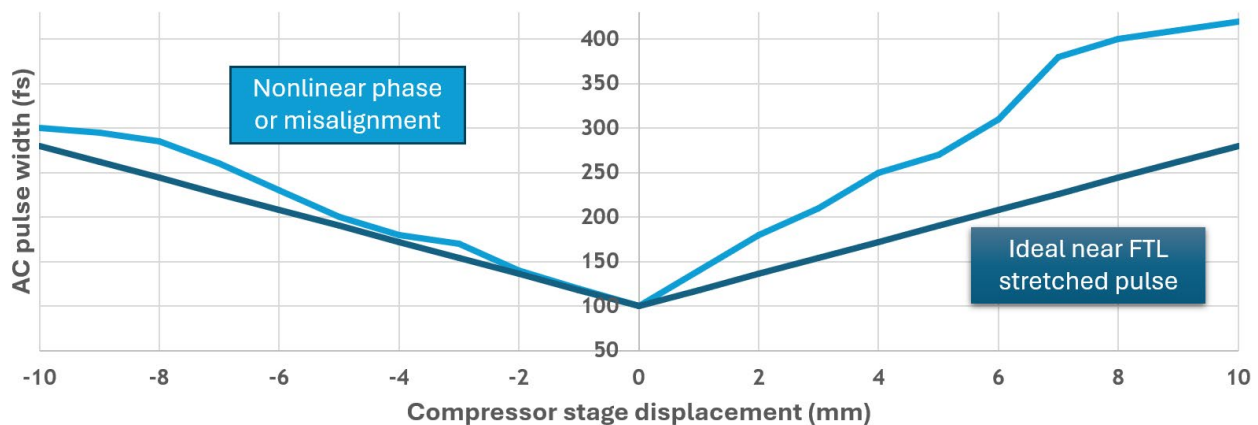


Figure 19 - Example of the pulse duration changes as a function of the compressor stage displacement around the optimal position

This leads to a similar procedure of the assessment of the autocorrelation measurement but with a different observable.

- The autocorrelation of the near-FTL pulse is measured.
- The compressor stage is moved around the optimal position.
- The new autocorrelation is recorded.

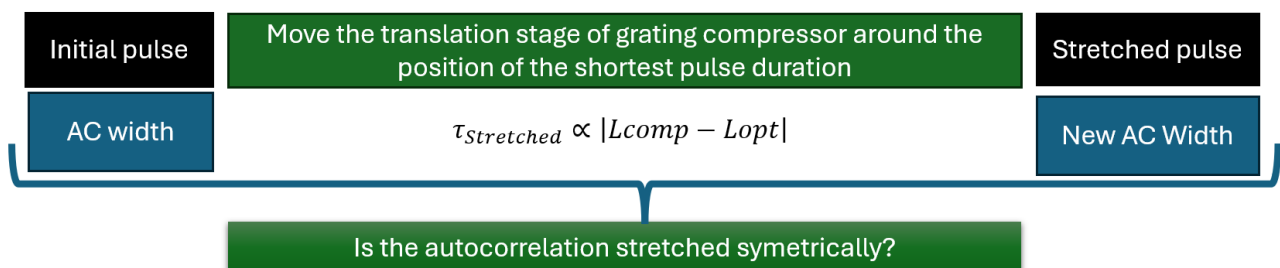


Figure 20 - Assessment of the autocorrelation measurement by added compressor dispersion

The question is then: is the autocorrelation stretched symmetrically around the optimal position? If this behaviour is observed, the measurement can be considered reliable. If not, this does not necessarily indicate an incorrect measurement; however, the possible influence of residual nonlinear spectral phase, as discussed for the glass-dispersion assessment, should also be considered here, leading to the same conclusions.

Conclusion

The autocorrelation of a short and ultrashort pulse gives access to the pulse duration, provided a strong assumption is made on the temporal shape of the pulse. The assessment of the measurement can be carried out in several ways.

- A basic assessment using the Fourier relationship and the autocorrelation

deconvolution relationship. In case of near FTL pulses, this procedure may be enough to validate the measurement

- A more advanced assessment by the use of a known dispersion. For pulses < 50 fs, the insertion of a fused-silica plate of thickness < 1 cm will temporally stretch the pulse and it will give a longer autocorrelation width that can be compared to the expected value. For longer pulses $>$ (longer than 50 fs), material dispersion is not strong enough to induce clearly measurable changes and highly dispersive devices like a grating compressor must be used. In that case, the symmetry and the linearity of the autocorrelation width with respect to the grating distance will be used as a metric to validate the measurement.

Special care must also be taken with fused silica depending on the operating wavelength, especially in the IR. The influence of dispersion decreases and even vanishes while approaching the zero-dispersion wavelength; therefore, other materials must be chosen according to their dispersion at the operating wavelength.

In all cases, these methods are valid when near-FTL pulses are diagnosed. In the presence of higher-order dispersion or residual nonlinear phases, these methods based on adding dispersion may lead to misleading results. The measurement is not necessarily wrong but the observed results may be skewed by the combination of these non-negligible high-order or nonlinear phase residues with the added dispersion. In this case, it is recommended to use the complete field reconstruction method to characterise the laser pulse.

4.3.3 Assessment of third-order cross-correlators with high dynamic range/ laser pulse contrast

Accurate measurement of pulse duration is vital for high-intensity laser experiments, serving as a primary parameter alongside pulse energy and beam size. While the dynamic range of standard pulse duration measurements depends heavily on the underlying nonlinear process (achieving up to five orders of magnitude over several hundred femtoseconds in commercial devices), experiments exceeding the relativistic intensity threshold (greater than $2 \cdot 10^{18}$ W/cm² at 800 nm) demand a comprehensive characterisation of the temporal intensity contrast over a much wider temporal window. The dynamics of plasma generation, formation and expansion profoundly influence the overall experimental outcome. Consequently, detailed knowledge of both the plasma scale length and the exact pulse shape is indispensable for comparing results across different facilities and validating numerical simulations. Depending on the target medium, plasma formation thresholds vary from 1010 W/cm² for solids to 10^{13} W/cm² for gases, necessitating diagnostic devices with a dynamic range of at least nine orders of magnitude. For modern laser systems with peak intensities far

exceeding these absolute ionisation thresholds, even higher dynamic ranges are required. State-of-the-art commercial cross-correlators, such as the Amplitude Laser *Sequoia* or the Ultra Fast Innovations *Tundra*, address this by achieving up to 14 orders of magnitude. This performance is enabled by third-harmonic generation within a scanning cross-correlator, where the fundamental beam is scanned across the generated second-harmonic pulse. In the *Sequoia*, neutral density filters dynamically attenuate the incoming beam to resolve low-intensity amplified spontaneous emission (ASE) without saturating the detector during the main peak. However, switching between these filters can introduce direction-dependent offset artefacts in the contrast curve. The most reliable results are obtained by scanning outward from the main peak, specifically moving in the negative temporal direction for the pre-pulse contrast and in the positive direction for post-pulses. Ultimately, the critical question remains whether the recorded traces accurately reflect the genuine laser pulse profile or include systematic artefacts inherent to the device or measurement principle.

4.3.4 Definition of the temporal intensity contrast

A single numerical value is insufficient to fully characterise the temporal intensity contrast. Depending on the relevant time scale and physical origin, three distinct regions can be identified.

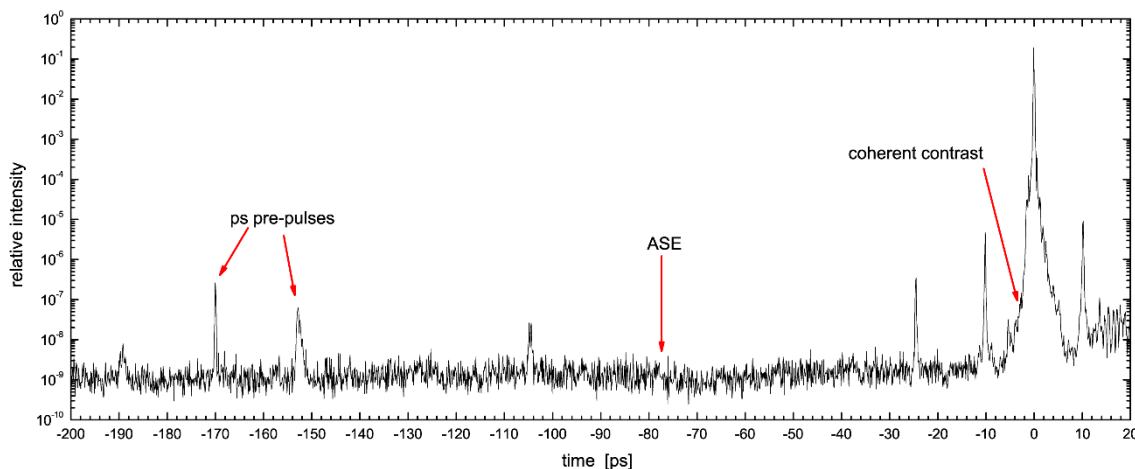


Figure 21 - Temporal intensity contrast of the JETi40 laser system

ASE establishes the baseline of the contrast curve, with its absolute level determined by the specific laser amplifier architecture, such as single versus double chirped-pulse amplification (CPA), pre-amplification prior to stretching, or optical parametric CPA (OPCPA). Within the temporal scanning window of standard diagnostic devices, this ASE pedestal remains nearly constant. Although fast Pockels cells are commonly implemented within the amplifier chain to improve the temporal contrast while the pulses are stretched, their cleaning window is fundamentally limited. Consequently, Pockels cells cannot suppress the ASE closer to the main peak than the stretched pulse duration, which typically spans several hundred picoseconds to nanoseconds for petawatt-class laser systems. Finally, to verify the experimental dynamic range of the cross-correlator, the noise floor can

be characterised by individually blocking both beam paths during the measurement.

The second characteristic feature of the contrast curve is the coherent contrast, commonly referred to as the picosecond (ps) pedestal. This pedestal originates from uncompensated spectral phases as well as scattering from various optical elements throughout the laser chain. The final components comprise pre- and post-pulses, which typically arise from reflections of parallel surfaces and manifest as replicas of the main pulse. Their respective intensity levels are determined by their specific generation mechanism and position within the laser chain. Due to the non-linear nature of third-harmonic generation, these pre- and post-pulses can produce secondary replicas, as well as instrumental artefacts inherent to the measurement device itself, such as double reflections within the frequency-doubling crystal. Consequently, a long-standing and widely debated question remains: which of these detected pulses represent genuine laser features, which are merely measurement artefacts, and how can the two be reliably distinguished?

4.3.5 Assessment of real and ghost pulses

The following discussion and measurements refer to the Sequoia from Amplitude Laser. To investigate the response of the diagnostic tool to pre- and post-pulses, a thin (2 mm), uncoated BK7 substrate was positioned in front of the device. This setup introduces a well-defined post-pulse via internal double reflection within the glass medium, with an expected arrival time of approximately 20 ps and a relative amplitude of approximately 10^{-3} . Due to the architectural configuration of the device (specifically the self-referenced mixing of the temporally symmetric second-harmonic beam with the fundamental beam) the resulting third-harmonic signal is inherently asymmetric. Consequently, the intensity ratio of a measurement-induced ghost pre-pulse scales as the square of the genuine post-pulse intensity (see Figure 22).

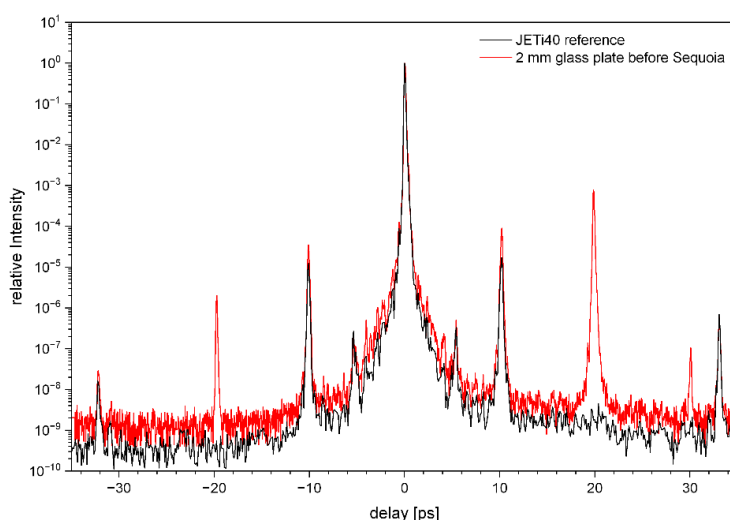


Figure 22 - Generation of artificial post-pulses using a 2 mm thick BK7 plate

Applying this argument to the experimental data shown in Figure 22, the pulses recorded at -10 ps and 10 ps exhibit nearly identical amplitudes, with the feature on the negative temporal side being only marginally lower. This observation strongly indicates that the pre-pulse is not a measurement artefact (ghost pulse), but rather a real physical feature triggered by a high B-integral within the laser chain while the pulses are still stretched. Under these conditions, a minor post-pulse can interfere with the main pulse, modulating the spectral intensity profile. Accompanied by a high B-integral, this modulation translates into a sinusoidal phase ripple, which effectively acts as a temporal grating that redistributes energy to generate symmetric pre- and post-pulses in the time domain upon compression. The energy ratio is given by¹⁷

$$E_{pre-pulse} = 0.58 B^2 E_{post-pulse} .$$

This nonlinear effect can be verified by precisely evaluating the amplitude ratio of an artificially generated post-pulse. For this purpose, the same thin BK7 glass substrate was positioned in front of a regenerative amplifier. In this configuration, the amplitude of the resulting pre-pulse exceeds that of the reference signal, and this is accompanied by a distinct modification of the overall pulse profile.

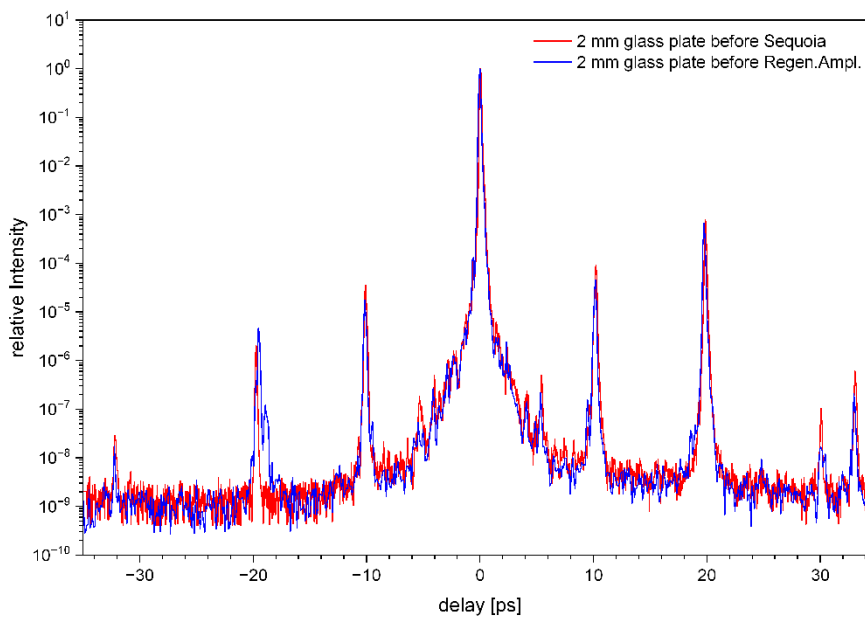


Figure 23 - Influence of the B-integral in the amplifier chain on the generation of real pre-pulses from post-pulses

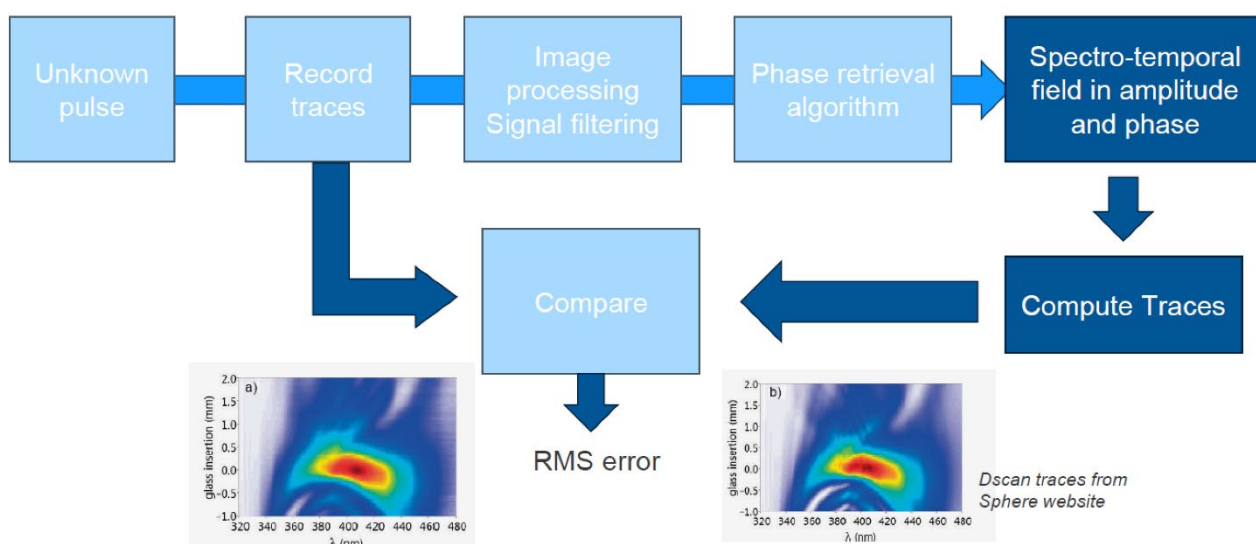
¹⁷ N. Didenko *et al.*, “Contrast degradation in a chirped-pulse amplifier due to generation of pre-pulses by postpulses”, Optics Express 16, 3178 (2008)

Conclusion

Third-order cross-correlators are widely utilised to characterise the temporal intensity contrast of high-intensity laser systems over a broad temporal range with a high dynamic range. Although commercial devices are readily available for standard Ti:Sapphire and Yb-based systems, transmissive optical components can introduce artefacts into the recorded traces depending on the system design. Consequently, determining the correct sign of the arrival time for smaller replica pulses requires careful consideration. The intensity ratio between these pulses serves as the criterion to distinguish real pulses from measurement artefacts, ultimately enabling the identification of specific components responsible for contrast degradation within the laser system.

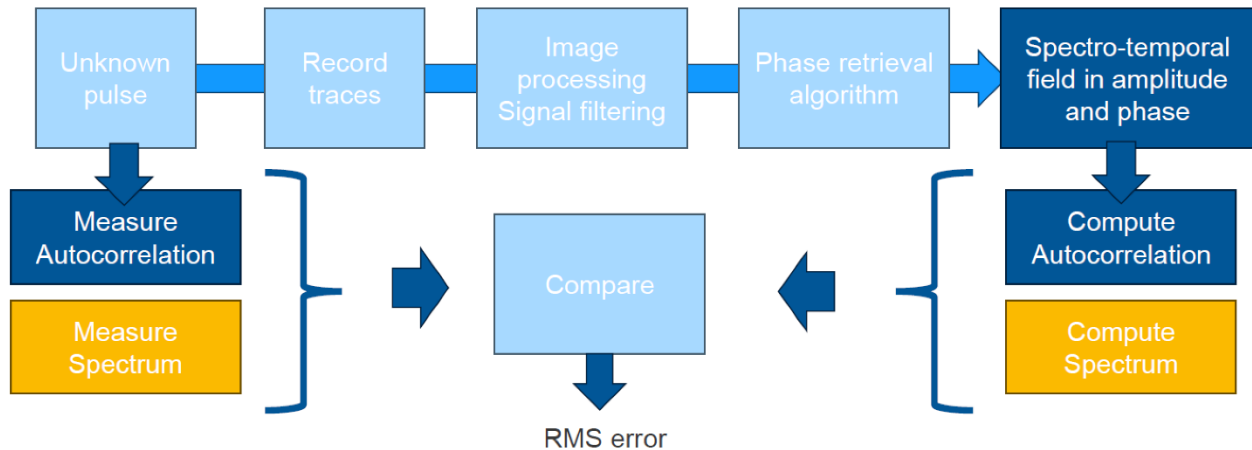
4.3.6 Assessment of spectro-temporal field reconstruction

Characterising the pulse duration is a primary objective in laser diagnostics. While this measurement alone is sufficient for FTL pulses, a comprehensive determination of the spectral phase becomes essential for pulses that do not satisfy this condition. Different orders of the spectral phase alter the temporal profile symmetrically (even orders) or asymmetrically (odd orders). While second- and third-order dispersions can typically be compensated within a grating compressor by adjusting the grating separation and the angle of incidence, higher-order phase distortions (which are critical for the fs-to-ps contrast) require compensation via an acousto-optic programmable dispersive filter (AOPDF), such as the DAZZLER (Fastlite, now Amplitude Laser). By establishing a direct feedback loop between the diagnostic tool and the filter, the spectral phase can be effectively flattened across the entire pulse spectrum.

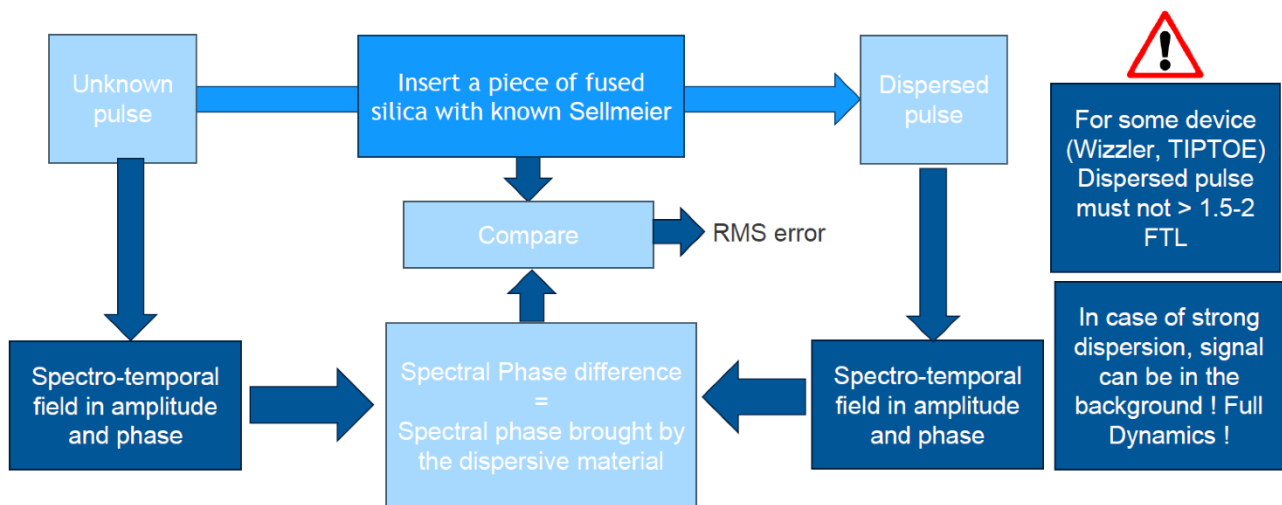


First, the traces are recorded using the diagnostic device, followed by the application of a suitable phase retrieval algorithm. Depending on the specific technique employed, this reconstruction

process is either iterative (e.g. FROG) or deterministic (e.g. SPIDER, SRSI). Based on the retrieved spectro-temporal electric field in both amplitude and phase, the theoretical traces are calculated and subsequently compared against the experimental data. To validate the accuracy of the reconstruction, the RMS error between the measured and computed traces must be minimised.



To assess the measurement performance, the retrieved amplitude and phase can be utilised to compute both the autocorrelation trace and the spectrum of the laser pulse, which are subsequently compared against benchmarks from a previously established, well-characterised autocorrelator. For benchmarking purposes, a fused silica substrate can be used as a reference material. The dispersed pulse is directed into the diagnostic device and the retrieved phase is compared to that of the unperturbed initial pulse. The introduced plate induces a predictable spectral phase; its absolute value should precisely match the spectral phase terms calculated via the Sellmeier equation. However, special care must be taken when evaluating techniques or devices that rely on higher-order nonlinear processes (e.g., Wizzler, TIPTOE). In these systems, the stretched pulse duration should ideally not exceed 1.5 to 2 times the FTL duration. Beyond this threshold, the signal level approaches the noise floor and the resulting reduction in dynamic range leads to severe errors in pulse reconstruction, rendering the retrieval algorithm unreliable or non-viable.



4.4 Conclusion: how and when to assess pulse measurements

The characterisation of ultrashort pulses is essential for designing and analysing experiments. Ideally, a complete diagnostics suite aims to fully reconstruct the spatio-temporal electric field distribution with a high dynamic range. While capturing all these parameters simultaneously on a single-shot basis remains an active area of scientific research, measuring the spectrum, energy, beam diameter and pulse duration provides a sufficient description for most user experiments conducted within the Lasers4EU access programme. Within this parameter space, pulse duration plays a pivotal role, demanding a variety of diagnostic techniques to cover a broad temporal range. Concurrently, the chosen detector must exhibit adequate spectral sensitivity tailored to the laser wavelength. High-speed photodiodes paired with fast oscilloscopes enable direct temporal measurements down to tens of picoseconds. For shorter pulse durations, nonlinear optical processes, such as sum-frequency generation, must be leveraged, with optical autocorrelators being among the most widely implemented devices. This relatively simple instrumentation remains highly robust, provided the previously outlined validation procedures are strictly performed. The Fourier-transform-limited duration, calculated directly from the measured spectrum, serves as the benchmark for pulse compression and optimisation. In an FTL scenario, the spectral phase is flat, meaning that inserting a well-defined thickness of a transparent dispersive material will cause the measured pulse duration to increase to a value that precisely matches the theoretical calculation. This validation principle remains equally valid when applying advanced retrieval algorithms to reconstruct both the spectral amplitude and the phase of the laser pulse, where the algorithm is expected to yield the exact dispersion value of the added medium.

For high-intensity experiments, the temporal intensity contrast determines the formation and evolution of a pre-plasma, which profoundly influences the interaction of the main pulse with the

target. While the coherent contrast within the several hundred femtoseconds regime can be actively controlled and accurately measured using commercial diagnostics, the ps-to-ns range is primarily governed by the fundamental laser architecture. For next-generation laser systems exceeding the petawatt level, and thus reaching peak intensities on the order of 10^{23} W/cm^2 , an extraordinary dynamic range spanning more than 12 orders of magnitude is strictly required to precisely pinpoint the onset of plasma creation and subsequent pre-heating before the arrival of the main pulse. By utilising the same fused silica substrate as in previous steps, post-pulses with a well-defined amplitude and temporal separation can be artificially introduced. This approach serves as a reliable benchmark to evaluate the response of the diagnostic tool, ultimately helping to differentiate genuine laser features from instrumental or method-dependent artefacts.

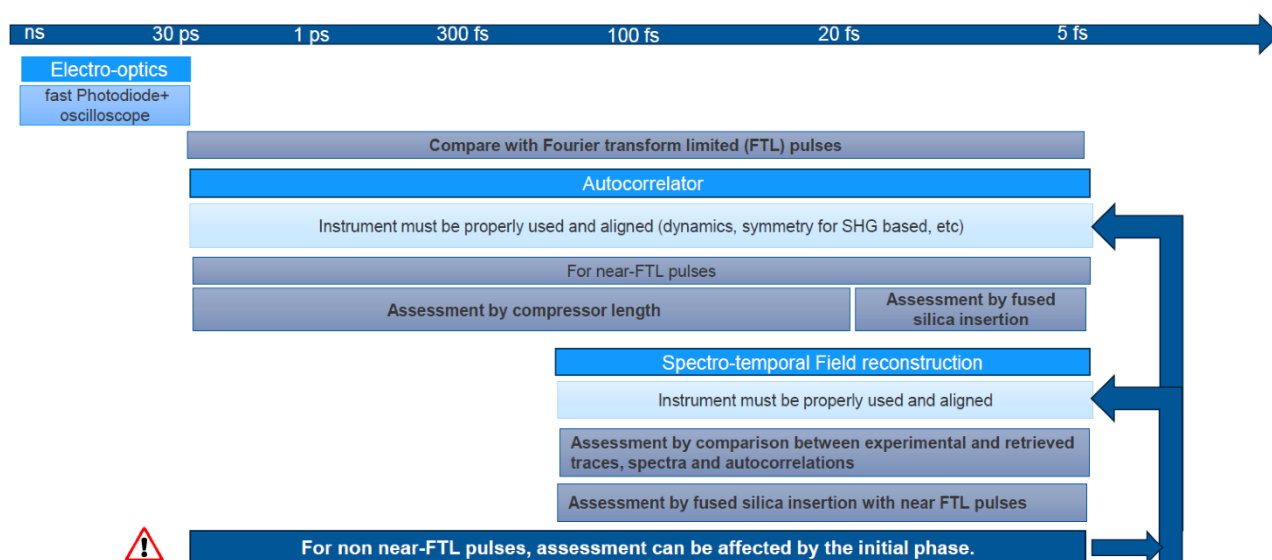


Figure 24 - Assessment of short pulse duration measurement: How?

In conclusion, we have identified a universal reference component for benchmarking and comparing diverse diagnostic devices and techniques across laser facilities, thereby enabling a standardised assessment of experimental data: a thin fused silica substrate of well-defined thickness. The introduced dispersion is analytically described with high precision by the Sellmeier equation, allowing for an accurate numerical calculation of the expected temporal pulse profile. Consequently, the measured quantities can be evaluated and the reconstruction error calculated; a strong agreement between the theoretical model and the experimental data provides high confidence in the accuracy of the measurement.

A remaining operational question is the required frequency of such performance assessments. Collaborative experience across the participating institutions indicates that when a diagnostic device is permanently installed and operated by trained personnel under fixed conditions, a single initial

validation is sufficient. However, a comprehensive re-evaluation becomes necessary if measurement results exhibit inconsistencies or unphysical values. Furthermore, devices operating on fundamentally different measurement principles should be cross-checked in the event of persistent deviations. Ultimately, implementing these routine sanity checks is highly recommended, particularly during the onboarding and training of new personnel.

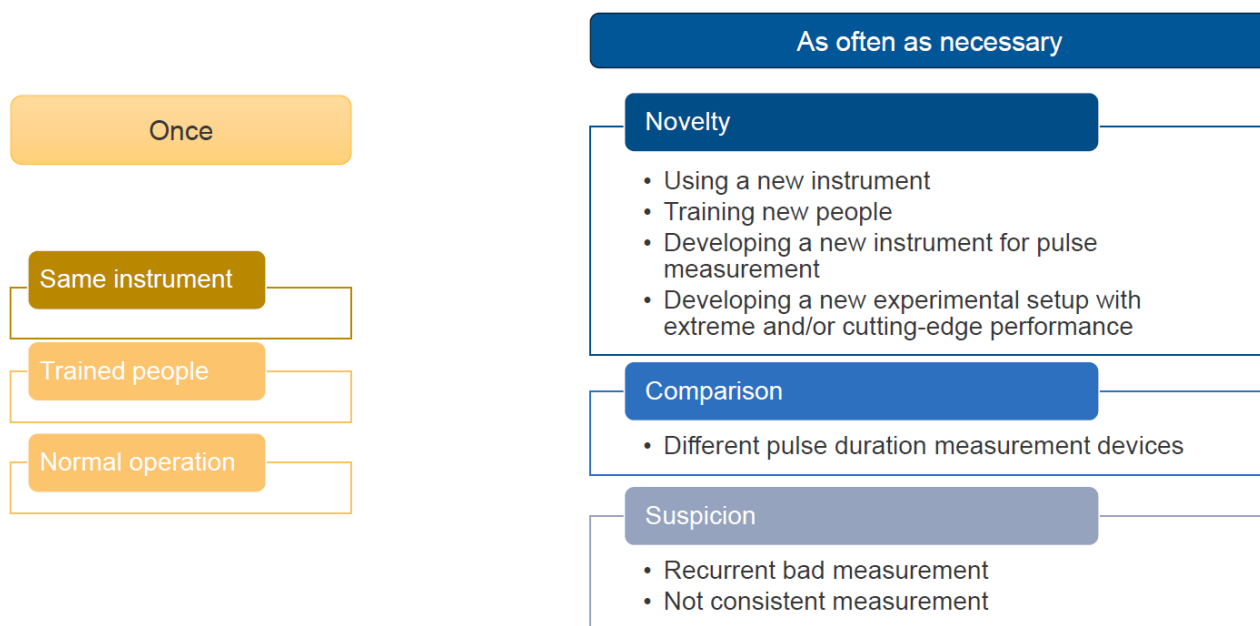


Figure 25 - Assessment of short pulse duration: When?

5 Conclusion

In conclusion, the work of the three working groups, complemented by discussions at the dedicated workshop held at ELI Beamlines in Prague, resulted in three distinct approaches to performance assessment and standardisation, reflecting the specific requirements of the respective scientific communities. For Diffuse Correlation Spectroscopy, aiming to develop devices ultimately suitable for use in clinics, the key requirement was to agree on a consistent set of FOMs related to clinically relevant measurands in order to compare the outcome of different instruments in a consistent manner. In the case of Transient Absorption Spectroscopy, which is more focussed on fundamental laboratory studies of complex materials, the approach was to identify a set of well-characterised and readily available reference compounds that can be measured across different laboratories and adapted to specific instrument configurations. Finally, for the Characterisation of Ultrafast Pulses, an organic test-path with checkpoints and milestones was drafted to permit the operator to control every crucial aspect of short pulse generation.

The next steps of this Task will imply testing some aspects of these protocols in routine user access and consider publication in scientific journals or open repositories.