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EUROMET-PR.S1.1

Final Report

Bilateral Inter-comparison of Chromatic Dispersion Reference Fibres

Bern-Wabern, October 2006
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1 Introduction

After completion of the inter-comparison of chromatic dispersion reference fibres that was carried out under EUROMET Project 666 (EUROMET-PR.S1), the Helsinki University of Technology (HUT) asked for a new bilateral inter-comparison, in order to validate the corrective modifications that they made on their measurement system. This bilateral inter-comparison was carried out by using the same rules and technical procedures that were applied for EUROMET-PR.S1. The related technical document [1] and the final report of EUROMET-PR.S1 [2] are available at the following addresses:

http://www.euromet.org/projects/search/reports/666_PHORA_Final.pdf
Metrologia, 2006, **43**, *Tech. Suppl.*, 02001.

This bilateral inter-comparison was carried out by using two of the reference fibres that were previously used for EUROMET-PR.S1, namely one G655-Leaf and one G653 fibre. A detailed description of the artefacts and of their properties is given in the technical document "Bilateral Inter-comparison METAS – HUT, Inter-comparison of Chromatic Dispersion Reference Fibres" [3].

2 Participants

Laboratory	Contact person	email
Helsinki University of technology, HUT, Finland Helsinki University of Technology (HUT in this comparison) and Centre for Metrology and Accreditation (MIKES) have established a joint laboratory in January 2005. The laboratory name will in future comparisons be abbreviated as MIKES	Antti Lamminpää	antti.lamminpaa@tkk.fi
Federal Office of Metrology, METAS, Switzerland. Pilot laboratory.	Jacques Morel	Jacques.morel@metas.ch

Table 1. List of participants.

3 Technical part

3.1 Measured quantities

The calibrated quantities are shown in Table 2.

Quantity	Symbol	Units
Overall chromatic dispersion	D	ps/nm
Zero dispersion wavelength	λ_0	nm
Dispersion slope at λ_0	S_0	ps/nm^2

Table 2. List of the calibrated quantities.

No normalisation to the fibre length was considered for this inter-comparison.

3.2 Measurement methods and data processing

HUT and METAS used two different setups based on the same phase shift measurement technique.

HUT Measurement system is outlined in Fig 1. The light source is a narrow linewidth wavelength-tunable laser (Photonetics TUNICS-PRI). The laser wavelength is continuously monitored with an accurate wavelength meter (HP 86120B) during the experiments. The output of the laser is intensity modulated with a sinusoidal signal (Agilent E4426B). The modulation frequency is 1 GHz. After the modulator the light enters the component under test and is also coupled to the reference fibre. The optical signals are detected and electrically amplified before they are mixed down to 100 MHz by another signal generator (HP 8647A). After mixers signals are low-pass filtered and amplified and sent to lock-in amplifier (Stanford SR844) for analysis of the phase and amplitude. The measurements are fully automated using the computer to control the wavelength of the tuneable laser, the data acquisition and the wavelength measurement.

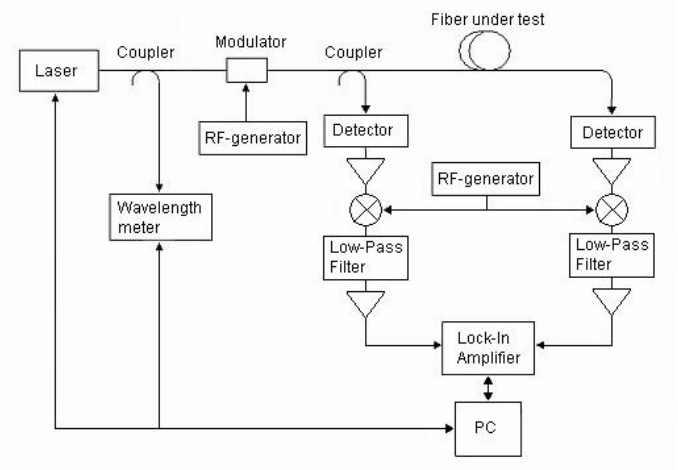


Fig. 1. HUT experimental setup based on the phase shift method.

METAS uses a measurement system based on a somewhat equivalent technique, which is shown in Fig. 2.

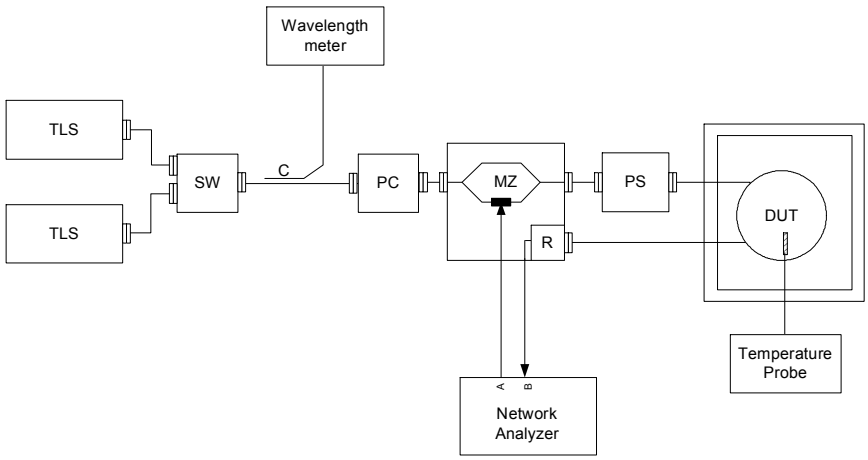


Fig. 2. METAS phase shift measurement setup.

The optical sources are Tuneable Laser Sources (TLS) with a spectral width of about 300 kHz, which are modulated using a Mach-Zehnder Modulator (MZ). Typical modulation frequencies ranging from 10 MHz to 9 GHz are used, depending on the properties of the Device Under Test (DUT). The optical signal is coupled into the DUT and is converted into an electrical signal using a fast photoreceiver (R). The phase shift between the measured signal and the RF modulation signal is measured using a RF network analyzer. An accurate measurement of the wavelength is performed using a Wavemeter. The DUT is placed in a thermally shielded chamber allowing achieving the necessary temperature stability. Online monitoring of the temperature in the DUT chamber is performed during each calibration. Special measurement procedures using a monitoring of the temperature induced phase shift during the calibration are implemented and allow the correction of the calibration data.
Phase shift calibration techniques involve a curve fitting (least squares) of the differential group delay data. For these cases, one of the polynomial functions as given in Table 3 was recommended.

Fibre type	**Wavelength domain**	**Model**	**Equation**
G653	Around λ_o= 1550 nm	Parabolic	$\tau(\lambda) = a\lambda^2 + b\lambda + c$
	Wider range	Sellmeier 5 terms	$\tau(\lambda) = a\lambda^4 + b\lambda^2 + c\lambda^{-2} + d\lambda^{-4} + e$
G655		Sellmeier 5 terms	$\tau(\lambda) = a\lambda^4 + b\lambda^2 + c\lambda^{-2} + d\lambda^{-4} + e$

Table 3. List of the standard fitting functions.

Other curve fitting models were allowed, when proved that they would significantly improve the quality of the fit.

3.3 Reporting of the calibration results

The calibration of the chromatic dispersion was performed in a wavelength domain ranging from 1480 nm to 1596 nm and the results were reported in 2 nm steps. The zero dispersion wavelength λ_o and the dispersion slope S_o around λ_o were also derived. The fitting functions applied by both laboratories are summarized for each reference fibre in Table 4.

Participant	**Ref. 2 (G653)**	**Ref. 4 (G655), Leaf**
HUT	Sellmeier 5 terms for *D* Sellmeier 3 terms for λ_o and S_o.	Sellmeier 5 terms for *D* Sellmeier 3 terms for λ_o and S_o.
METAS	Sellmeier 5 terms for *D* Sellmeier 5 terms for λ_o and S_o.	Sellmeier 5 terms for *D* Sellmeier 5 terms for λ_o and S_o.

Table 4. Curve fitting functions used by each laboratory for the data processing.

3.4 Uncertainty budget

Relevant parameters for the calculation of the uncertainty budget strongly depend on the measurement technique and on the applied data processing (curve fitting) methods. Some of the most relevant influence factors to the uncertainty budget of D, S_o and λ_o are given in Table 5.

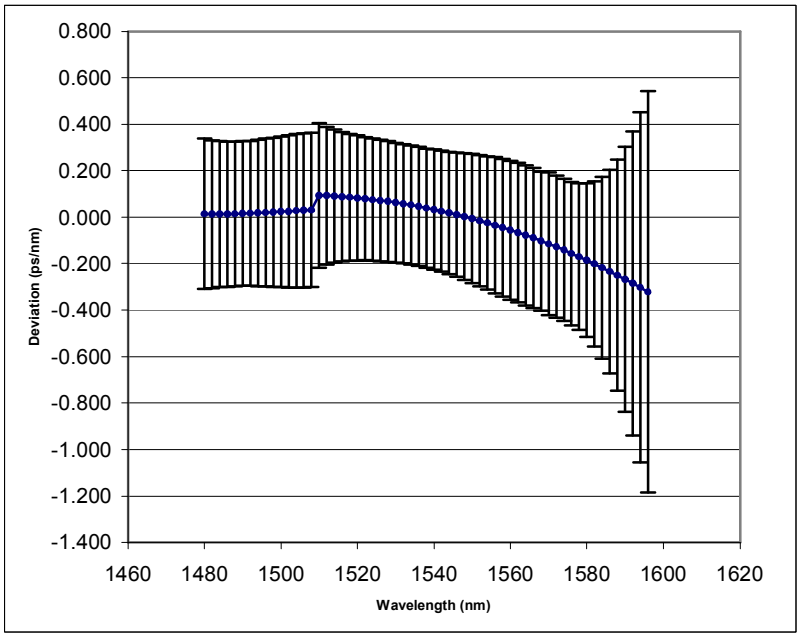
Quantity	Description
u_τ	Uncertainty in the determination of the differential group delay due to the measurement system
u_T	Uncertainty due to thermal drifts
u_{fit}	Uncertainty due to the curve fitting
U_{PMD2}	Uncertainty due to the 2nd order PMD
u_λ	Uncertainty in the determination of the wavelength associated to each measurement point

Table 5. Most relevant parameters for the calculation of the uncertainty budget.

Both laboratory developed different methods for the calculation of the uncertainty budgets, which makes a detailed comparison of the different contributing quantities almost impossible. Nevertheless, the uncertainty of each quantity was reported as the combined standard uncertainty multiplied by a coverage factor $k = 2$, estimated according to the ISO guide [4]. The reported measurement uncertainty contained contributions originating from the measurement standards, from the calibration method, from the environmental conditions and from the artefacts being calibrated.

3.5 Stability of the Reference Fibres

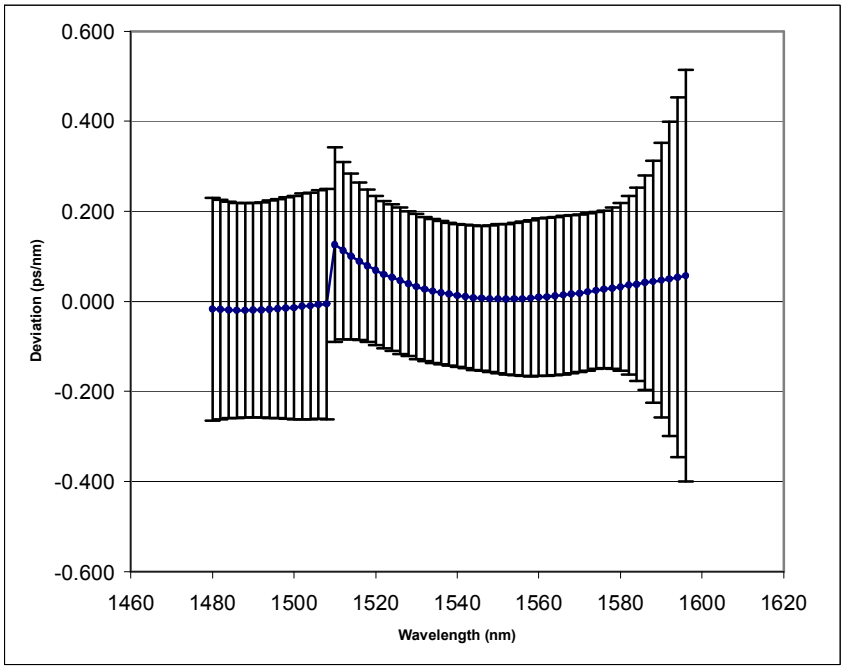
The long term stability of the G653 and G655-Leaf reference fibres was checked by comparing METAS calibration results obtained for EUROMET-PR.S1 with measurements performed during this bilateral inter-comparison (EUROMET-PR.S1.1). No significant deviations were observed, neither for the chromatic dispersion D, nor for the zero dispersion wavelength λ_o and for the dispersion slope S_o. The corresponding results are shown in Figs. (3) and (4).



Deviation of
Zero Dispersion wavelength:
$\Delta\lambda_o$ =(-0.001 ± 0.113) nm

Deviation of Dispersion slope:
ΔS_o =(-0.002 ± 0.007) ps/nm^2

Fig. 3. Long term stability of G653 Reference Fibre. The reported deviations correspond to the difference observed between METAS measurements performed during EUROMET-PR.S1 and during this inter-comparison.



Deviation of
Zero Dispersion wavelength:
$\Delta\lambda_o$ =(0.039 ± 0.113) nm

Deviation of Dispersion slope:
ΔS_o =(0 ± 0.007) ps/nm^2

Fig. 4. Long term stability of G655-Leaf Reference Fibre. The reported deviations correspond to the difference observed between METAS measurements performed during EUROMET-PR.S1 and during this inter-comparison.

3.6 Measurement results and analysis

The deviations between HUT and METAS results and their related uncertainties were calculated according to the following equations:

$$\Delta Q = Q_{HUT} - Q_{METAS}\,, \tag{1}$$

$$U_{\Delta Q} = \sqrt{U^2_{Q_{HUT}} + U^2_{Q_{METAS}}}\,, \tag{2}$$

Where Q represents one of the three calibrated quantities, namely the chromatic dispersion D, the zero dispersion wavelength λ_o and the dispersion slope S_o.

The measured values and the deviations between HUT and METAS measurements obtained for both reference fibres are detailed in the next two sections.

3.6.1 G653 Reference Fibre

3.6.1.1 Measurement results

	METAS		HUT		Deviation HUT - METAS	
Wavelength (nm)	D (ps/nm)	U_D (ps/nm)	D (ps/nm)	U_D (ps/nm)	ΔD (ps/nm)	$U_{\Delta D}$ (ps/nm)
1480	-65.316	0.248	-65.240	0.586	0.076	0.637
1482	-63.466	0.244	-63.382	0.437	0.084	0.501
1484	-61.621	0.241	-61.529	0.355	0.092	0.429
1486	-59.780	0.240	-59.680	0.257	0.100	0.352
1488	-57.944	0.239	-57.836	0.209	0.108	0.317
1490	-56.112	0.239	-55.996	0.177	0.116	0.298
1492	-54.286	0.240	-54.162	0.162	0.124	0.289
1494	-52.463	0.242	-52.331	0.162	0.132	0.291
1496	-50.645	0.244	-50.505	0.162	0.140	0.293
1498	-48.832	0.247	-48.684	0.162	0.148	0.295
1500	-47.023	0.249	-46.867	0.162	0.156	0.297
1502	-45.219	0.251	-45.055	0.162	0.164	0.299
1504	-43.418	0.253	-43.246	0.162	0.172	0.300
1506	-41.622	0.255	-41.442	0.162	0.180	0.302
1508	-39.830	0.256	-39.643	0.162	0.187	0.303
1510	-38.043	0.257	-37.847	0.162	0.196	0.304
1512	-36.259	0.256	-36.056	0.162	0.203	0.303
1514	-34.480	0.256	-34.269	0.162	0.211	0.303
1516	-32.705	0.254	-32.486	0.162	0.219	0.301
1518	-30.933	0.252	-30.707	0.162	0.226	0.299
1520	-29.166	0.250	-28.932	0.162	0.234	0.298
1522	-27.402	0.247	-27.162	0.162	0.240	0.295
1524	-25.643	0.245	-25.395	0.162	0.248	0.293
1526	-23.887	0.242	-23.632	0.162	0.255	0.291
1528	-22.135	0.240	-21.873	0.162	0.262	0.289
1530	-20.387	0.238	-20.118	0.162	0.269	0.288
1532	-18.642	0.237	-18.367	0.162	0.275	0.287
1534	-16.901	0.236	-16.619	0.162	0.282	0.286
1536	-15.164	0.237	-14.876	0.162	0.288	0.287
1538	-13.431	0.238	-13.136	0.162	0.295	0.288
1540	-11.701	0.241	-11.400	0.162	0.301	0.290
1542	-9.974	0.244	-9.667	0.162	0.307	0.293
1544	-8.251	0.248	-7.939	0.162	0.312	0.296
1546	-6.531	0.253	-6.214	0.162	0.317	0.300
1548	-4.815	0.259	-4.492	0.162	0.323	0.305
1550	-3.102	0.265	-2.774	0.162	0.328	0.310
1552	-1.393	0.270	-1.060	0.162	0.333	0.315
1554	0.314	0.275	0.651	0.162	0.337	0.319
1556	2.017	0.280	2.359	0.162	0.342	0.323
1558	3.717	0.284	4.063	0.162	0.346	0.327
1560	5.413	0.287	5.764	0.162	0.351	0.329
1562	7.107	0.288	7.461	0.162	0.354	0.330
1564	8.797	0.289	9.155	0.162	0.358	0.331
1566	10.485	0.288	10.845	0.162	0.360	0.330
1568	12.169	0.286	12.533	0.162	0.364	0.328
1570	13.850	0.284	14.217	0.162	0.367	0.327
1572	15.529	0.282	15.898	0.162	0.369	0.325
1574	17.204	0.282	17.575	0.162	0.371	0.325
1576	18.876	0.285	19.250	0.162	0.374	0.328
1578	20.546	0.293	20.921	0.162	0.375	0.335
1580	22.213	0.309	22.590	0.162	0.377	0.349
1582	23.877	0.335	24.255	0.162	0.378	0.372
1584	25.538	0.373	25.917	0.162	0.379	0.406
1586	27.197	0.422	27.576	0.177	0.379	0.458
1588	28.853	0.484	29.232	0.225	0.379	0.534
1590	30.506	0.558	30.885	0.257	0.379	0.614
1592	32.157	0.644	32.535	0.355	0.378	0.735
1594	33.805	0.744	34.183	0.454	0.378	0.872
1596	35.450	0.855	35.827	0.586	0.377	1.037

3.6.1.2 HUT – METAS deviation

The deviation results of the measured chromatic dispersion indicated a rather good agreement between HUT and METAS results. Deviation values slightly larger than their associated uncertainties were only observed in the wavelength domain from 1536 nm to 1582 nm.

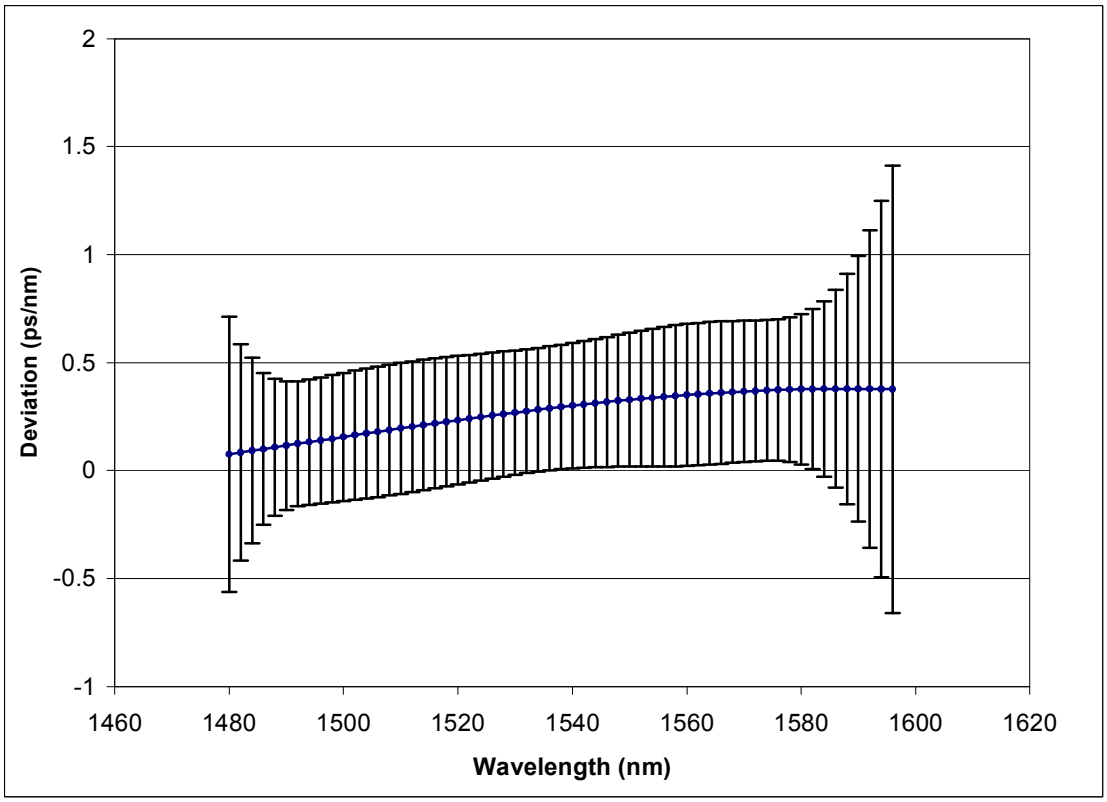


Fig. 5. Deviation of the chromatic dispersion of the G653 reference fibre. Deviations slightly larger than the reported measurement uncertainty were observed between 1536 nm and 1582 nm.

Zero Dispersion Wavelength and Dispersion slope

$\lambda_{o\,METAS}$	$U_{\lambda_{o\,METAS}}$	$\lambda_{o\,HUT}$	$U_{\lambda_{oHUT}}$	$S_{o\,METAS}$	$U_{S_{o\,METAS}}$	$S_{o\,HUT}$	$U_{S_{oHUT}}$
1553.601	0.080	1553.18	0.15	0.855	0.005	0.854	0.010

Deviation HUT - METAS

$\Delta\lambda_o$ (nm)	$U_{\Delta\lambda_o}$ (nm)	ΔS_o (ps/nm^2)	$U_{\Delta S_o}$ (ps/nm^2)
-0.421	0.170	-0.001	0.011

The measurement of the zero dispersion wavelength λ_o showed a somewhat large deviation. A possible explanation may be the contribution of the PMD of the fibre [4], which was in this case rather large (mean DGD of about 1.96 ps).

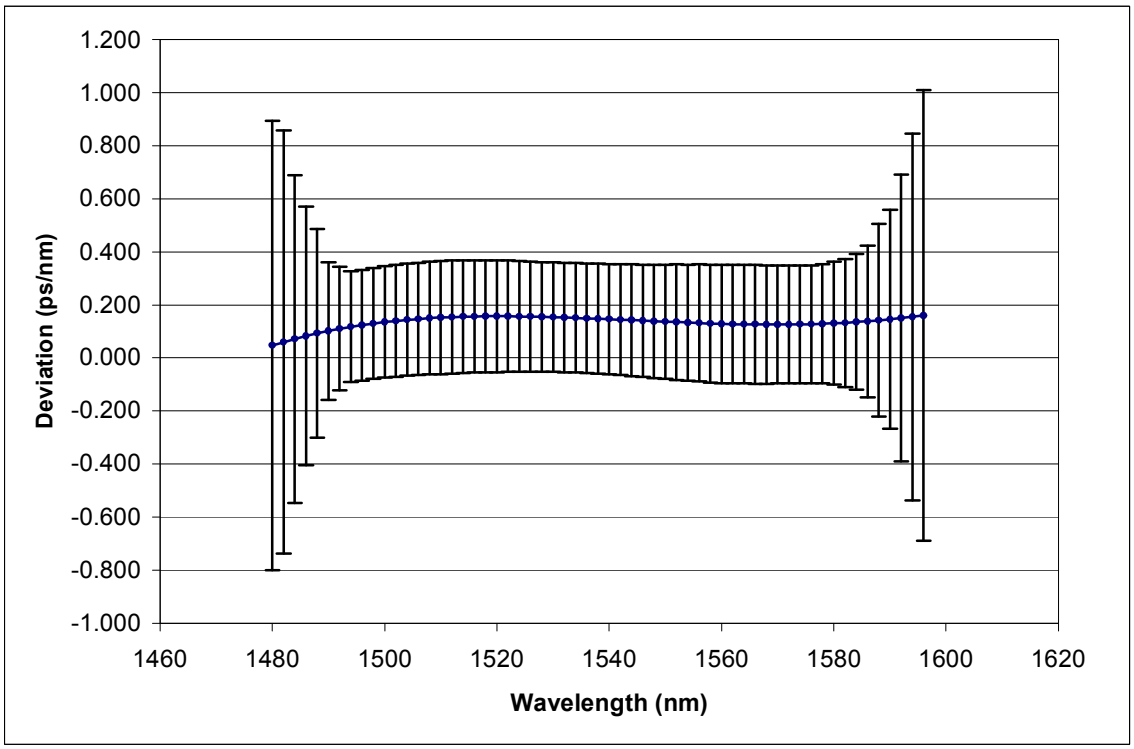
3.6.2 G655-Leaf Reference Fibre

3.6.2.1 Measurement results

	METAS		HUT		Deviation HUT - METAS	
Wavelength (nm)	D (ps/nm)	U_D (ps/nm)	D (ps/nm)	U_D (ps/nm)	ΔD (ps/nm)	$U_{\Delta D}$ (ps/nm)
1480	-18.956	0.134	-18.909	0.835	0.047	0.846
1482	-17.164	0.132	-17.104	0.786	0.060	0.797
1484	-15.374	0.130	-15.302	0.603	0.072	0.617
1486	-13.586	0.129	-13.503	0.471	0.083	0.488
1488	-11.799	0.129	-11.706	0.372	0.093	0.393
1490	-10.013	0.129	-9.912	0.225	0.101	0.259
1492	-8.230	0.130	-8.120	0.193	0.110	0.233
1494	-6.448	0.131	-6.330	0.162	0.118	0.208
1496	-4.667	0.132	-4.543	0.162	0.124	0.209
1498	-2.888	0.133	-2.758	0.162	0.130	0.209
1500	-1.111	0.134	-0.976	0.162	0.135	0.210
1502	0.665	0.135	0.804	0.162	0.139	0.211
1504	2.438	0.136	2.582	0.162	0.144	0.211
1506	4.211	0.137	4.358	0.162	0.147	0.212
1508	5.981	0.138	6.131	0.162	0.150	0.212
1510	7.750	0.138	7.902	0.162	0.152	0.212
1512	9.517	0.138	9.671	0.162	0.154	0.212
1514	11.282	0.138	11.438	0.162	0.156	0.212
1516	13.046	0.137	13.202	0.162	0.156	0.212
1518	14.808	0.136	14.965	0.162	0.157	0.211
1520	16.568	0.135	16.725	0.162	0.157	0.211
1522	18.326	0.133	18.483	0.162	0.157	0.209
1524	20.083	0.132	20.240	0.162	0.157	0.209
1526	21.838	0.131	21.994	0.162	0.156	0.208
1528	23.591	0.129	23.746	0.162	0.155	0.207
1530	25.342	0.129	25.496	0.162	0.154	0.207
1532	27.091	0.128	27.244	0.162	0.153	0.206
1534	28.839	0.128	28.990	0.162	0.151	0.206
1536	30.585	0.128	30.734	0.162	0.149	0.206
1538	32.329	0.129	32.477	0.162	0.148	0.207
1540	34.071	0.130	34.217	0.162	0.146	0.207
1542	35.812	0.132	35.956	0.162	0.144	0.209
1544	37.550	0.134	37.692	0.162	0.142	0.210
1546	39.287	0.136	39.427	0.162	0.140	0.211
1548	41.022	0.139	41.160	0.162	0.138	0.213
1550	42.755	0.142	42.891	0.162	0.136	0.215
1552	44.486	0.145	44.621	0.162	0.135	0.217
1554	46.216	0.148	46.349	0.162	0.133	0.219
1556	47.943	0.150	48.075	0.162	0.132	0.220
1558	49.669	0.152	49.799	0.162	0.130	0.222
1560	51.393	0.154	51.522	0.162	0.129	0.223
1562	53.115	0.154	53.243	0.162	0.128	0.223
1564	54.835	0.154	54.962	0.162	0.127	0.223
1566	56.553	0.154	56.680	0.162	0.127	0.223
1568	58.270	0.153	58.396	0.162	0.126	0.223
1570	59.984	0.152	60.110	0.162	0.126	0.222
1572	61.697	0.151	61.823	0.162	0.126	0.221
1574	63.408	0.151	63.535	0.162	0.127	0.221
1576	65.117	0.152	65.244	0.162	0.127	0.222
1578	66.824	0.157	66.953	0.162	0.129	0.225
1580	68.529	0.165	68.660	0.162	0.131	0.231
1582	70.233	0.179	70.365	0.162	0.132	0.241
1584	71.934	0.198	72.069	0.162	0.135	0.256
1586	73.634	0.223	73.772	0.177	0.138	0.285
1588	75.331	0.256	75.473	0.257	0.142	0.363
1590	77.027	0.294	77.173	0.290	0.146	0.413
1592	78.721	0.339	78.871	0.421	0.150	0.541
1594	80.413	0.391	80.568	0.570	0.155	0.691
1596	82.104	0.450	82.264	0.719	0.160	0.848

3.6.2.2 HUT – METAS deviation

The deviation results showed an excellent agreement between HUT and METAS results for the chromatic Dispersion *D* and for λ_o and S_o.



Zero Dispersion Wavelength and Dispersion slope

$\lambda_{o\,METAS}$	$U_{\lambda_{o\,METAS}}$	$\lambda_{o\,HUT}$	$U_{\lambda_{oHUT}}$	$S_{o\,METAS}$	$U_{S_{o\,METAS}}$	$S_{o\,HUT}$	$U_{S_{oHUT}}$
1501.276	0.080	1501.31	0.10	0.887	0.005	0.931	0.050

Deviation HUT - METAS

$\Delta\lambda_o$ (nm)	$U_{\Delta\lambda_o}$ (nm)	ΔS_o (ps/nm^2)	$U_{\Delta S_o}$ (ps/nm^2)
0.034	0.128	0.044	0.050

4 Conclusions

This bilateral inter-comparison allowed validating the HUT modified measurement system and also provided the link to the results of EUROMET-PR.S1 project. The calibration of the G655-Leaf fibres proved an excellent agreement between METAS and HUT measurements. Measurements performed on the G633 Reference Fibre showed some larger deviations of the Dispersion in the wavelength range 1536 nm to 1582 nm and in the determination of the zero dispersion wavelength. This is most probably related to the large PMD (mean DGD of 1.96 ps) of this fibre, which should be more precisely considered for a proper determination the uncertainty budgets.

5 References

[1] J. Morel, “Technical protocol EUROMET Project 666, Inter-comparison of Chromatic Dispersion Reference Fibres”.

[2] J. Morel et al. “Intercomparison of Chromatic Dispersion Reference Fibres”, *Metrologia*, 2006, **43**, *Tech. Suppl.*, 02001.

[3] J. Morel, “Technical protocol, Bilateral Inter-comparison METAS – HUT, Inter-comparison of Chromatic Dispersion Reference Fibres”

[4] Guide to the Expression of Uncertainty in Measurement, ISO, (1995).

[5] Franzen, D. L. Mechels, S. E. Schlager, J. B. (OPTOELECTRONICS DIVISION – 8 15), “Accurate Measurement of the Zero-Dispersion Wavelength in Optical Fibers”, *Journal of Research of the National Institute of Standards and Technology*, May 01, (1997).