EURAMET.PR-S3
Final Report

Bilateral Inter-comparison of Chromatic Dispersion Reference Fibres

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1 Introduction

This supplementary inter-comparison was asked by VNIIOFI in order to establish the link with previous works, which were performed in the frame of EUROMET-PR.S1. 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 reference fibres, namely one G.652 and one G.653 fibre. A detailed description of the artefacts and of their properties is given in the corresponding technical document [3].

2 Participants

Laboratory	**Contact person**	**email**
All-Russian Research Institute for Optical and Physical Measurements, VNIIOFI	Vladimir Kravtsov	Kravtsov-F3@vniiofi.ru
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

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

VNIIOFI Measurement system is outlined in Fig 1. The light sources are narrow linewidth wavelength-tunable lasers with a typical linewidth of about 500 KHz. The light of sources comes to the Mach-Zehnder modulator (MZ) and to the wavelength meter through a Y-coupler. The MZ modulator is controlled by an offset voltage controller, which sets the operating point. The Network analyzer delivers a RF signal to the MZ modulator with a frequency ranging from 100 MHz to 8 GHz. The modulated optical signal is then coupled to the DUT. At the output of DUT the optical signal is received and converted to an electrical one by the optical receiver. The phase shift between the RF signal and the signal measured with the optical receiver is measured by the network analyser. The signal is then mathematically processed, using least squares curve fitting methods. The setup is referenced before preforming every measurement of the DUT. All measurements are performed at constant temperature, which is monitored using a built-in temperature sensor. The DUT case is thermally insulated for better performances.

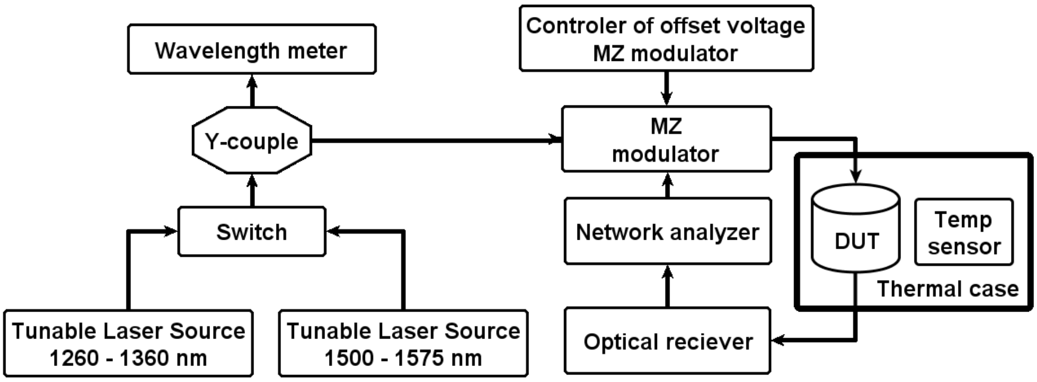


Fig. 1. VNIIOFI experimental setup based on the phase shift method.

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

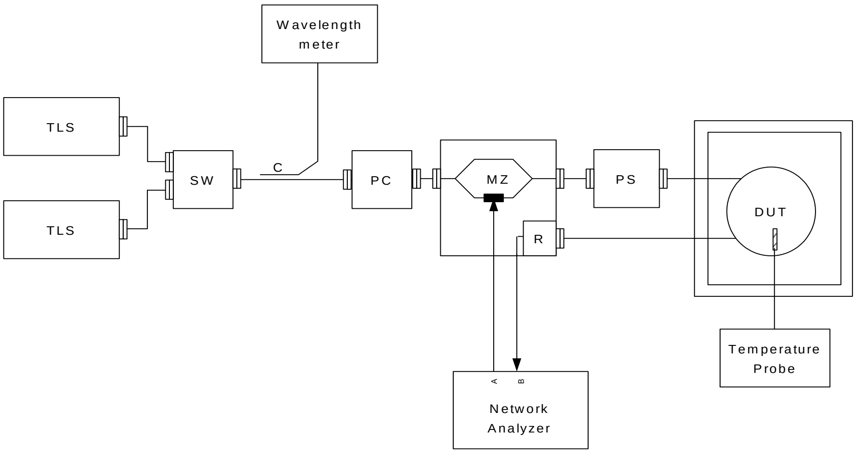


Fig. 2. METAS phase shift measurement setup.

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**
G.652	1310 nm (around λ_o)	Sellmeier 3 terms	$\tau(\lambda) = a\lambda^2 + b\lambda^{-2} + c$
	Wider range	Sellmeier 5 terms	$\tau(\lambda) = a\lambda^4 + b\lambda^2 + c\lambda^{-2} + d\lambda^{-4} + e$
G.653	Around λ_o= 1550 nm	Parabolic	$\tau(\lambda) = a\lambda^2 + b\lambda + c$
	Wider range	Sellmeier 5 terms	$\tau(\lambda) = a\lambda^4 + b\lambda^2 + c\lambda^{-2} + d\lambda^{-4} + e$

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 two wavelength domains ranging from 1260 nm to 1360 nm and from 1510 nm to 1574 nm. 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. 1 (G.652)**	**Ref. 2 (G.653)**
VNIIOFI 1260 nm – 1360 nm	Sellmeier 3 terms for D Sellmeier 3 terms for λ_o and S_o.	Sellmeier 5 terms for D
VNIIOFI 1510 nm – 1574 nm	Sellmeier 5 terms for D	Parabolic for D Parabolic for λ_o and S_o.
METAS 1260 nm – 1360 nm	Sellmeier 5 terms for D Parabolic terms for λ_o and S_o.	Sellmeier 5 terms for D
METAS 1510 nm – 1574 nm	Sellmeier 5 terms for D	Sellmeier 5 terms for D Parabolic for λ_o andS_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 andλ_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 laboratories defined different influence factors and parameters for the determination 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 Measurement results and analysis

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

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

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

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 VNIIOFI and METAS measurements obtained for both reference fibres are detailed in the next two sections. METAS results are the reference points for this comparison.

3.5.1 VNIIOFI – METAS deviation analysis

3.5.1.1 G.652 Reference Fibre

The deviation results of the measured chromatic dispersion, of the zero dispersion wavelength and of the dispersion slope showed a very good agreement. All deviations are much smaller than the corresponding uncertainty.

Chromatic Dispersion

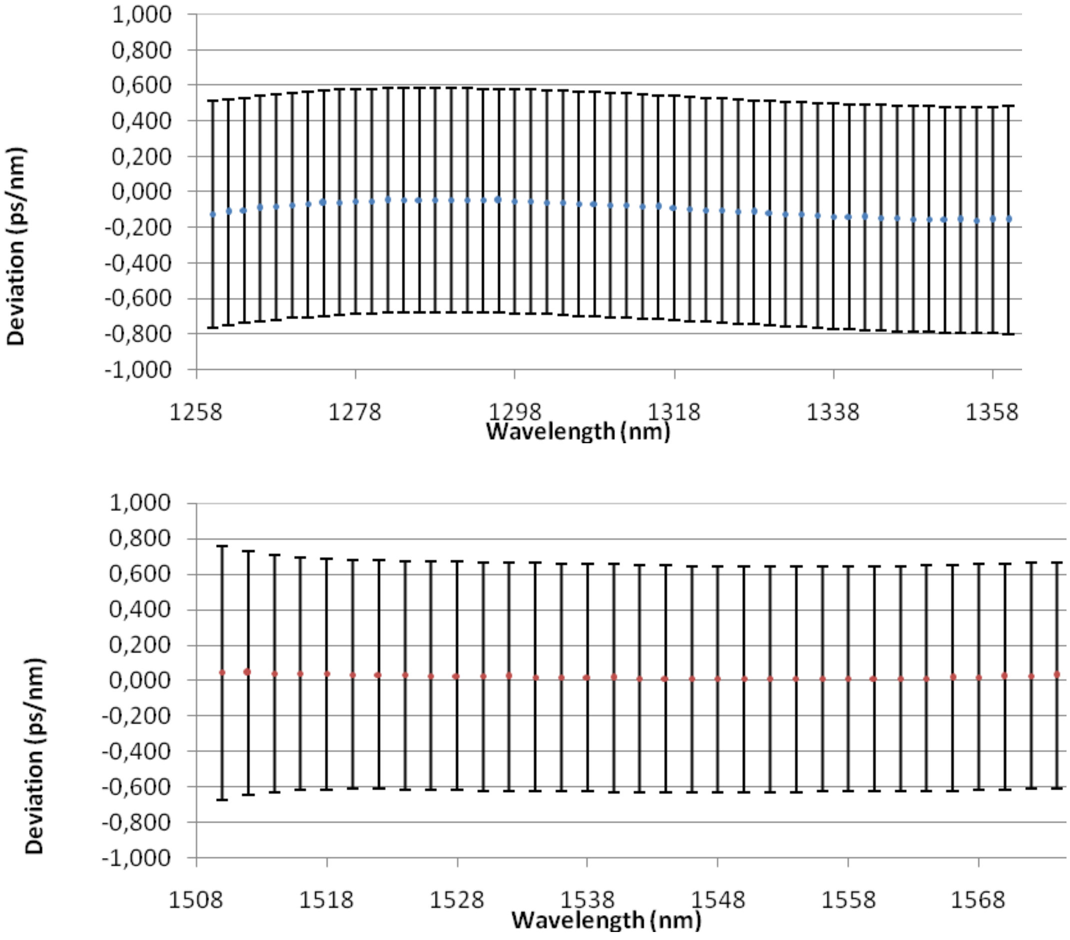


Fig. 5. Deviation of the chromatic dispersion of the G.652 reference fibre measured by VNIIOFI and METAS.

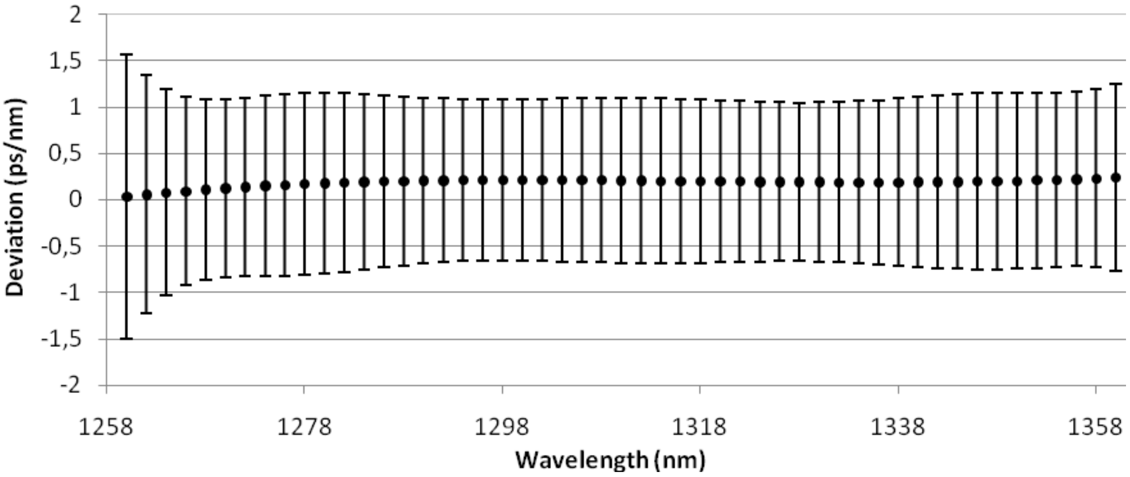
Zero Dispersion Wavelength and Dispersion slope

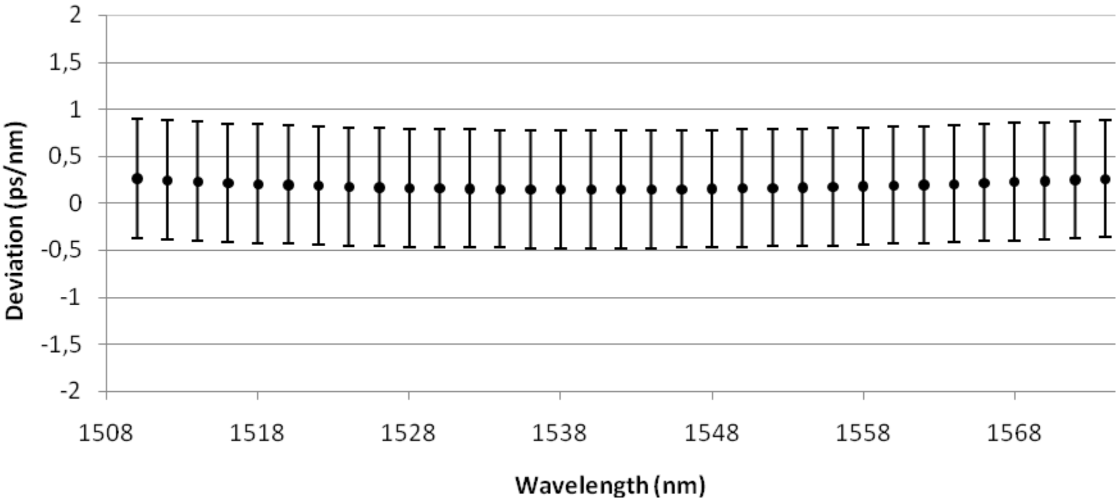
	METAS	VNIIOFI
λ_o	(1312.296± 0.080) nm	(1312.31 ± 0.15) nm
S_o	(1.107± 0.005) ps·nm^{-2}	(1.106 ± 0.008) ps·nm^{-2}
$\Delta\lambda_o$	(0.01 ± 0.17) nm	
ΔS_o	(-0.001 ± 0.009) ps·nm^{-2}	

3.5.1.2 G.653- Reference Fibre

The deviation results of the measured chromatic dispersion showed a very good agreement. All deviations are much smaller than the corresponding uncertainty. The zero wavelength dispersion results show a somewhat larger deviation, which is in the limit of the uncertainty. This effect may be attributed to the PMD of the fibre [5].

Chromatic Dispersion





Zero Dispersion Wavelength and Dispersion slope

	METAS	VNIIOFI
λ_o	(1552.806 ± 0.080) nm	(1552.58± 0.20) nm
S_o	(0.873 ± 0.007) ps·nm^{-2}	(0.877± 0.009) ps·nm^{-2}
$\Delta\lambda_o$	(-0.23 ± 0.22) nm	
ΔS_o	(0.004 ± 0.011) ps·nm^{-2}	

4 Conclusions

This bilateral inter-comparison allowed validating the VNIOFI measurement system and also provided the link to the results of EUROMET-PR.S1 project. Measurement of the chromatic dispersion performed on both the G.652 and the G.653 reference fibres showed a very good agreement. The determination of the zero dispersion wavelength of G.653 fibre showed deviations that were on the limit of the measurement uncertainty.

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 –VNIIOFI, 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).

6 Annex A. Chromatic Dispersion Measurement results

6.1.1.1 G.652 Reference Fibre

	METAS		VNIIOFI		Deviation VNIIOFI - 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)
1260	-61.458	0.151	-61.583	0.621	-0.125	0.639
1262	-58.970	0.136	-59.084	0.621	-0.114	0.636
1264	-56.494	0.130	-56.597	0.621	-0.103	0.634
1266	-54.029	0.129	-54.121	0.621	-0.092	0.634
1268	-51.575	0.130	-51.659	0.621	-0.084	0.634
1270	-49.132	0.131	-49.208	0.621	-0.076	0.635
1272	-46.700	0.132	-46.769	0.621	-0.069	0.635
1274	-44.278	0.132	-44.341	0.621	-0.063	0.635
1276	-41.868	0.131	-41.926	0.621	-0.058	0.635
1278	-39.468	0.128	-39.522	0.621	-0.054	0.634
1280	-37.079	0.125	-37.130	0.621	-0.051	0.633
1282	-34.701	0.122	-34.749	0.621	-0.048	0.633
1284	-32.333	0.118	-32.380	0.621	-0.047	0.632
1286	-29.976	0.115	-30.021	0.621	-0.045	0.632
1288	-27.629	0.112	-27.675	0.621	-0.046	0.631
1290	-25.293	0.110	-25.339	0.621	-0.046	0.631
1292	-22.968	0.109	-23.014	0.621	-0.046	0.630
1294	-20.653	0.109	-20.700	0.621	-0.047	0.630
1296	-18.348	0.109	-18.397	0.622	-0.049	0.631
1298	-16.053	0.110	-16.105	0.622	-0.052	0.632
1300	-13.769	0.111	-13.823	0.622	-0.054	0.632
1302	-11.495	0.112	-11.552	0.622	-0.057	0.632
1304	-9.231	0.113	-9.292	0.622	-0.061	0.632
1306	-6.978	0.114	-7.042	0.622	-0.064	0.632
1308	-4.734	0.114	-4.802	0.622	-0.068	0.632
1310	-2.501	0.114	-2.573	0.622	-0.072	0.632
1312	-0.277	0.114	-0.353	0.622	-0.076	0.632
1314	1.936	0.112	1.856	0.622	-0.08	0.632
1316	4.140	0.111	4.055	0.622	-0.085	0.632
1318	6.334	0.110	6.244	0.622	-0.09	0.632
1320	8.518	0.108	8.423	0.622	-0.095	0.631
1322	10.692	0.107	10.592	0.622	-0.1	0.631
1324	12.856	0.106	12.752	0.622	-0.104	0.631
1326	15.011	0.106	14.901	0.622	-0.11	0.631
1328	17.156	0.106	17.042	0.622	-0.114	0.631
1330	19.291	0.108	19.172	0.622	-0.119	0.631
1332	21.417	0.110	21.294	0.622	-0.123	0.632
1334	23.533	0.113	23.406	0.622	-0.127	0.632
1336	25.640	0.116	25.508	0.622	-0.132	0.633
1338	27.737	0.119	27.601	0.622	-0.136	0.633
1340	29.825	0.122	29.686	0.623	-0.139	0.635
1342	31.903	0.125	31.761	0.623	-0.142	0.635
1344	33.972	0.127	33.827	0.623	-0.145	0.636
1346	36.032	0.127	35.884	0.623	-0.148	0.636
1348	38.083	0.127	37.932	0.623	-0.151	0.636
1350	40.124	0.126	39.971	0.623	-0.153	0.636
1352	42.157	0.125	42.001	0.623	-0.156	0.635
1354	44.180	0.125	44.023	0.623	-0.157	0.635
1356	46.194	0.127	46.036	0.623	-0.158	0.636
1358	48.198	0.135	48.041	0.623	-0.157	0.637
1360	50.194	0.151	50.037	0.623	-0.157	0.641

	METAS		VNIIOFI		Deviation VNIIOFI - 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)
1510	182.611	0.355	182.655	0.623	0.044	0.717
1512	184.187	0.295	184.230	0.623	0.043	0.689
1514	185.759	0.248	185.799	0.622	0.040	0.670
1516	187.326	0.213	187.364	0.622	0.038	0.657
1518	188.888	0.189	188.925	0.622	0.037	0.650
1520	190.446	0.176	190.481	0.621	0.035	0.645
1522	192.000	0.169	192.033	0.621	0.033	0.644
1524	193.550	0.168	193.580	0.621	0.030	0.643
1526	195.095	0.169	195.123	0.621	0.028	0.644
1528	196.636	0.170	196.662	0.621	0.026	0.644
1530	198.173	0.171	198.197	0.621	0.024	0.644
1532	199.706	0.171	199.728	0.621	0.022	0.644
1534	201.236	0.170	201.255	0.621	0.019	0.644
1536	202.761	0.168	202.778	0.621	0.017	0.643
1538	204.282	0.165	204.298	0.621	0.016	0.643
1540	205.799	0.161	205.813	0.621	0.014	0.642
1542	207.313	0.157	207.325	0.620	0.012	0.640
1544	208.823	0.153	208.834	0.620	0.011	0.639
1546	210.329	0.149	210.339	0.620	0.010	0.638
1548	211.832	0.146	211.841	0.620	0.009	0.637
1550	213.331	0.143	213.339	0.620	0.008	0.636
1552	214.826	0.141	214.834	0.620	0.008	0.636
1554	216.318	0.140	216.326	0.620	0.008	0.636
1556	217.806	0.140	217.815	0.620	0.009	0.636
1558	219.291	0.141	219.301	0.620	0.010	0.636
1560	220.773	0.142	220.783	0.620	0.010	0.636
1562	222.252	0.143	222.263	0.620	0.011	0.636
1564	223.727	0.145	223.740	0.620	0.013	0.637
1566	225.199	0.146	225.214	0.620	0.015	0.637
1568	226.667	0.148	226.686	0.620	0.019	0.637
1570	228.133	0.149	228.155	0.620	0.022	0.638
1572	229.595	0.150	229.621	0.620	0.026	0.638
1574	231.055	0.150	231.084	0.620	0.029	0.638

6.1.1.2 G.653 Reference Fibre

	METAS		VNIIOFI		Deviation VNIIOFI - 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)
1260	-281.442	1.405	-281.409	0.621	0.033	1.536
1262	-279.148	1.123	-279.095	0.621	0.053	1.283
1264	-276.863	0.923	-276.79	0.62	0.073	1.112
1266	-274.586	0.802	-274.494	0.62	0.092	1.014
1268	-272.317	0.744	-272.209	0.62	0.108	0.968
1270	-270.056	0.73	-269.933	0.62	0.123	0.958
1272	-267.803	0.736	-267.666	0.62	0.137	0.962
1274	-265.558	0.748	-265.409	0.62	0.149	0.972
1276	-263.320	0.756	-263.161	0.62	0.159	0.978
1278	-261.091	0.757	-260.922	0.621	0.169	0.979
1280	-258.868	0.749	-258.691	0.621	0.177	0.973
1282	-256.654	0.735	-256.469	0.621	0.185	0.962
1284	-254.447	0.715	-254.256	0.621	0.191	0.947
1286	-252.248	0.691	-252.052	0.621	0.196	0.929
1288	-250.056	0.668	-249.855	0.621	0.201	0.912
1290	-247.871	0.646	-247.667	0.621	0.204	0.896
1292	-245.694	0.628	-245.487	0.621	0.207	0.883
1294	-243.524	0.615	-243.315	0.621	0.209	0.874
1296	-241.361	0.607	-241.151	0.621	0.210	0.868
1298	-239.205	0.606	-238.994	0.621	0.211	0.868
1300	-237.057	0.608	-236.846	0.621	0.211	0.869
1302	-234.915	0.614	-234.704	0.621	0.211	0.873
1304	-232.781	0.621	-232.57	0.621	0.211	0.878
1306	-230.653	0.628	-230.444	0.621	0.209	0.883
1308	-228.532	0.634	-228.324	0.621	0.208	0.887
1310	-226.418	0.638	-226.212	0.621	0.206	0.890
1312	-224.311	0.639	-224.106	0.621	0.205	0.891
1314	-222.210	0.637	-222.007	0.621	0.203	0.890
1316	-220.116	0.632	-219.915	0.621	0.201	0.886
1318	-218.029	0.624	-217.83	0.621	0.199	0.880
1320	-215.948	0.614	-215.751	0.62	0.197	0.873
1322	-213.874	0.605	-213.679	0.62	0.195	0.866
1324	-211.806	0.596	-211.613	0.62	0.193	0.860
1326	-209.745	0.59	-209.553	0.62	0.192	0.856
1328	-207.689	0.587	-207.499	0.621	0.190	0.855
1330	-205.641	0.59	-205.451	0.621	0.190	0.857
1332	-203.598	0.598	-203.409	0.621	0.189	0.862
1334	-201.561	0.612	-201.373	0.621	0.188	0.872
1336	-199.531	0.63	-199.343	0.621	0.188	0.885
1338	-197.507	0.65	-197.318	0.621	0.189	0.899
1340	-195.489	0.671	-195.299	0.621	0.190	0.914
1342	-193.476	0.691	-193.285	0.621	0.191	0.929
1344	-191.470	0.707	-191.277	0.621	0.193	0.941
1346	-189.469	0.718	-189.274	0.621	0.195	0.949
1348	-187.475	0.722	-187.276	0.621	0.199	0.952
1350	-185.486	0.719	-185.283	0.621	0.203	0.950
1352	-183.503	0.712	-183.295	0.621	0.208	0.945
1354	-181.525	0.704	-181.312	0.621	0.213	0.939
1356	-179.554	0.706	-179.333	0.621	0.221	0.940
1358	-177.587	0.731	-177.36	0.622	0.227	0.960
1360	-175.627	0.797	-175.391	0.622	0.236	1.011

	METAS		VNIIOFI		Deviation VNIIOFI - 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)
1510	-37.608	0.101	-37.345	0.626	0.263	0.636
1512	-35.837	0.088	-35.590	0.625	0.247	0.633
1514	-34.069	0.078	-33.836	0.625	0.233	0.632
1516	-32.301	0.072	-32.082	0.625	0.219	0.630
1518	-30.535	0.068	-30.328	0.624	0.207	0.630
1520	-28.770	0.067	-28.574	0.624	0.196	0.630
1522	-27.006	0.067	-26.820	0.624	0.186	0.629
1524	-25.243	0.067	-25.066	0.623	0.177	0.629
1526	-23.482	0.068	-23.312	0.623	0.170	0.629
1528	-21.721	0.068	-21.558	0.623	0.163	0.628
1530	-19.962	0.068	-19.803	0.622	0.159	0.628
1532	-18.203	0.068	-18.049	0.622	0.154	0.628
1534	-16.446	0.067	-16.295	0.622	0.151	0.627
1536	-14.690	0.066	-14.541	0.622	0.149	0.626
1538	-12.934	0.065	-12.787	0.622	0.147	0.626
1540	-11.180	0.064	-11.033	0.621	0.147	0.625
1542	-9.426	0.063	-9.279	0.621	0.147	0.625
1544	-7.674	0.062	-7.525	0.621	0.149	0.625
1546	-5.922	0.061	-5.771	0.621	0.151	0.625
1548	-4.171	0.060	-4.016	0.621	0.155	0.625
1550	-2.421	0.060	-2.262	0.621	0.159	0.624
1552	-0.671	0.059	-0.508	0.620	0.163	0.624
1554	1.077	0.059	1.246	0.620	0.169	0.624
1556	2.825	0.059	3.000	0.620	0.175	0.624
1558	4.572	0.059	4.754	0.620	0.182	0.624
1560	6.318	0.060	6.508	0.620	0.190	0.624
1562	8.064	0.060	8.262	0.620	0.198	0.623
1564	9.809	0.061	10.016	0.620	0.207	0.623
1566	11.554	0.061	11.771	0.620	0.217	0.623
1568	13.298	0.061	13.525	0.620	0.227	0.623
1570	15.041	0.062	15.279	0.620	0.238	0.623
1572	16.784	0.062	17.033	0.620	0.249	0.623
1574	18.526	0.062	18.787	0.620	0.261	0.623