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Comparison of Regular Transmittance Scales of Four National Standardizing Laboratories

A comparison of the regular spectral transmittance scales of National Institute of Standards and Technology (USA), Institut National de Metrologie (France), National Research Council (Canada), and All-Union Research Institute for Optical and Physical Measurements (CIS) was accomplished using neutral glass filters with transmittances ranging from approximately 0.92 to 0.001. Storing the filters for almost four years produced no conclusive evidence of improvement over a previous interchange between NIST and three different national standardizing laboratories when the filters were stored for only 30 days. The agreement ranges from 0.01% to 0.3% depending on the laboratory and the filter used. The uncertainties (99.7% estimated confidence level) are generally greater than the differences between NIST and the individual laboratories. The sample-induced error contributed 20% or more of the total uncertainty except for a few cases as found in the previous comparison. This interchange, similar to the previous one, is part of an ongoing effort to obtain international standardization. © *1993 by John Wiley & Sons, Inc.*

INTRODUCTION

A previous comparison of regular transmittance measurements between the standardizing laboratories of the United States, Germany, the United Kingdom, and Hungary has been published.[1] That comparison will be referred to as Comparison I. The present comparison with three different laboratories and NIST is reported in a parallel manner with Comparison I so that the results can be easily evaluated. The interchange described in this article is referred to as Comparison II. One aspect of Comparison I was the large contribution of sample-induced uncertainties. The NIST filters used for Comparison I were first measured about 30 days after cleaning. No further cleaning was done before subsequent measurements except for a light dusting with a clean camel-hair brush. For Comparison II, the filters had been stored for almost four

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CCC 0361-2317/93/010035-06

years. If the bulk absorbing samples were subject to a surface film, it was anticipated that the longer aging period would reduce the sample contribution to the uncertainty. This was not the case, as discussed below. Comparisons I and II show that reference instruments with systematic uncertainties which are small either by correction or instrument design, and with random uncertainties which are also small, can produce excellent results. The results show that agreement between laboratories is better than the small total uncertainty. This is in contrast to the results of a transmittance Measurement Assurance Program[2] (MAP) in which similar comparisons were made with industrial laboratories with disagreement often much larger than the total measurement uncertainty.

ORGANIZATION OF COMPARISON

A comparison of regular transmittance between Institut National de Metrologie (INM), National Research Council (NRC), All-Union Research Institute for Optical and Physical Measurements (VNIIOFI), and National Institute of Standards and Technology (NIST) similar to that in Comparison I was deemed necessary to serve the international industrial community. At first, the intention was to use the same set of filters for all four laboratories. However, the logistics made it desirable to introduce a second set of filters for the NIST-VNIIOFI interchange. The measurement sequences would be NIST-NRC-NIST-INM-NIST, and NIST-VNIIOFI-NIST. NIST supplied two sets of absorbing filters of seven per set.[3] NIST measured the nonuniformity of the filters before and after the measurements of INM, NRC, and VNIIOFI. Each laboratory illuminated a 15-mm diameter spot on the filters except VNIIOFI, which used a 10-mm diameter spot. NIST examined these filters for a difference in transmittance using a 15-mm spot and a 10-mm spot.

INSTRUMENTATION

All four reference spectrophotometers [4–7] used in this intercomparison are well characterized with estimates of systematic and statistical uncertainties. Their important features are given in Table I. A number of features are common to the measurement systems: they all use reflecting optics to eliminate interreflections between the optics and the sample, and to collimate the radiation incident on the sample to minimize obliquity effects. System linearity is measured, and corrections are made. Systematic uncertainties are either negligible by instrumental design or are made small by numerical corrections. The common sources of systematic uncertainty are beam displacement and defocusing effects, interreflections, obliquity, polarization, linearity, wavelength bias, and stray light. A treatment of the uncertainty analysis following current international statistical practice may be found in Ref. 4.

The instruments are automated so that it is straightforward to repeat measurements and to evaluate statistical uncertainties. INM and VNIIOFI reported their total uncertainties, which were put on a 3σ basis (U_{lab} in Tables II and IV, respectively). The uncertainties, U_{lab} in Tables II–IV for NIST and Table III for NRC, are the combination in quadrature of an upper bound for the systematic uncertainty, ΔT_s (3σ), and the statistical uncertainty expressed as three times the standard deviation of the mean, $3\Delta T_R$:

$$U_{\text{lab}} = [(\Delta T_s)^2 + (3\Delta T_R)^2]^{1/2}, \tag{1}$$

where

$$\Delta T_R = \left[\sum_{i=1}^{n} (\tau_i - \bar{\tau})^2/n(n-1)\right]^{1/2}$$

Here τ_i is the measured transmittance, $\bar{\tau}$ the mean of the set of measurements, and n is the number of measurements in the set. Sample-induced errors were evaluated for the specimens.

RESULTS

The results of the intercomparisons are shown in Tables II–IV. The wavelengths λ chosen for the laboratory comparison, are the same that NIST normally uses for the MAP service. An estimate of the uncertainty, U_{sample}, is given for each specific filter. It is the addition in quadrature of the observed change in the filter and nonuniformity of the filter (3σ estimates). Each individual filter change was estimated from the first and second NIST measurements. It was estimated that each laboratory could position the filters to 1-mm accuracy using their normal procedure. For the NIST instrument, some of the types of errors that can contribute to this 1-mm uncertainty are as follows:

(a) The alignment laser and the tungsten lamp used for the measurement do not follow the same path. It is estimated they can differ by an angle of 0.004 radian. Since the limiting aperture and the filter are separated by 50 mm, this can cause an uncertainty of 0.2 mm.

(b) The alignment laser spot in the sample compartment is over 2 mm in diameter with a fuzzy edge, causing another 0.2 mm uncertainty.

(c) The position of the filter in its holder is uncertain by 0.3 mm.

(d) The device for measuring uniformity itself has a position uncertainty of 0.2 mm.

If all of the above act in the same direction, a conservative 3σ estimate is 0.9 mm, rounded to 1.0 mm. Therefore nonuniformity was estimated for a 2-mm displacement from the center position at 548.5 nm for the MAP filters. This is a conservative 3σ estimate that assumes NIST had a placement error of 1 mm in one direction, and the particular laboratory had a 1 mm placement error in the opposite direction. 2-mm displacements of the filters were made in four directions—up, down, left, and right, with all movement perpendicular to the light beam. The displacement that gave the largest change in transmittance from the center position was chosen as the displacement

TABLE I. Instrument characteristics.

Lab	Band-pass (nm)	Diameter of the illuminating area (mm)	Temp. (°C)	Lamp	Collimating optics	Collimation (rad)	Monochromator	High-order rejection	Detection system	Wavelength accuracy (nm)	Amplification
NIST	1.5	15	23 ± 0.5	Tungsten ribbon	Off-axis mirrors	0.0025	Grating	Prism predisperser	Averaging sphere and photomultiplier	0.04	dc
INM	0.52	15	23 ± 0.5	Quartz halogen	Spherical mirrors	<0.0017	Filter and holographic grating	Filter	Averaging sphere and photomultiplier	0.02	dc
NRC	1.5	15	23 ± 0.5	Quartz halogen	Spherical mirrors	<0.0119	Grating	Prism predispenser	Ground quartz and silicon photodiodes; photomultipliers	0.1	dc
VNIIOFI	2.4	10	23 ± 1.0	Tungsten ribbon	Spherical mirrors	0.009	Double-grating	Filter	Averaging sphere and photodiode	0.05	dc

TABLE II. Results of interchange with INM.

λ (nm)	NIST τ (before)	NIST τ (after)	NIST τ (ave)	INM τ	U_{NIST}	U_{INM}	U_{sample}	U_{total}	$\Delta\tau$
Filter 2-1									
539.50	0.9157	0.9149	0.9153	0.9153	0.00017	0.00033	0.00045	0.0006	0.0000
542.50	0.9157	0.9149	0.9153	0.9152	0.00018	0.00036	0.00043	0.0006	−0.0001
548.50	0.9159	0.9150	0.9155	0.9153	0.00013	0.00030	0.00046	0.0006	−0.0002
554.50	0.9159	0.9152	0.9156	0.9154	0.00013	0.00033	0.00041	0.0005	−0.0002
557.50	0.9160	0.9152	0.9156	0.9155	0.00017	0.00030	0.00044	0.0006	−0.0001
Filter 2-2									
539.50	0.6924	0.6923	0.6923	0.6922	0.00011	0.00033	0.00028	0.0004	−0.0001
542.50	0.6926	0.6926	0.6926	0.6926	0.00013	0.00024	0.00028	0.0004	0.0000
548.50	0.6928	0.6927	0.6927	0.6926	0.00013	0.00024	0.00028	0.0004	−0.0001
554.50	0.6924	0.6923	0.6923	0.6922	0.00012	0.00030	0.00028	0.0004	−0.0001
557.50	0.6918	0.6917	0.6918	0.6917	0.00014	0.00024	0.00028	0.0004	−0.0001
Filter 2-3									
539.50	0.5182	0.5183	0.5182	0.5176	0.00010	0.00042	0.00014	0.0005	−0.0006
542.50	0.5187	0.5188	0.5187	0.5182	0.00012	0.00033	0.00014	0.0004	−0.0005
548.50	0.5190	0.5190	0.5190	0.5184	0.00010	0.00057	0.00013	0.0006	−0.0006
554.50	0.5184	0.5185	0.5184	0.5178	0.00011	0.00048	0.00013	0.0005	−0.0006
557.50	0.5176	0.5177	0.5177	0.5170	0.00010	0.00021	0.00014	0.0003	−0.0007
Filter 2-4									
539.50	0.2360	0.2361	0.2360	0.2362	0.00008	0.00039	0.00017	0.0004	0.0002
542.50	0.2367	0.2368	0.2368	0.2369	0.00009	0.00036	0.00016	0.0004	0.0001
548.50	0.2374	0.2375	0.2374	0.2375	0.00008	0.00048	0.00016	0.0005	0.0001
554.50	0.2369	0.2370	0.2369	0.2371	0.00010	0.00042	0.00017	0.0005	0.0002
557.50	0.2361	0.2362	0.2362	0.2365	0.00008	0.00036	0.00017	0.0004	0.0003
Filter 2-5									
539.50	0.09605	0.09606	0.09605	0.09597	0.000079	0.000039	0.000063	0.00011	−0.00008
542.50	0.09653	0.09656	0.09654	0.09648	0.000072	0.000039	0.000065	0.00010	−0.00006
548.50	0.09701	0.09701	0.09701	0.09691	0.000075	0.000045	0.000062	0.00011	−0.00010
554.50	0.09666	0.09668	0.09667	0.09656	0.000083	0.000060	0.000063	0.00012	−0.00011
557.50	0.09613	0.09619	0.09616	0.09606	0.000074	0.000054	0.000069	0.00011	−0.00010
Filter 2-6									
539.50	0.009145	0.009149	0.009147	0.009135	0.0000145	0.0000111	0.0000083	0.000020	−0.000012
542.50	0.009191	0.009201	0.009196	0.009187	0.0000145	0.0000096	0.0000094	0.000020	−0.000009
548.50	0.009231	0.009237	0.009234	0.009222	0.0000145	0.0000108	0.0000086	0.000020	−0.000012
554.50	0.009186	0.009194	0.009190	0.009175	0.0000146	0.0000126	0.0000090	0.000021	−0.000015
557.50	0.009132	0.009144	0.009138	0.009122	0.0000150	0.0000144	0.0000099	0.000023	−0.000016
Filter 2-7									
539.50	0.0009263	0.0009265	0.0009264	0.0009272	0.00000216	0.00000720	0.00000211	0.0000078	0.0000008
542.50	0.0009346	0.0009343	0.0009345	0.0009352	0.00000248	0.00000600	0.00000211	0.0000068	0.0000007
548.50	0.0009396	0.0009395	0.0009395	0.0009413	0.00000230	0.00000630	0.00000211	0.0000070	0.0000018
554.50	0.0009334	0.0009326	0.0009330	0.0009342	0.00000259	0.00000660	0.00000215	0.0000074	0.0000012
557.50	0.0009258	0.0009263	0.0009260	0.0009246	0.00000264	0.00000960	0.00000213	0.0000102	−0.0000014

TABLE III. Results of interchange with NRC.

λ (nm)	NIST τ (before)	NIST τ (after)	NIST τ (ave)	NRC τ	U_{NIST}	U_{NRC}	U_{sample}	U_{total}	Δτ
Filter 2-1									
539.50	0.9160	0.9157	0.9158	0.9159	0.00014	0.00046	0.00025	0.0005	0.0001
542.50	0.9160	0.9157	0.9159	0.9160	0.00020	0.00052	0.00027	0.0006	0.0001
548.50	0.9161	0.9159	0.9160	0.9161	0.00013	0.00052	0.00023	0.0006	0.0001
554.50	0.9162	0.9159	0.9161	0.9161	0.00016	0.00047	0.00026	0.0006	0.0000
557.50	0.9163	0.9160	0.9162	0.9161	0.00019	0.00051	0.00028	0.0006	−0.0001
Filter 2-2									
539.50	0.6929	0.6924	0.6926	0.6927	0.00010	0.00037	0.00033	0.0005	0.0001
542.50	0.6932	0.6926	0.6929	0.6930	0.00016	0.00028	0.00036	0.0005	0.0001
548.50	0.6934	0.6928	0.6931	0.6932	0.00011	0.00031	0.00035	0.0005	0.0001
554.50	0.6930	0.6924	0.6927	0.6927	0.00013	0.00034	0.00037	0.0005	0.0000
557.50	0.6925	0.6918	0.6921	0.6921	0.00015	0.00031	0.00038	0.0005	−0.0000
Filter 2-3									
539.50	0.5185	0.5182	0.5183	0.5184	0.00010	0.00029	0.00017	0.0004	0.0001
542.50	0.5190	0.5187	0.5188	0.5188	0.00012	0.00019	0.00018	0.0003	−0.0000
548.50	0.5194	0.5190	0.5192	0.5190	0.00011	0.00017	0.00021	0.0003	−0.0002
554.50	0.5188	0.5184	0.5186	0.5185	0.00014	0.00022	0.00020	0.0003	−0.0001
557.50	0.5180	0.5176	0.5178	0.5177	0.00011	0.00025	0.00020	0.0003	−0.0001
Filter 2-4									
539.50	0.2365	0.2360	0.2362	0.2361	0.00012	0.00010	0.00032	0.0004	−0.0001
542.50	0.2372	0.2367	0.2369	0.2368	0.00010	0.00014	0.00026	0.0003	−0.0001
548.50	0.2378	0.2374	0.2376	0.2375	0.00008	0.00010	0.00027	0.0003	−0.0001
554.50	0.2373	0.2369	0.2371	0.2370	0.00015	0.00012	0.00028	0.0003	−0.0001
557.50	0.2366	0.2361	0.2364	0.2362	0.00009	0.00010	0.00029	0.0003	−0.0002
Filter 2-5									
539.50	0.09616	0.09605	0.09610	0.09602	0.000081	0.000115	0.000087	0.00017	−0.00008
542.50	0.09670	0.09653	0.09661	0.09653	0.000079	0.000112	0.000108	0.00018	−0.00008
548.50	0.09711	0.09701	0.09706	0.09696	0.000079	0.000123	0.000083	0.00017	−0.00010
554.50	0.09682	0.09666	0.09674	0.09662	0.000085	0.000123	0.000102	0.00018	−0.00012
557.50	0.09633	0.09613	0.09623	0.09613	0.000075	0.000118	0.000122	0.00019	−0.00010
Filter 2-6									
539.50	0.009167	0.009145	0.009156	0.009147	0.0000150	0.0000210	0.0000140	0.000029	−0.000009
542.50	0.009219	0.009191	0.009205	0.009194	0.0000149	0.0000226	0.0000160	0.000031	−0.000011
548.50	0.009257	0.009231	0.009244	0.009233	0.0000147	0.0000209	0.0000155	0.000030	−0.000011
554.50	0.009219	0.009186	0.009202	0.009189	0.0000148	0.0000221	0.0000182	0.000032	−0.000013
557.50	0.009167	0.009132	0.009150	0.009137	0.0000161	0.0000214	0.0000194	0.000033	−0.000013
Filter 2-7									
539.50	0.0009296	0.0009263	0.0009280	0.0009261	0.00000217	0.00000804	0.00000231	0.0000086	−0.0000019
542.50	0.0009378	0.0009346	0.0009362	0.0009334	0.00000228	0.00000901	0.00000227	0.0000096	−0.0000028
548.50	0.0009437	0.0009396	0.0009416	0.0009401	0.00000261	0.00000547	0.00000262	0.0000066	−0.0000015
554.50	0.0009384	0.0009334	0.0009359	0.0009334	0.00000242	0.00000563	0.00000296	0.0000068	−0.0000025
557.50	0.0009293	0.0009258	0.0009275	0.0009264	0.00000291	0.00000564	0.00000238	0.0000068	−0.0000011

which gave an upper bound for transmittance to the nonuniformity estimate. Separate estimates were made for the 10-mm and 15-mm spot sizes. The spot sizes of the illuminating light are given in Table I. The uncertainty due to bandpass differences is negligible. The temperature effect for neutral glasses of this type has been measured by other researchers for filters with transmittance of 0.1, 0.2, and 0.3.[8] According to them, an uncertainty of 0.5 °C in temperature causes an average change of transmittance of approximately 0.000 03 at 546.1 nm. Because of the spectral neutrality of the filters tested for temperature effects and due to the fact that the filters used in this comparison were measured on a plateau, a similar relative uncertainty in transmittance is expected for the latter filters. In any case, for this comparison, changes due to temperature variability will not change U_{lab} or U_{total} significantly. U_{total} is the square root of the quadrature sum of U_{NIST}, U_{lab}, and U_{sample}:

$$U_{total} = [U_{NIST}^2 + U_{lab}^2 + U_{sample}^2]^{1/2}. \tag{2}$$

The difference $\Delta\tau$ is the difference of transmittance measurements between the particular laboratory and NIST, $\Delta\tau = \tau_{lab} - \tau_{NIST}$, where τ_{NIST} is the average of the NIST measurements before and after τ_{lab}. An analysis of variance was made for each set of differences according to wavelength and filter. These analyses showed a dependence of the transmittance difference on the filters (1 through 7) [F value = 33.7; $P(>F)$ = 0] but not on wavelength [F value = 3.07; $P(>F)$ = 0.084]. A discussion of the statistical methods used may be found in Ref. 9. The averages over all wavelengths of the percent difference plotted versus transmittance are shown for the three labo-

TABLE IV. Results of interchange with VNIIOFI.

λ (nm)	NIST τ (before)	NIST τ (after)	NIST τ (ave)	VNIIOFI τ	U_{NIST}	$U_{VNIIOFI}$	U_{sample}	U_{total}	Δτ
Filter 3-1									
539.50	0.9151	0.9153	0.9152	0.9159	0.00018	0.00050	0.00023	0.0006	0.0007
542.50	0.9151	0.9152	0.9152	0.9159	0.00014	0.00050	0.00021	0.0006	0.0007
548.50	0.9153	0.9155	0.9154	0.9160	0.00020	0.00050	0.00024	0.0006	0.0006
554.50	0.9153	0.9155	0.9154	0.9161	0.00010	0.00050	0.00023	0.0006	0.0007
557.50	0.9154	0.9156	0.9155	0.9162	0.00010	0.00050	0.00022	0.0006	0.0007
Filter 3-2									
539.50	0.6913	0.6914	0.6914	0.6926	0.00012	0.00050	0.00061	0.0008	0.0012
542.50	0.6916	0.6918	0.6917	0.6929	0.00014	0.00050	0.00061	0.0008	0.0012
548.50	0.6918	0.6919	0.6919	0.6929	0.00014	0.00050	0.00061	0.0008	0.0010
554.50	0.6914	0.6915	0.6914	0.6923	0.00009	0.00050	0.00061	0.0008	0.0009
557.50	0.6909	0.6910	0.6909	0.6919	0.00009	0.00050	0.00061	0.0008	0.0010
Filter 3-3									
539.50	0.5183	0.5185	0.5184	0.5188	0.00010	0.00052	0.00033	0.0006	0.0004
542.50	0.5188	0.5190	0.5189	0.5192	0.00009	0.00052	0.00033	0.0006	0.0003
548.50	0.5191	0.5192	0.5192	0.5192	0.00012	0.00052	0.00033	0.0006	0.0000
554.50	0.5184	0.5187	0.5185	0.5184	0.00008	0.00052	0.00034	0.0006	−0.0001
557.50	0.5177	0.5179	0.5178	0.5176	0.00009	0.00052	0.00034	0.0006	−0.0002
Filter 3-4									
539.50	0.2367	0.2368	0.2368	0.2374	0.00008	0.00024	0.00028	0.0004	0.0006
542.50	0.2375	0.2375	0.2375	0.2379	0.00008	0.00024	0.00027	0.0004	0.0004
548.50	0.2381	0.2382	0.2382	0.2383	0.00008	0.00024	0.00027	0.0004	0.0001
554.50	0.2376	0.2377	0.2377	0.2376	0.00008	0.00024	0.00028	0.0004	−0.0001
557.50	0.2369	0.2370	0.2369	0.2367	0.00007	0.00024	0.00028	0.0004	−0.0002
Filter 3-5									
539.50	0.09572	0.09581	0.09576	0.09611	0.000075	0.000192	0.000095	0.00023	0.00035
542.50	0.09620	0.09629	0.09625	0.09654	0.000073	0.000193	0.000096	0.00023	0.00030
548.50	0.09665	0.09674	0.09670	0.09684	0.000081	0.000194	0.000097	0.00023	0.00016
554.50	0.09632	0.09643	0.09637	0.09636	0.000074	0.000193	0.000100	0.00023	−0.00001
557.50	0.09583	0.09593	0.09588	0.09585	0.000074	0.000192	0.000099	0.00023	−0.00003
Filter 3-6									
539.50	0.009469	0.009470	0.009470	0.009454	0.0000143	0.0000284	0.0000321	0.000045	−0.000016
542.50	0.009517	0.009521	0.009519	0.009502	0.0000142	0.0000285	0.0000321	0.000045	−0.000017
548.50	0.009552	0.009560	0.009556	0.009527	0.0000150	0.0000286	0.0000323	0.000046	−0.000029
554.50	0.009509	0.009517	0.009513	0.009494	0.0000165	0.0000285	0.0000324	0.000046	−0.000020
557.50	0.009456	0.009460	0.009458	0.009440	0.0000146	0.0000283	0.0000322	0.000045	−0.000018
Filter 3-7									
539.50	0.0009349	0.0009372	0.0009360	0.0009332	0.00000218	0.00000467	0.00000412	0.0000066	−0.0000028
542.50	0.0009418	0.0009444	0.0009431	0.0009401	0.00000243	0.00000470	0.00000417	0.0000067	−0.0000030
548.50	0.0009464	0.0009510	0.0009487	0.0009448	0.00000242	0.00000472	0.00000460	0.0000070	−0.0000039
554.50	0.0009408	0.0009440	0.0009424	0.0009392	0.00000243	0.00000470	0.00000428	0.0000068	−0.0000032
557.50	0.0009336	0.0009359	0.0009347	0.0009321	0.00000276	0.00000466	0.00000413	0.0000068	−0.0000026

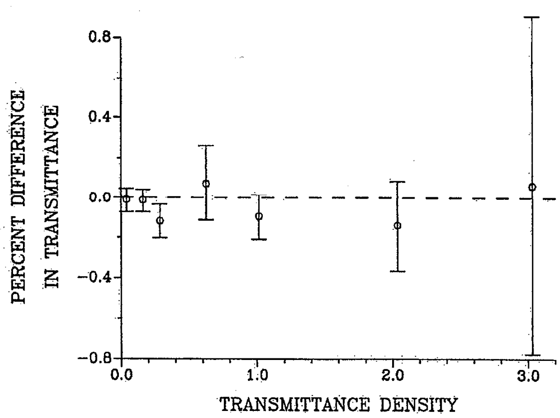

FIG. 1. Percent difference between INM and NIST versus transmittance (optical) density.

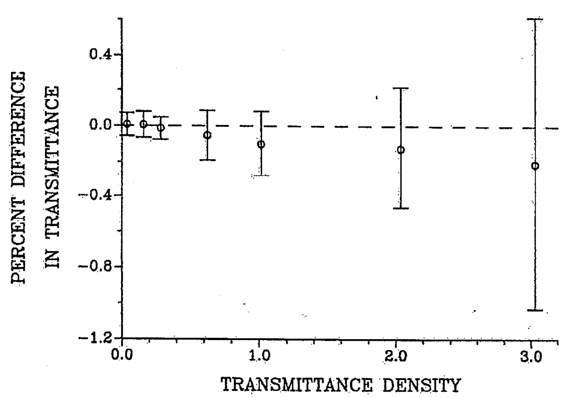

FIG. 2. Percent difference between NRC and NIST versus transmittance (optical) density.

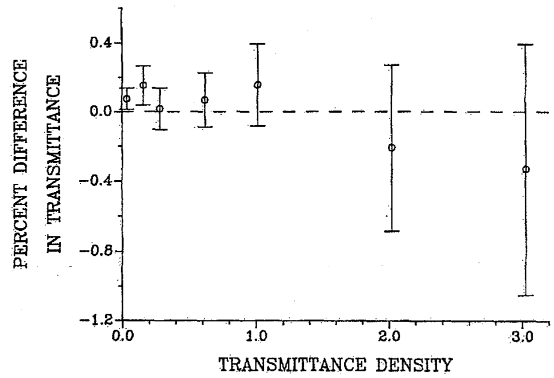

FIG. 3. Percent difference between VNIIOFI and NIST versus transmittance (optical) density.

ratories in Figs. 1–3. It may also be seen that in almost all cases this difference is smaller than the total uncertainty, U_{total}. To illustrate this, U_{total} as a percentage of transmittance is shown by the error bars. The transmittance differences between laboratories are larger than expected for filters 2-3 (INM) and 3-1 and 2 (VNIIOFI). The differences for these filters remain unexplained. Thus the differences between the laboratories, although real, are so small as to be of no practical significance. The major role of U_{sample} is seen in Fig. 4, where the average over wavelength of the fractional contribution of U_{sample}, $U_{sample}/(U_{NIST} + U_{lab} + U_{sample})$, is plotted versus transmittance for the INM, NRC, and VNIIOFI.

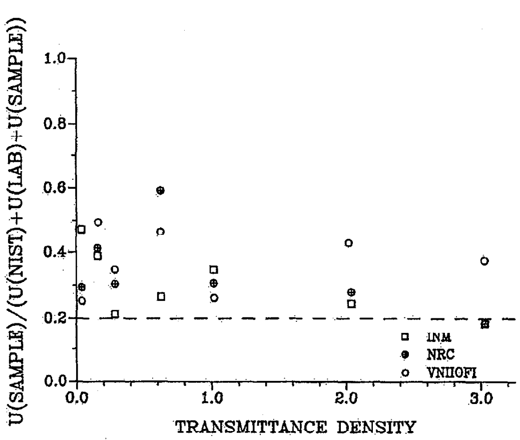

FIG. 4. $U_{sample}/(U_{NIST} + U_{lab} + U_{sample})$ for INM, NRC, and VNIIOFI versus transmittance (optical) density.

CONCLUSIONS

This comparison demonstrates the state of the art for transmittance measurements since the measurements were made with the four instruments built and maintained by national standards laboratories. The small measured disagreement between the four laboratories indicates a good ability to measure transmittance uniformly. Our analysis of the intercomparison leads to the following conclusions:

(a) The measured transmittance differences between the three laboratories and NIST generally were less than the uncertainty of the comparison, U_{total}. INM and NRC tend to measure lower values than NIST, while VNIIOFI tends to be higher for high transmittances and lower for low transmittances.

(b) The relative sample uncertainty U_{sample} is a significant factor to the total relative uncertainty U_{total} for most of the filters studied (see Fig. 4). The fractional contribution of U_{sample}, $U_{sample}/(U_{NIST} + U_{lab} + U_{sample})$, is 20% or more except in a few cases.[10]

(c) The results of this comparison indicate that aging of the filters produced no significant difference between Comparison II results over Comparison I results. Perhaps the use of other types of filters would be useful for this type of comparison.

ACKNOWLEDGMENT

Kenneth L. Eckerle of NIST wishes to thank Jack J. Hsia, Albert Parr, and Klaus D. Mielenz for their support.

1. K. L. Eckerle, E. Sutter, G. H. C. Freeman, G. Andor, and L. Fillinger, International intercomparison of regular transmittance scales, *Metrologia* **27**, 33–38 (1991).
2. K. L. Eckerle, J. J. Hsia, and V. R. Weidner, *Transmittance MAP Service*, Natl. Inst. Stand. Technol. (U.S.) Special Publ. No. 692, U.S. GPO, Washington, DC, 1985.
3. K. D. Mielenz, K. L. Eckerle, R. P. Madden, and J. Reader, New reference spectrophotometer. *Appl. Opt.* **12**, 1630–1641 (1973).
4. K. L. Eckerle, J. J. Hsia, K. D. Mielenz, and V. R. Weidner, *Regular Spectral Transmittance*, Natl. Inst. Stand. Technol. (U.S.) Special Publ. No. 250-6, U.S. GPO, Washington, DC, 1987.
5. Jean Bastie (private communication).
6. J. C. Zwinkels and D. S. Gignac, Development of a new reference spectrophotometer, *Optical Radiation Measurements II*, SPIE Vol. 1109, SPIE, Bellingham, WA, 1989, p. 89.
7. V. Sapritsky (private communication).
8. R. Mavrodineanu and J. R. Baldwin, *Glass Filters as a Standard Reference Material for Spectrophotometry-Selection, Preparation, Certification, use SRM 930*, Natl. Inst. Stand. Technol. (U.S.) Special Publ. No. 260-51, U.S. GPO, Washington, DC, 1975.
9. W. Mendenhall and T. Sincich, *Statistics for the Engineering and Computer Sciences*, Dellen, San Francisco, 1988, pp. 335–338.
10. In Comparison I, U_{sample}/U_{total} was plotted. That plot is misleading because U_{total} is the quadrature sums of U_{NIST}, U_{lab}, and U_{sample}. The fraction plotted in Fig. 4 of this Comparison is a better estimate of the contribution of U_{sample} to the total uncertainty.

Received 15 February 1992; accepted 3 June 1992