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A Color Gamut Assessment Standard: Construction, Characterization and Inter-Laboratory Measurement Comparison

John M. Libert[1], Edward F. Kelley, Paul A. Boynton, and Steven W. Brown
National Institute of Standards and Technology[2]

Christine Wall and Colin Campbell
National Physical Laboratory

Abstract

In earlier papers, NIST proposed a standard illumination source and optical filter targets with which to assess the state-of-the-art of display measurement. The Display Measurement Assessment Transfer Standard (DMATS) was designed to present the display metrologist with a rectangular array of targets such as color filters, polarizers, and grilles, back-lighted by uniform illumination, to be measured using methods and instruments typically used in display performance measurement. A "round robin" interlaboratory measurement exercise using the "standard" artifact suite would enable a first order assessment of display measurement reproducibility, i.e., measurement variability within the electronic display community. The rectangular array design of the DMATS was anticipated to present stray light and color contamination challenges to facilitate identification of error sources deriving from measurement protocols, laboratory environment, and equipment. However, complications in dealing with heating problems threatened to delay the planned laboratory intercomparison. The Gamut Assessment Standard (GAS) was thus designed as an interim solution to enable the NIST scientists and participating measurement laboratories to begin collecting data. The GAS consists of a 150 mm diameter integrating sphere standard illumination source with a stray light elimination tube (SLET) mounted at the exit port. A dual six-position filter wheel is mounted at the SLET exit port. One wheel holds a series of neutral density filters and a second interchangeable wheel holds various color filters. This paper describes the design and construction of the GAS, its initial performance characterization by NIST, and comparison measurements made at NPL. Possible design changes suggested by the results of the preliminary intercomparison are discussed, as are plans for future interlaboratory comparisons and potential use of the GAS as a transfer standard for laboratory self-certification.

Keywords: display measurement, colorimetry, interference filters

1. Introduction

1.1 Motivation

The electronic information display has become the principal communication interface for an increasing number of applications. Computer-driven displays have found their way into virtually all aspects of modern life from the simple numerical and graphical displays of the automobile dashboard to the high resolution display devices now used for viewing diagnostic x-rays and tomographic scans or microscopic pathology studies, now common in modern medical facilities. With the expansion of the Internet and the display of electronic images, it has become possible to select and buy virtually any product "online." Moreover, it is possible for a physician in a remote, underdeveloped part of the world to consult with a specialist anywhere in the world for assistance with a diagnosis, aided by high-resolution imagery and even motion video.

Because electronic information displays have come to play such a key role in commerce and industry, the National Institute of Standards and Technology (NIST) has directed technical resources toward assisting the display industry by developing robust methods for measuring display system performance and for characterizing display measurement devices. As part of this effort, we have undertaken a research project aimed at reducing the interlaboratory variance of color and other measurements used to characterize electronic display performance.

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[1] Correspondence: Email: libert@eeel.nist.gov Telephone: 301-975-3828; Fax: 301-975-3157

[2] Electricity Division, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Technology Administration, U.S. Department of Commerce.

Fig. 1 Each DMATS unit will consist of a uniform illumination source with a suite of optical targets mounted in a faceplate, power supply, monitoring devices, and a laptop computer for automatic data logging.

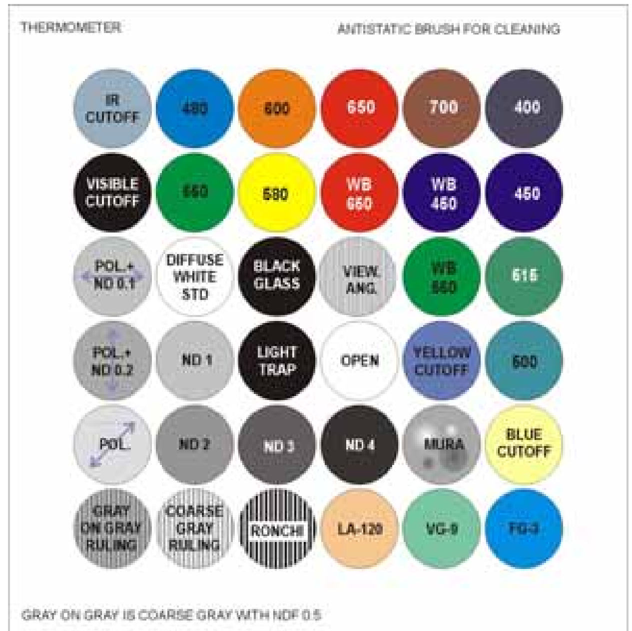

Fig. 2 One proposed faceplate configuration including narrow-band and wide-band (WB) interference filters, neutral density (ND) filters, and other artifacts.

1.2 DMATS

In previous papers, Libert proposed use of a Display Measurement Assessment Transfer Standard (DMATS) in an interlaboratory measurement comparison to evaluate the interlaboratory reproducibility of various display measurements [1] [2]. The original DMATS concept, depicted in Fig.1, consists of a standard illumination source constructed from a polystyrene container with a selection of filters and other optical targets mounted at the exit port. Such containers were shown through earlier work at NIST [3] to serve quite well as light integrating devices, able to produce surprisingly uniform illumination across a very large exit port [1][3].

Figure 2 shows one possible configuration of optical targets considered for the DMATS. Narrow band interference filters are included in the test artifact suite to enable the metrologist to examine the color gamut measurement capability of measurement instruments. In this case, it is assumed that should an instrument accurately measure the saturated colors, it should likely be able to measure accurately the more limited color gamut of an actual display. Moreover, departures from expected chromaticity values might be diagnostic of error in spectral measurements [4] from noise, stray light, wavelength error, and other sources. Other artifacts and their juxtaposition in the target array were designed to assess confounding effects of ambient stray light and effects of inadequate masking of contaminating light sources on the faceplate itself. For example, measures of ambient stray light in the environment could be diagnosed via measurements of black glass and white reflectance sample in comparison to that of the light trap. The series of neutral density filters would reveal measurement non-linearities. That several ND filters are backed by polarizers at different orientations might provide clues to possible polarization biases of instruments. Grilles are provided to examine small area contrast measurements.

Improvements have been made over the prototype DMATS described in previous papers. Principally, the device has been redesigned to better maintain structural stability with handling and shipping. Figure 3 shows the current DMATS. The polystyrene box is used as an insert for the rugged container constructed using commercially available extruded aluminum girders and expanded PVC panels. The front panel is machined from plate aluminum and features threaded apertures for mounting filters in standard optical filter holders. Additional apertures are provided to accommodate photodiodes and thermocouples for monitoring purposes.

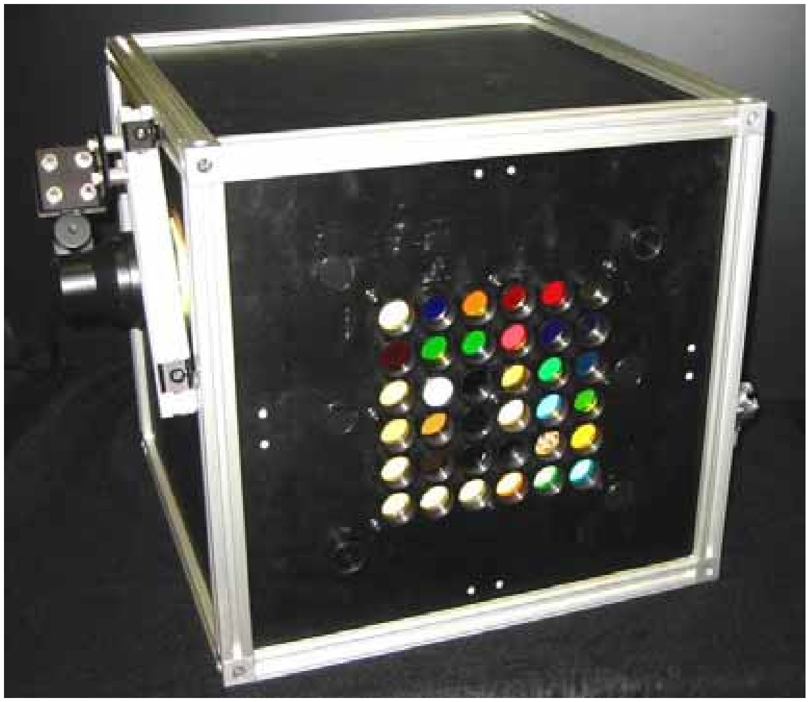

Fig. 3 Current “ruggedized” DMATS constructed of extruded aluminum components, expanded PVC shell, and polystyrene box liner. Exterior dimensions (w x h x d) are 44 cm x 43 cm x 43 cm.

Difficulties were encountered in stabilizing the temperature of the DMATS. A cooling scheme using fans was an obvious remedy, but might introduce undesirable vibration. Successful passive cooling, without perturbing the light reflection behavior of the interior, was achieved by installing heat-absorbing glass over the illuminator ports. This achieved the desired temperature control, but at the expense of altering the source spectrum to an undesirable degree, even in the visible band. Moreover, as one feature of the DMATS was to help diagnose possible IR contamination of measurements, an alternate cooling strategy is being developed.

Before fielding the DMATS, other enhancements include a biaxial positioning system, possibly built into the shipping container. The plan calls for automating control of this positioning system via a laptop computer to be shipped with the DMATS to simplify and standardize positioning of the DMATS for the laboratory intercomparison. The laptop computer will also handle control and monitoring of power supply current, and will log temperature and response of both photopic-filtered and unfiltered photodiodes.

2. Gamut Assessment Standard

2.1 Construction

Because of delays to the schedule for constructing DMATS units for distribution and for implementation of the planned laboratory intercomparison, we designed an alternative device to enable us to begin collecting data on reproducibility of color measurements. While lacking some of the diagnostic features designed into the DMATS, we recognized that a simpler device could be used effectively to begin to obtain a baseline assessment of color and luminance measurement variability. Moreover, by using an arrangement of filter wheels illuminated by a standard broadband integrating sphere source for our initial measurement intercomparison, we might be better able to interpret the confounding effects of stray light or color contamination more likely to occur with the DMATS.

A new measurement artifact was constructed as shown in Figs. 4 and 5. In that the compact device provides a means to evaluate color measurement methods and instrumentation, we refer to it as the *Gamut Assessment Standard* (GAS). This name should not be taken to imply that the GAS presumes to replicate the color gamut of any actual display device. But, as will be explained later, it is proposed as a test artifact by which to assess the state-of-the-art of display color gamut measurement.

The illumination source was a modified Hoffman[3] integrating sphere source, LS-65-D having a 15.0 cm diameter and 2.5 cm exit port. This source is normally fitted with a micrometer aperture adjustment mechanism. Out of concern that such a mechanism might inadvertently be misadjusted during an interlaboratory comparison, or broken

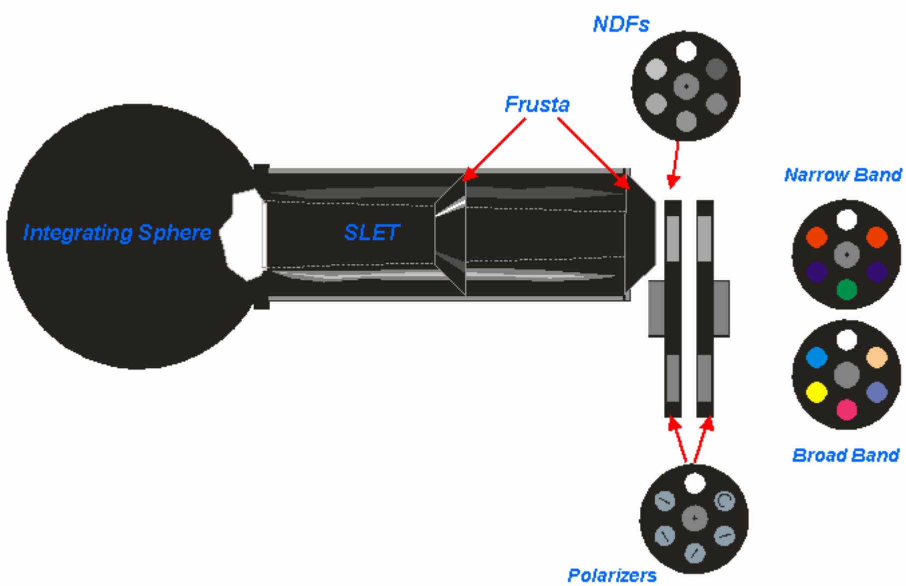

Fig. 4 Schematic of GAS showing internal frusta of SLET and dual filter wheel arrangement.

off during transport or handling, it was removed. The adjustable aperture was replaced with an aluminum plate into which was machined a 1.65 mm fixed aperture providing a constant, maximum illumination of the interior of the sphere. A stray light elimination tube (SLET)[5] was fabricated from aluminum tubing and fitted with opposing frusta as depicted to reduce internal reflections. The SLET enables illumination of the optical targets, including highly reflective thin film interference filters, at sufficient distance to significantly reduce back-reflection into the source. Thus, with even the most reflective of the metallic thin-film filters, source luminance readings of over 9000 cd/m^2 were perturbed by less than 1 cd/m^2.

Figure 5 is a photograph of the GAS, the measurement of which is discussed in the remainder of this paper. Wheel 0, the proximal wheel (i.e., that nearest the source), includes one empty position and a series of neutral density filters having optical densities 0.1, 1.0, 2.0, 3.0, and 4.0. This wheel remains in place during all measurements and, when calibrated, provides a measure of instrument linearity. It is used alone or in combination with any of the color filters or other artifacts mounted in the distal wheel. The current configuration includes three interchangeable wheels to be mounted in the distal position. These are fitted with transmission filter artifacts as summarized in Table 1.

Wheel 1 is fitted with narrow band interference filters to sample the spectrum locus of the visible color space. These filters were selected with the expectation that saturated-color, narrow band filters would be most likely to reveal disparity among color measurements. The underlying assumption here is that accurate measurement of the white point and the saturated colors included in the GAS test suite should provide reasonable assurance that any display color gamut could be measured within the uncertainty limits found in measuring the GAS test suite. This idea explains why we do not propose simply using a flat panel display as a test artifact. That is, our objective is to

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[3] Brand names are mentioned only for the purpose of specifying the experimental apparatus and procedures. Hence, their use here does not constitute an endorsement of the product by NIST, NPL, or by other government agencies of the U. S. or U. K., nor should it be taken to imply unsuitability of alternative products for the application described herein.

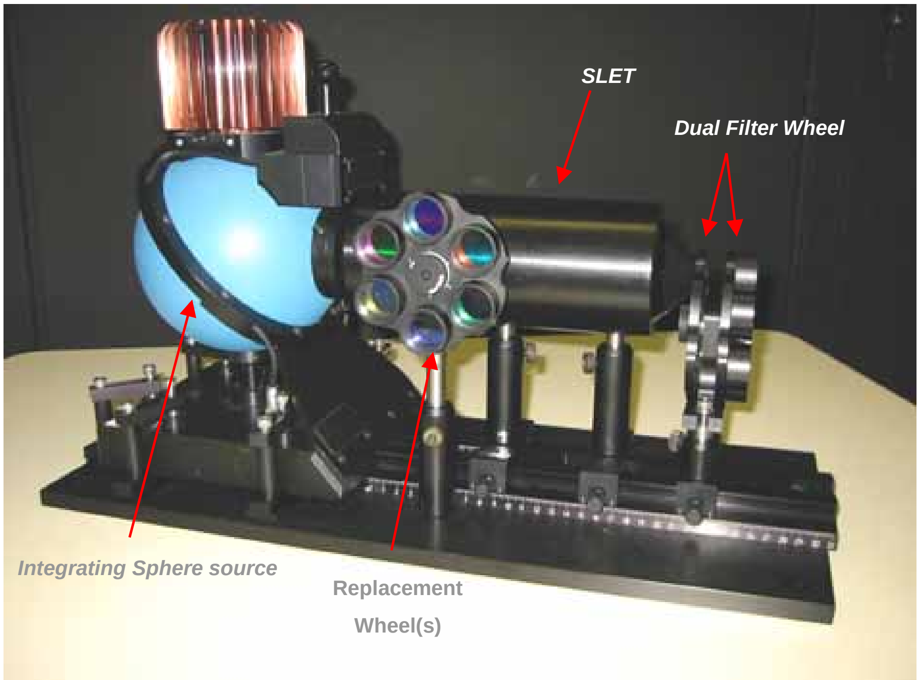

Fig. 5 Gamut Assessment Standard. The proximal filter wheel is equipped with neutral density filters, and the distal wheel is fitted with various color filters. Other wheels fitted with alternate filter suites can be interchanged easily.

develop a measurement artifact that will stress measurement capabilities used to measure displays that might have an extended color gamut not yet found in an existing display.

The filter suite of Wheel 1 includes 400 nm and 700 nm filters. The investigators note that low signal-to-noise ratios for filters at the visible spectrum extrema might become an issue for some measurement systems, but such filters are included in part to evaluate such problems.

Table 1 Optical target arrangement in each of four filter wheels.

	Wheel 0	**Wheel 1**	**Wheel 2**	**Wheel 3**
		Narrow Band	**Color Processing Filters**	**(Mostly)**
Position		**Interference Filters**		**Cut-off, Cut-on Filters**
1	Empty	Empty	Additive Red	550 nm Short Pass
2	ND 0.1	λ=400 nm $\Delta\lambda$=10 nm	Subtractive Cyan	550 nm Long Pass
3	ND 1.0	λ=480 nm $\Delta\lambda$=10 nm	Subtractive Magenta	700 nm Short Pass
4	ND 2.0	λ=514.5 nm $\Delta\lambda$=10 nm	Subtractive Yellow	700 nm Long Pass
5	ND 3.0	λ=580 nm $\Delta\lambda$=10 nm	Additive Blue	Hoya VG-9 (Green glass)
6	ND 4.0	λ=780 nm $\Delta\lambda$=10 nm	Additive Green	Hoya FG-3 (Blue glass)

Wheel 2 is fitted with series of additive and subtractive color filters. These are standard color process filters and examples of broadband colors falling within the interior of the CIE color space. Wheel 3 contains short pass and long pass 550 nm and 700 nm filters and two broadband colored glass filters.

2.2 Characterization

Figure 6 shows the spectrum of the source illuminator for reference. Figures 7 – 10 show percent spectral transmission of the each of the filters included in the current configuration of the GAS device. The ND filters (Fig. 7) exhibit the expected flat spectral transmittance except the filter having optical density 4.0. With the apparatus used for these measurements, spectral radiance at each wavelength, λ_i , from 360 nm to 830 nm is repeatable with expanded uncertainty, U , of 0.6 % or less with a k-factor of 2.

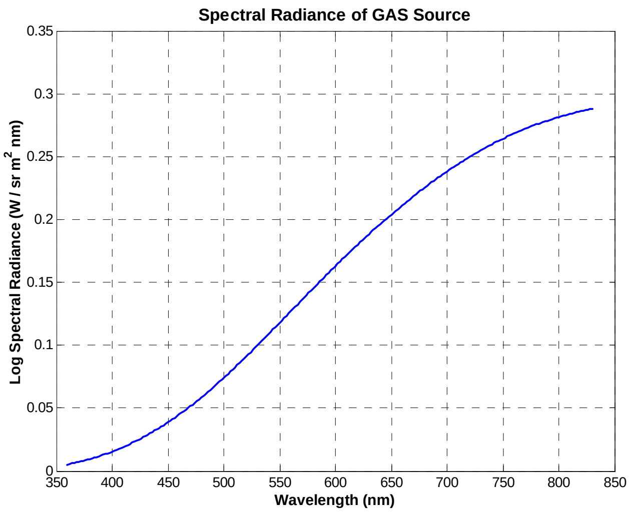

Fig. 6 Spectral radiance of GAS source illuminator.

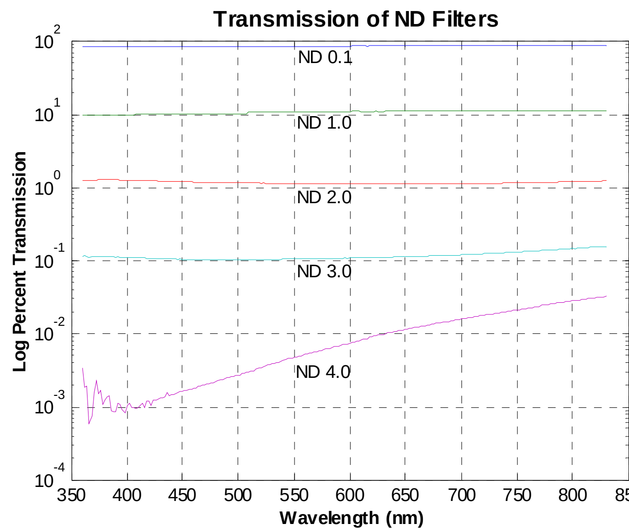

Fig. 7 Log percent transmission of neutral density filters of Wheel 0. Note that filter having optical density 4 is decidedly non-linear over the wavelength range considered.

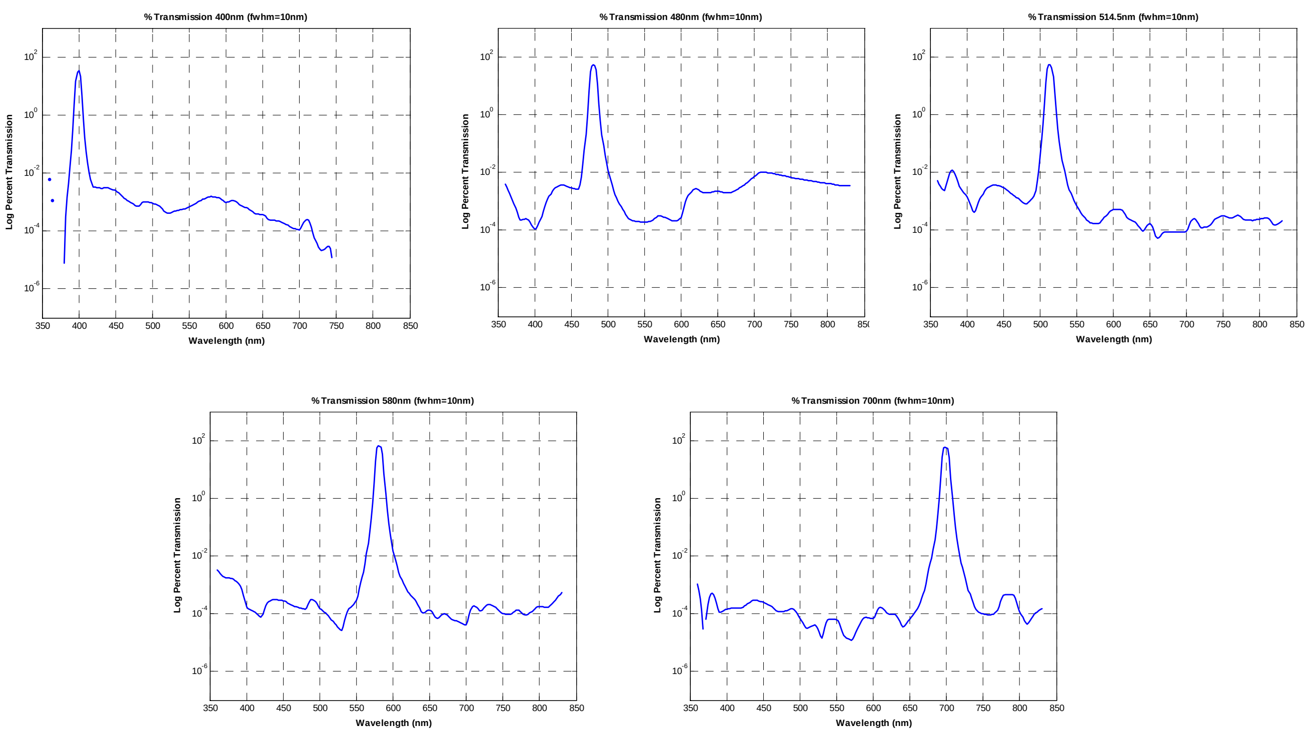

Fig. 8 Spectral transmission curves for narrow-band interference filters (Wheel 1).

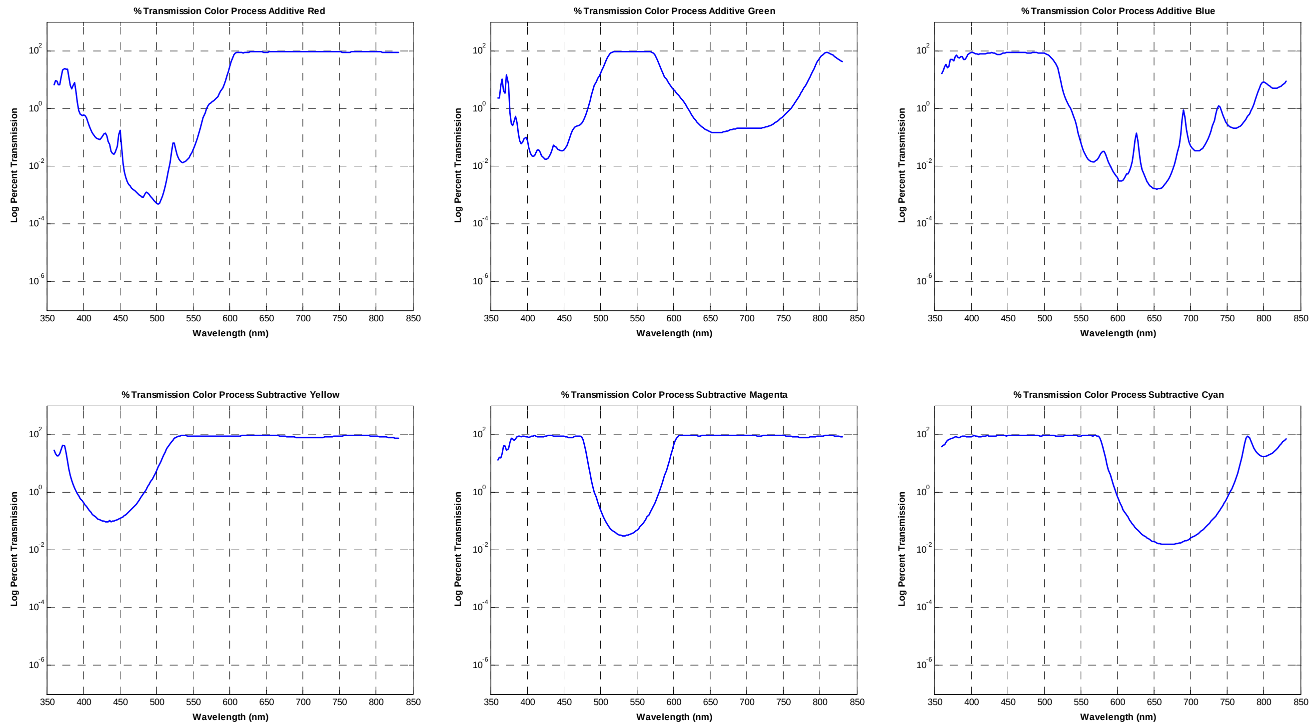

Fig. 9 Spectral transmission curves for additive and subtractive color process filters (Wheel 2).

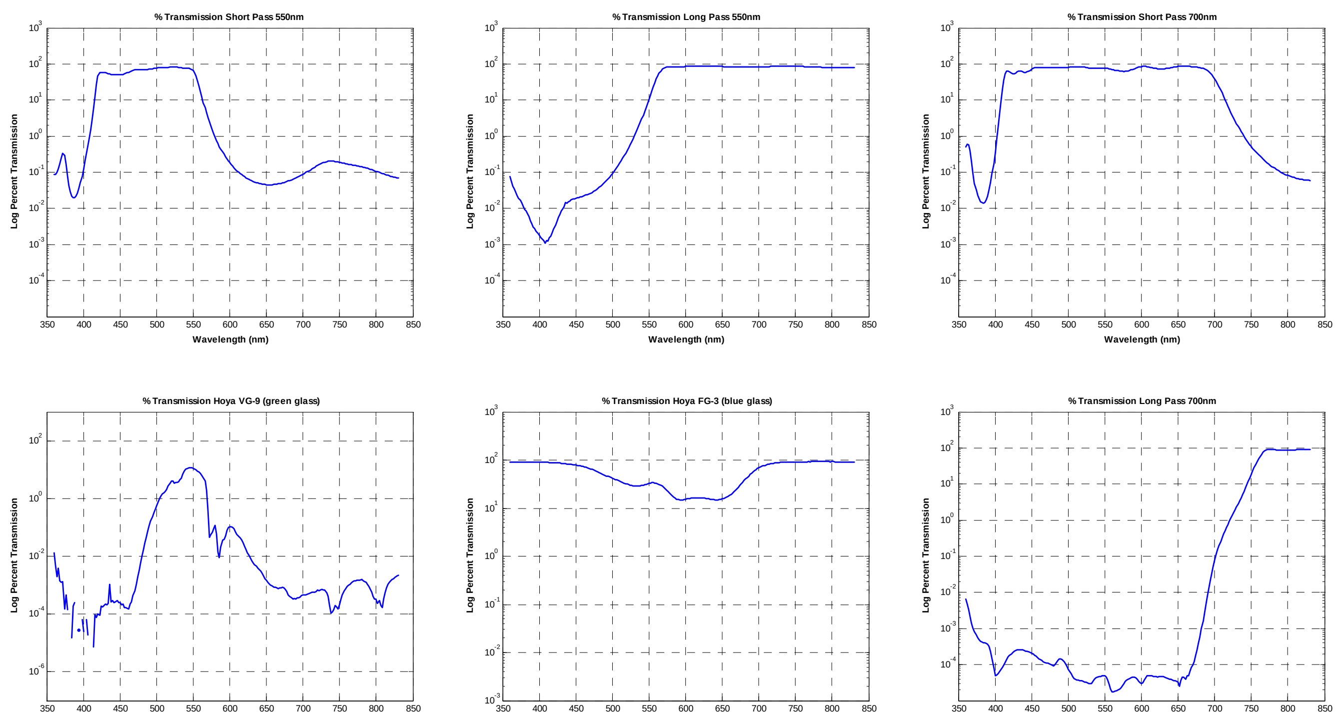

Fig. 10 Spectral transmission of short pass and long pass filters and colored glass filters (Wheel 3).

NIST measurements were made with an Optronics Laboratories OL-750D double monochromator equipped with input reflex telescope and dc current driven photomultiplier tube (PMT) detector. Input aperture, middle, and exit slit were configured for a 2 nm bandwidth. As configured, the instrument had a field of view of 0.4°, corresponding to a 1 cm diameter circular sample of the center of the 2.5 cm filter targets.

Scans were made from wavelengths 360 nm to 830 nm. The source and broadband filter targets, including the short- and long-pass filters, were scanned at a 2 nm sampling interval and 2 nm bandwidth over the entire wavelength range. Narrow-band interference filters were sampled at 2 nm increments and 2 nm bandwidth over the interval ±20 nm about the center wavelength. Spectral regions outside this 40 nm interval were sampled at 10 nm intervals using a 2 nm bandwidth. This latter sampling scheme was determined through experiment (see Appendix) to be a reasonable means to shorten the scan times while permitting 2 nm resolution of the narrow-band peak signals. The major spectral features of these artifacts were well known to the investigators though previous measurements. The variable interval sampled spectra were filled in via interpolation using a piecewise Hermite cubic polynomial interpolation method [6] constrained such that the curve would pass though all measured values of the spectrum.

2.3 Source Stability and Short-Term Repeatability

Following construction of the GAS device, repeated measurements were made of the source in the configuration pictured above in order to evaluate its stability and to establish a baseline of measurement variation to be expected using a single instrument in a constant measurement geometry and environment. For these tests, a series of repeat measurements were made on each of a number of days.

Table 2 summarizes the statistics of nine series of sequential measurements[4] of the GAS source, each on a separate day. In each case, the source was allowed to "warm up" for a one hour period. Then, with the two filter wheels rotated to the “open” position, a sequence of measurements was made running the OL-750 monochromator in unattended scan mode. Each complete scan took approximately 7 min, and was followed immediately by the next scan, the first 30 s of which was allocated to measurement of the dark current background.

Table 2 Mean and standard deviation of GAS source luminance (cd/m^2) and CIE 1931 chromaticity coordinates as measured over repetitive spectral radiance measurements made on nine separate days. Global statistics are shown in the shaded row.

		Luminance		*x*		*y*	
Session	**N**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
1	12	9273	9	0.45011	0.00013	0.41197	0.00003
2	16	9254	36	0.44964	0.00008	0.41187	0.00003
3	66	9211	9	0.44984	0.00010	0.41185	0.00005
4	19	9168	9	0.44987	0.00010	0.41184	0.00003
5	9	9241	29	0.44958	0.00006	0.41185	0.00006
6	12	9259	11	0.45004	0.00004	0.41194	0.00001
7	25	9268	15	0.45001	0.00008	0.41192	0.00004
8	5	9274	14	0.45004	0.00006	0.41203	0.00002
9	15	9174	39	0.44962	0.00003	0.41184	0.00003
Global	179	9225.9	40.5	0.449853	0.000177	0.411878	0.000063

Thus, Table 2 indicates that repeatability for luminance measurements tends to be on the order of ±0.5 % (relative standard uncertainty) and *x* and *y* chromaticity measurements of the source tend to be repeatable to within ±0.0002 and ±0.00006, respectively.

[4] The measurements described in this paper were performed for evaluation purposes only, and do not constitute a calibration of any particular measurement device. Nor do the results purport to serve as an interlaboratory comparison of the realization of any photometric or colorimetric quantity.

These data are shown graphically in Figs. 11-13. As the distribution of mean values over the various measurement sessions does not appear to exhibit any systematic trend over time, it is most likely that the observed variation in the source is representative of the combined uncertainty of the source illumination itself and the measurement instrument used. Tentatively, we suspect the PMT detector to account for much of the observed variation, and have planned follow-up experiments to test this hypothesis. In particular we will examine temperature effects and possible effects of insufficient recovery time on the PMT detector response. In this regard, we observe that during one measurement session, luminance measurements were made at intervals between monochromator measurements

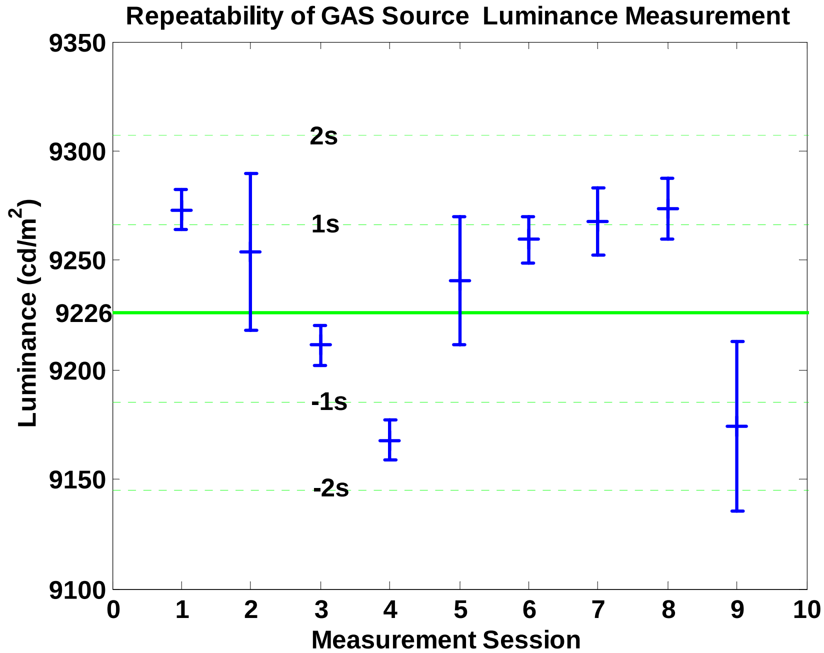

Fig. 11 Mean luminance of GAS source for each of ten measurement sequences. Error bars are ±1s about the mean values. Horizontal lines indicate global mean (solid line) and ±1s and ±2s.

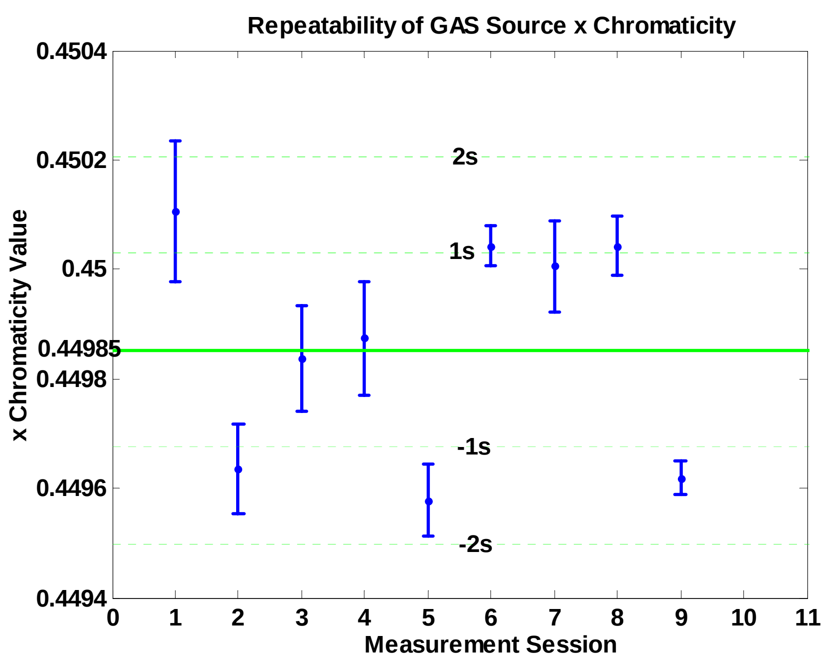

Fig. 12 Mean *x* chromaticity value of GAS source for each of ten measurement sequences. Error bars are ±1s about the mean values. Horizontal lines indicate global mean (solid line) and ±1s and ±2s.

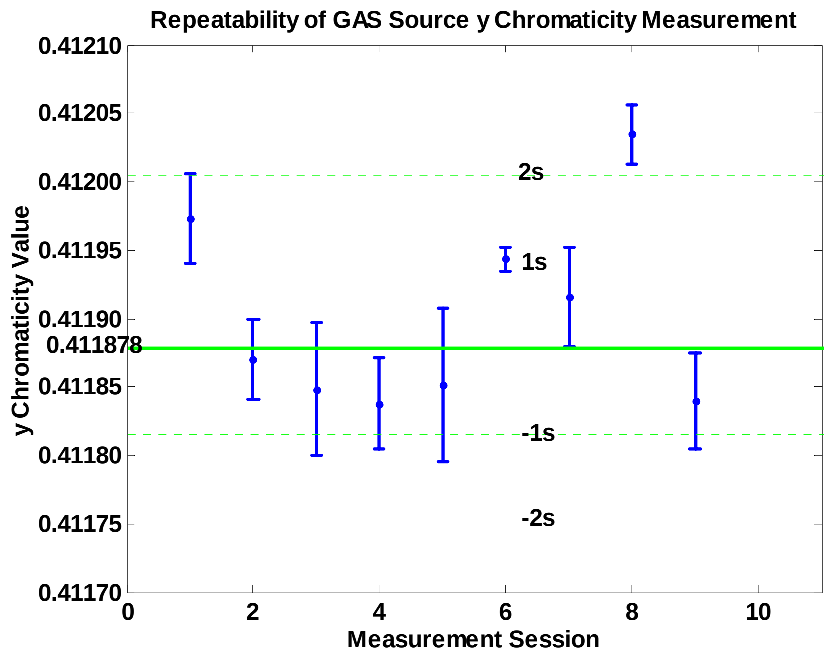

Fig. 13 Mean ***y*** chromaticity value of GAS source for each of ten measurement sequences. Error bars are ±1s about the mean values. Horizontal lines indicate global mean (solid line) and ±1s and ±2s.

using a luminance meter. Luminance meter measurements were found to vary less than 3 parts in over 9200 cd/m^2, 0.03 %, whereas monochromator measurements of the source showed luminance variation on the order of ±0.5 %. Additional experiments have been designed to evaluate variation in source luminance. Manufacturer specifications indicate stability of ±0.2 % for 8 hours at 23°C and accuracy of ±2 % relative to NIST standards within the first 100 hours of use.

Based on the multiple measurements of the GAS source illumination, we can express the Type A [7] relative standard uncertainty with coverage factor of 2 for any of the measurements as the ratio *2s/m*, where *s* and *m* are the standard deviation and mean of the measurements. Thus, calculated from global statistics of Table 2, the uncertainty in the luminance measurement is ±0.010. The Type A standard uncertainties for the Commission Internationale de l'Eclairage (CIE) 1931 chromaticity coordinates, *(x, y)*, are ±0.0004 and ±0.0002, respectively. These uncertainty estimates represent both short-term and long-term *repeatability*, including measurement runs spanning several weeks with at least one complete disassembly, transport, and reassembly of the GAS device and repositioning with respect to the measurement system. The issue of *reproducibility* is addressed in the discussion of the next section and in that of the interlaboratory comparison.

2.4 Pivot Lab Reproducibility

One of the objectives of the present investigation was to examine the robustness of the GAS system to transport and reassembly. In order for a successful interlaboratory study, it must be possible for the device to exhibit relative stability in its measured characteristics following transport and handling. The GAS was measured both before transport to and upon return from NPL using the same instrumentation, laboratory environment, procedures, and metrologist. What we will term, “pivot lab reproducibility” is evaluated by comparing the measurements after transport to those upon return of the GAS to the NIST laboratory and reconfiguration and repositioning for measurement.

Table 3 summarizes the results of the two sets of measurements performed in the NIST laboratory. The percent differences shown for luminance are calculated according to the expression

$$\Delta Y(\%) = \frac{Y_1 - Y_2}{Y_1} * 100\%$$

Simple differences are shown for CIE 1931 x, y chromaticity coordinates, i.e., $M_1 - M_2$, $M \in \{x, y\}$. In general, the largest differences are observed with targets having the lowest luminance and especially for those filters transmitting mainly in spectral regions having the lowest source radiance and low values of the color matching functions. These measurements would tend to be most affected by noise. Chromaticity differences are of order 10^{-4} to 10^{-3}, with some

Table 3 Measurements of GAS source and filter artifacts before and after transport to NPL. Luminance differences are expressed as difference percentage of the first of two measurements, i.e., that prior to transport. Chromaticity comparison is made as simple difference in *x* and *y*.

	NIST Measurement			NIST Measurement 2			Difference		
	Y(cd/m^2)	x	y	Y(cd/m^2)	x	y	%Δ Y	Δ x	Δ y
Src	9284.48	0.4502	0.4120	9286.46	0.4498	0.4120	-0.02	0.0004	0.0000
ND 0.1	7733.31	0.4510	0.4122	7730.43	0.4508	0.4122	0.04	0.0002	0.0000
ND 1.0	973.63	0.4542	0.4133	972.54	0.4541	0.4133	0.11	0.0001	0.0001
ND 2.0	104.96	0.4462	0.4098	104.69	0.4463	0.4099	0.25	-0.0001	0.0000
ND 3.0	9.77	0.4557	0.4094	9.77	0.4564	0.4102	0.01	-0.0007	-0.0008
ND 4.0	0.57	0.5443	0.4000	0.57	0.5518	0.4068	0.60	-0.0075	-0.0068
Src	9282.22	0.4503	0.4120	9293.07	0.4502	0.4120	-0.12	0.0002	0.0000
λ=400nm, Δλ=10nm	0.09	0.2021	0.0463	0.08	0.2003	0.0430	12.07	0.0018	0.0033
λ=480nm, Δλ=10nm	27.13	0.0909	0.1373	26.79	0.0912	0.1364	1.25	-0.0002	0.0009
λ=515nm, Δλ=10nm	152.24	0.0335	0.7912	150.20	0.0331	0.7909	1.34	0.0005	0.0003
λ=580nm, Δλ=10nm	526.93	0.5218	0.4773	522.54	0.5213	0.4778	0.83	0.0005	-0.0005
λ=700nm, Δλ=10nm	4.19	0.7343	0.2654	4.17	0.7346	0.2654	0.50	-0.0003	0.0000
AR	2024.48	0.6886	0.3110	1932.814	0.6908	0.3088	4.53	-0.0003	0.0000
AG	4608.83	0.3263	0.6474	4589.276	0.3292	0.6454	0.42	-0.0027	-0.0035
AB	570.13	0.1161	0.1644	566.807	0.1154	0.1679	0.58	-0.0021	-0.0007
SY	7594.26	0.5297	0.4633	7553.22	0.5305	0.4626	0.54	-0.0008	0.0007
SM	2252.19	0.5465	0.2394	2229.215	0.5487	0.2401	1.02	0.0006	-0.0034
SC	4873.59	0.2532	0.4734	4883.388	0.2559	0.4769	-0.20	-0.0029	0.0019
SPF550	2578.22	0.1694	0.4818	2577.52	0.1688	0.4810	0.03	0.0005	0.0008
LPF550	4793.84	0.6057	0.3935	4819.36	0.6055	0.3937	-0.53	0.0002	-0.0002
SPF700	6942.99	0.4535	0.4119	6967.41	0.4535	0.4117	-0.35	0.0000	0.0002
LPF700	0.28	0.7299	0.2655	0.27	0.7358	0.2646	1.90	-0.0059	0.0009
VG-9	276.37	0.2859	0.6944	276.49	0.2852	0.6949	-0.05	0.0007	-0.0006
FG-3	2327.59	0.3354	0.3479	2332.61	0.3355	0.3478	-0.22	-0.0001	0.0001
						Mean	1.07	-0.0008	-0.0003
						Stdev.	2.62	0.0022	0.0020

differences on the order of 10^{-5}. Several artifacts show differences larger than the desired 0.002, however.

In general, agreement between luminance measurements is within the 2 % uncertainty desired for these measurements with several exceptions. However, a 12 % difference is observed between measurements of the 400 nm narrow-band filter. This, of course. reflects an actual difference of only 0.01 cd/m^2 and may have been due to the influence of noise on such a low-level signal combined with small values of $V(\lambda)$ in this spectral region.

Other large luminance differences are observed with the additive and subtractive color process filters. An alignment problem was found to have affected the repeat measurements of these artifacts (Wheel 2). By the time the Wheel 2 measurements could be repeated, the lamp had burned for around 200 additional hours. Over this time, the source lamp luminance had dropped from around 9400 cd/m^2 to around 9000 cd/m^2. This produced a systematic offset to luminance values for these targets. This systematic effect was compensated by multiplying each of the measured luminance values by the factor, 1.04767. The chromaticity coordinates, however, are reported as measured. While design modifications of the GAS are expected to reduce the likelihood of large changes in the source, this example does highlight the need to expand the GAS instrumentation package to provide independent monitoring of the source luminance and other performance characteristics. Thus, when such a record of source behavior is temporally correlated with interlaboratory measurements, it should be possible to determine the extent to which observed measurement differences are due to measured changes in the source.

3. Laboratory Intercomparison

The GAS device was transported to NPL for a preliminary measurement comparison and to examine how well the device would sustain the shocks of transport. The results obtained at NPL are to be considered preliminary, as the experiment was undertaken as a "test case" to identify design and procedural issues that would need to be considered in the larger laboratory intercomparison to follow. It is possible that changes will be made to the GAS prior to subsequent interlaboratory tests.

Table 4 Luminance (Y) and x, y CIE 1931 (2° observer) chromaticity coordinate measurements of NPL and the first set of NIST measurements for each of the GAS optical targets and differences in luminance, x and y.

	NPL			NIST Measurements 1			Difference (NIST1-NPL)		
	Y	x	y	Y	x	y	ΔY(%)	Δx	Δy
Src	9122.16	0.44774	0.41137	9284.48	0.45022	0.41200	**1.7483**	**0.0025**	**0.0006**
ND 0.1	7512.61	0.44864	0.41176	7733.31	0.45102	0.41220	**2.8538**	**0.0024**	**0.0004**
ND 1.0	960.06	0.45183	0.41305	973.63	0.45419	0.41334	**1.3934**	**0.0024**	**0.0003**
ND 2.0	103.28	0.44485	0.40991	104.96	0.44623	0.40984	**1.6043**	**0.0014**	**-0.0001**
ND 3.0	9.46	0.45404	0.40952	9.77	0.45572	0.40943	**3.1394**	**0.0017**	**-0.0001**
Src	9129.75	0.44746	0.41153	9282.22	0.45032	0.41198	**1.6426**	**0.0029**	**0.0005**
λ=480nm, Δλ=10nm	27.86	0.09245	0.13864	27.13	0.09095	0.13730	**-2.7009**	**-0.0015**	**-0.0013**
λ=515nm, Δλ=10nm	148.69	0.03373	0.78495	152.24	0.03355	0.79124	**2.3287**	**-0.0002**	**0.0063**
λ=580nm, Δλ=10nm	524.57	0.52387	0.47489	526.93	0.52181	0.47730	**0.4478**	**-0.0021**	**0.0024**
λ=700nm, Δλ=10nm	3.71	0.72073	0.26864	4.19	0.73427	0.26538	**11.4233**	**0.0135**	**-0.0033**
AR	2139.32	0.68340	0.31550	2024.48	0.68864	0.31102	**-5.6729**	**0.0052**	**-0.0045**
AG	4531.26	0.32432	0.64824	4608.83	0.32633	0.64736	**1.6830**	**0.0020**	**-0.0009**
AB	560.84	0.11817	0.16108	570.13	0.11608	0.16443	**1.6294**	**-0.0021**	**0.0034**
SY	7526.42	0.52704	0.46461	7594.26	0.52966	0.46327	**0.8934**	**0.0026**	**-0.0013**
SM	2294.44	0.54572	0.24175	2252.19	0.54653	0.23937	**-1.8757**	**0.0008**	**-0.0024**
SC	4740.94	0.24880	0.47054	4873.59	0.25318	0.47342	**2.7217**	**0.0044**	**0.0029**
						Mean	**1.4537**	**0.0022**	**0.0002**
						Stdev.	**3.5333**	**0.0037**	**0.0027**

The NPL measurements were made with a Bentham M330 single monochromator, with a telescope attachment for the input optics. The telescope was set up for a field of view of 20 arc minutes. The monochromator was configured for a 5 nm bandwidth using input and exit slits of 1.85 mm. The monochromator is equipped with a holographic grating having 1200 lines/mm with a reciprocal dispersion of 2.70 nm/mm. The detector was a PMT of the Venetian blind type (end-on detector). Targets were scanned over the wavelength range from 380 nm to 780 nm at a 5 nm sample interval.

Table 5 Luminance (Y) and x, y CIE 1931 (2 ° observer) chromaticity coordinate measurements of NPL and the first set of NIST measurements for each of the GAS optical targets and differences in luminance, x and y.

	NPL			NIST Measurements 2			Difference (NIST2-NPL)		
	Y	x	y	Y	x	y	ΔY(%)	Δx	Δy
Src	9122.16	0.44774	0.41137	9286.46	0.44985	0.41195	**1.7693**	**0.0021**	**0.0006**
ND 0.1	7512.61	0.44864	0.41176	7730.43	0.45079	0.41224	**2.8176**	**0.0021**	**0.0005**
ND 1.0	960.06	0.45183	0.41305	972.54	0.45414	0.41327	**1.2833**	**0.0023**	**0.0002**
ND 2.0	103.28	0.44485	0.40991	104.69	0.44634	0.40988	**1.3533**	**0.0015**	**0.0000**
ND 3.0	9.46	0.45404	0.40952	9.77	0.45637	0.41021	**3.1271**	**0.0023**	**0.0007**
Src	9129.75	0.44746	0.41153	9293.07	0.45017	0.41202	**1.7575**	**0.0027**	**0.0005**
λ=480nm, $\Delta\lambda$=10nm	27.86	0.09245	0.13864	26.79	0.09119	0.13642	**-4.0047**	**-0.0013**	**-0.0022**
λ=515nm, $\Delta\lambda$=10nm	148.69	0.03373	0.78495	150.20	0.03308	0.79094	**1.0036**	**-0.0006**	**0.0060**
λ=580nm, $\Delta\lambda$=10nm	524.57	0.52387	0.47489	522.54	0.52135	0.47778	**-0.3878**	**-0.0025**	**0.0029**
λ=700nm, $\Delta\lambda$=10nm	3.71	0.72073	0.26864	4.17	0.73459	0.26538	**10.9822**	**0.0139**	**-0.0033**
AR	2139.32	0.68340	0.31550	1932.81	0.69083	0.30885	**-10.6843**	**0.0074**	**-0.0066**
AG	4531.26	0.32432	0.64824	4589.28	0.32920	0.64544	**1.2641**	**0.0049**	**-0.0028**
AB	560.84	0.11817	0.16108	566.81	0.11543	0.16786	**1.0526**	**-0.0027**	**0.0068**
SY	7526.42	0.52704	0.46461	7553.22	0.53047	0.46259	**0.3548**	**0.0034**	**-0.0020**
SM	2294.44	0.54572	0.24175	2229.22	0.54867	0.24008	**-2.9258**	**0.0029**	**-0.0017**
SC	4740.94	0.24880	0.47054	4883.39	0.25587	0.47691	**2.9169**	**0.0071**	**0.0064**
						Mean	**0.7300**	**0.0028**	**0.0004**
						Stdev.	**4.4026**	**0.0041**	**0.0037**

Tables 4 and 5 compare luminance (Y) and CIE 1931 chromaticity coordinates (x,y) for the GAS as measured by the two laboratories. Rather than comparing the single set of NPL measurements with the average of the two NIST measurements, it was considered more appropriate to examine the NPL measurements in comparison with each of the two sets of NIST measurements. Thus, we assess the interlaboratory in the context of measurement reproducibility by the pivot laboratory before and after transport of the device to NPL. Luminance differences are expressed as percent difference according to the expression given previously. Simple differences, $M_{NPL} - M_{NIST}$, $M \in \{x,y\}$, are given for the chromaticity coordinates. It is noted that only a subset of the artifacts listed previously are considered in the NIST – NPL intercomparison[5].

Figs. 14 - 16 show in graphical form the relative measurement differences for the three comparisons, *NIST1-NIST2*, *NIST1 – NPL*, and *NIST2 – NPL*, i.e., the results of Tables 3 – 5. As in the tables, luminance differences are expressed in percent differences according to the formula given previously, and simple differences are shown for *x* and *y* chromaticity values. In general, the reproducibility of NIST luminance measurements is less than ±2 %. The exception is found with the repeat measurement of the additive red filter. As noted previously, all of the wheel 2 artifacts tended to show greater disparity due to a drop in lamp luminance, presumably due to aging. In that this and the other wheel 2 artifacts show comparatively large differences in chromaticity as well is consistent with spectral changes of the source lamp. Changes in the lamp, however, may not be a sufficient explanation as this set of artifacts shows comparatively large variation among the interlaboratory comparisons also.

NIST-to-NPL comparisons tend to show larger differences, but in all but two cases, the percent difference remains less than ±5 %. As with the NIST measurements, the additive red filter shows a relatively large disparity. Also, the 700 nm narrow-band filter exhibits a large percentage difference. Of course, when convolved with the very low values of the $V(\lambda)$ function in this spectral region, this measurement is susceptible to noise.

Similar trends appear in Figs. 15 and 16 in which most of the NIST measurements vary less than or in the neighborhood of ±0.002. Again, the additive and subtractive filters show greater variation among the NIST measurements and show the greatest differences in the interlaboratory comparisons. Most of the interlaboratory comparisons show differences less than or in the neighborhood of ±0.005.

[5] Wheel 3 measurements were excluded due to a misunderstanding over initialization of the GAS source current. Several of the extremely low signal artifacts were excluded as time did not permit modifications to instrumentation to optimize instrument performance for these filters.

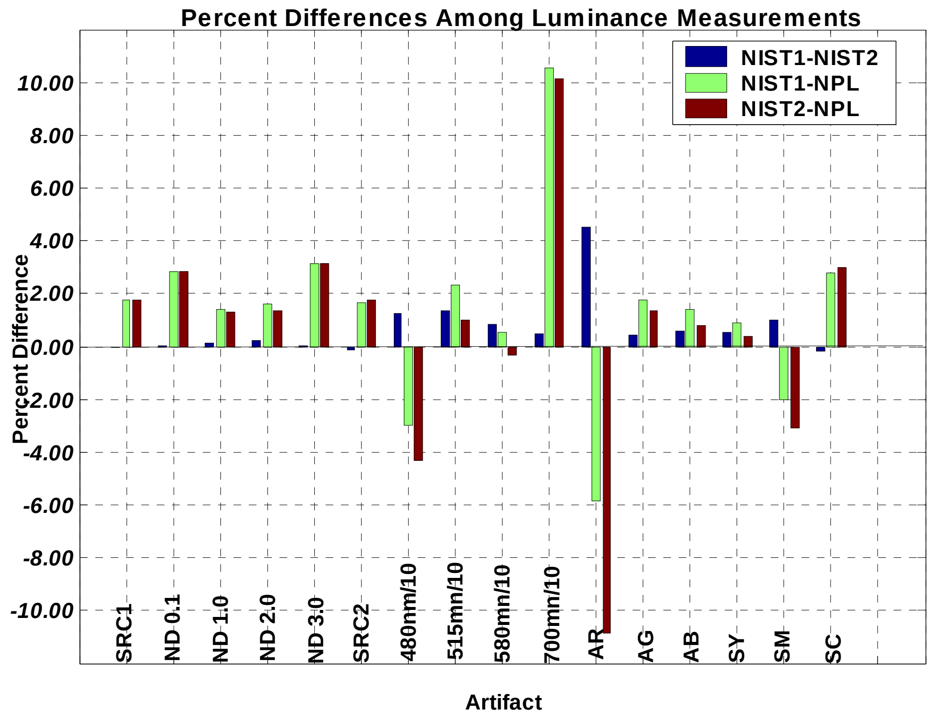

Fig. 14 Percent differences in luminance measurements with comparison of NPL with each of two NIST measurements of GAS artifacts.

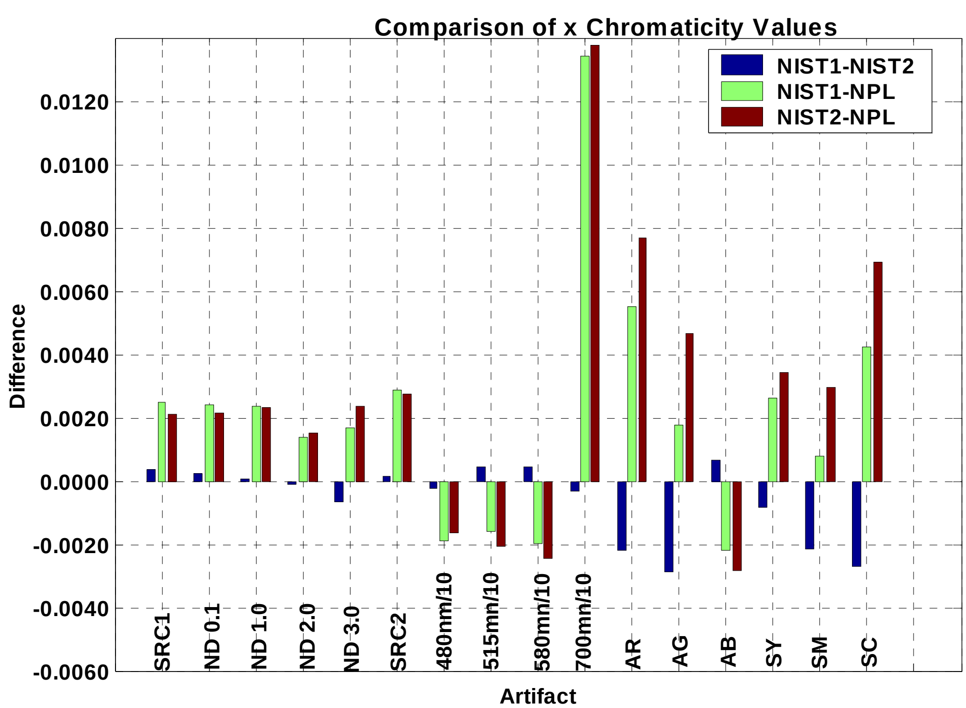

Fig. 15 Differences of x chromaticity in comparison of NPL measurements with each of two NIST measurements of GAS artifacts.

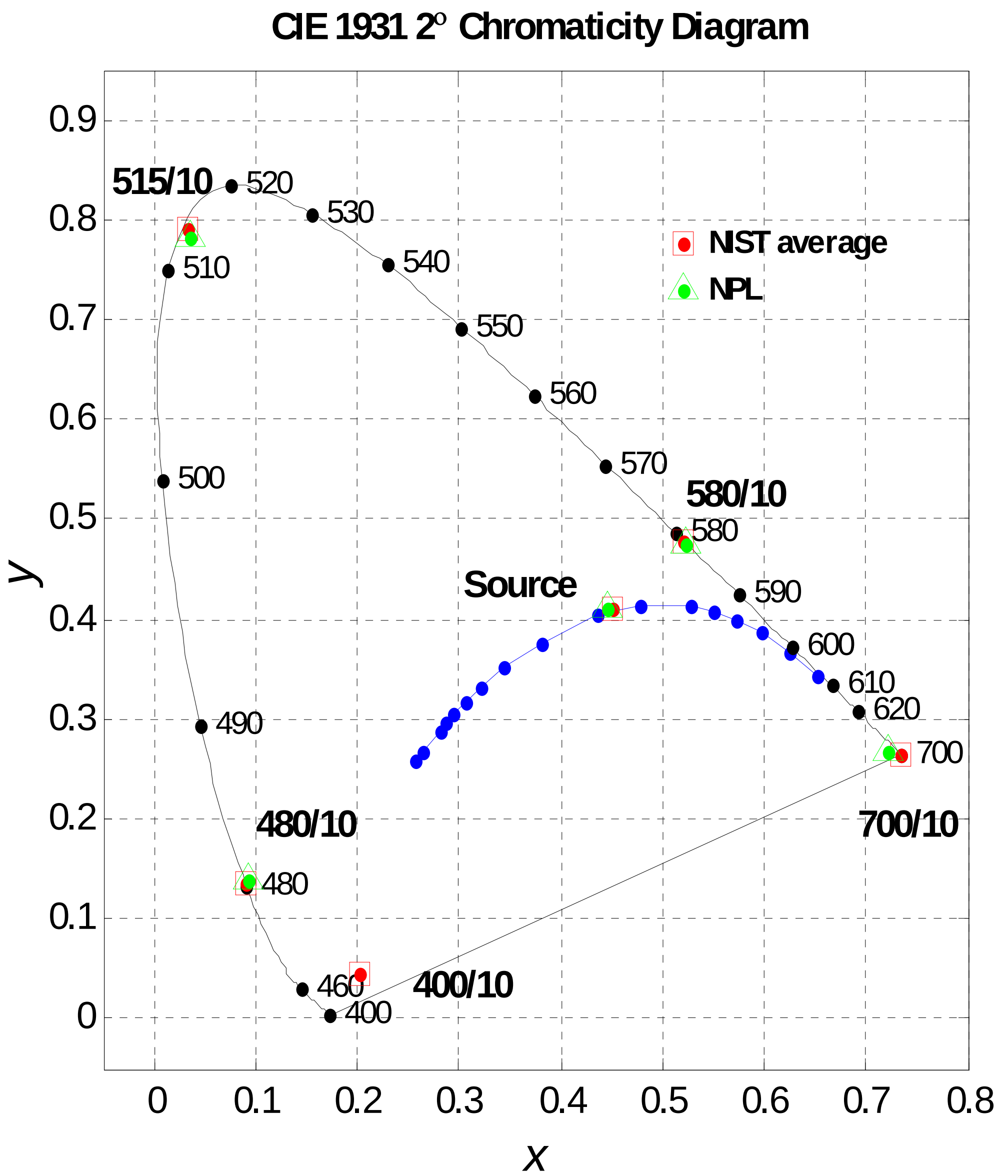

Fig. 17 Chromaticity coordinates for narrow-band interference filters (Wheel 1). Square (dot-centered) markers indicate x, y color loci for average of two NIST measurements and triangular markers indicate positions of NPL measurements.

In Figs. 17 and 18, the chromaticity measurements are displayed on the CIE 1931 chromaticity diagram for the 2° observer. In these diagrams, the NPL coordinate positions are compared to the average of the two NIST measurements.

4. Summary and Conclusions

A color measurement comparison device was developed by NIST as part of its efforts to support the development of standard measurement methods for the characterization and performance specification of electronic displays. Through collaboration with NPL of the United Kingdom and other national standards laboratories, devices such as the DMATS and the GAS will be circulated among instrument manufacturers and display measurement laboratories to collect data on the repeatability of measurements being applied to displays. The GAS device, described in the

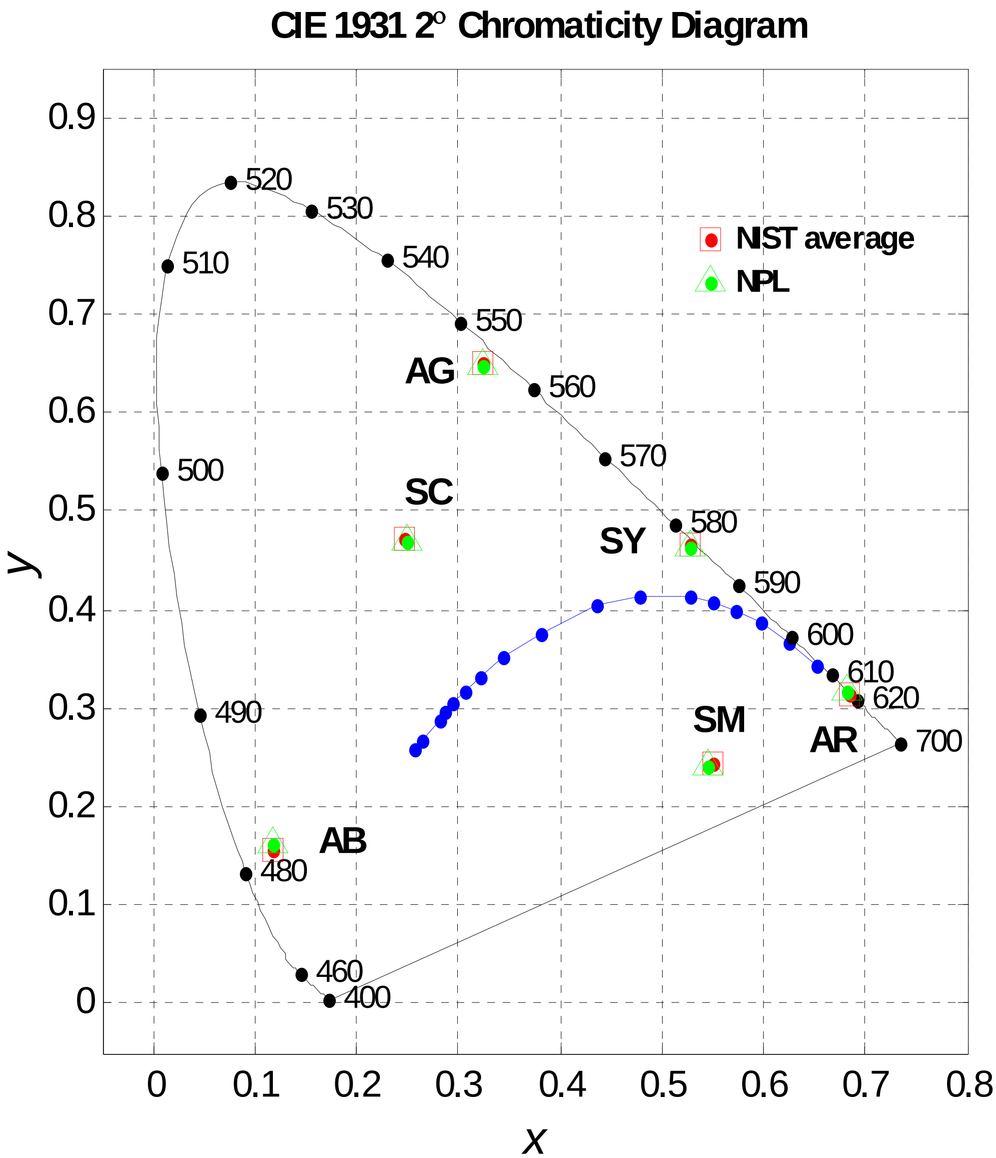

Fig. 18 Chromaticity coordinates for additive and subtractive color process filters. Square (dot-centered) markers indicate x, y color loci for average of two NIST measurements and triangular markers indicate positions of the NPL measurements.

present paper, examines mainly the measurement of transmitted color illumination, though other artifacts might include those suitable for small area contrast measurement and examination of polarization effects.

The interlaboratory comparison results of the present study confirm feasibility of transporting the GAS to participants while maintaining physical integrity of the device. Pivot lab repeatibility for most measurements were within ±2 % for luminance and ±0.002 for chromaticity values, indicating that even with extensive handling, transport, and limited assembly and reassembly, the GAS device remained stable. Interlaboratory measurement variability was found to be somewhat higher, but still remained at or below ±5 % for most luminance measurements and ±0.005 for chromaticity values. As the data presented herein are considered preliminary, a detailed uncertainty analysis is left for a later paper. For the present, we find it encouraging that the results of this experiment, in general, are consistent with CIE uncertainty criteria on the order of ±2 % for an individual laboratory and ±5 % for interlaboratory comparison.

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6. Appendix

For characterization of the filters used in this experiment it was anticipated that multiple measurements of a given filter might be required. Some of the targets, notably the narrow band interference filters, transmitted such low signals outside their peak wavelength regions that scan times became impractically lengthy for repeat measurements. In order to preserve resolution of measurements in the peak regions, a sample scheme was used wherein a 2 nm sample increment was used in a zone of ± 20 nm (i.e., four times the full width at half maximum, FWHM, for these filters) and 10 nm sampling outside this region. Prior to analysis, the variable sample rate spectra were resampled at a uniform 2 nm spacing using a piecewise Hermite cubic polynomial fit to the data, constraining the resampling to use all actual measurements. The authors emphasize that were only a single measurement of each filter anticipated, such a practice would not be suggested.

A simple experiment was performed to evaluate the use of interpolation to "fill in" the out-of-band regions of the spectra of the narrow band interference filters. The 400 nm/10 nm, 480 nm/10 nm, 580 nm/10 nm, and 700 nm/10 nm artifacts were scanned at a 2 nm sample interval over the entire wavelength range 360 nm to 830 nm. The same filter artifacts were also scanned at 2nm interval in the region ±20 nm about the center peak wavelength and at 10 nm intervals over the spectrum outside this band. In all cases, the scans were made with the monochromator set for a 2 nm measurement bandwidth.

Table A.1 shows the luminance and x, y chromaticity coordinates of each of the measurements as well as the percent difference. Only the 400 nm filters exhibits measurement differences of concern. The signal-to-noise level is low for this filter such that its measurement uncertainty tends to be comparatively large, at least for the apparatus configuration used in the present study. Moreover, inspection of the chromaticity values would tend to suggest that the effect of background noise of the out of band regions actually displaced the locus of this filter toward the white point as indicted by the slightly elevated x and y values.

Table A.1 Comparison of luminance and chromaticity coordinates obtained from spectral measurements of narrow band filters at 2 nm increment and at sparse (10 nm) spacing in out-of-band regions.

Increment	Cntr □ / fwhm	Y	x	y	%dY	%dx	%dy
2 nm/10 nm	400 nm / 10 nm	0.083413	0.200644	0.043406			
2 nm	400 nm / 10 nm	0.088993	0.202267	0.046152	6.27	0.803	5.949
2 nm/10 nm	480 nm / 10 nm	27.34017	0.091306	0.136098			
2 nm	480 nm / 10 nm	27.28594	0.091343	0.136059	0.20	0.041	0.029
2 nm/10 nm	580 nm / 10 nm	530.7655	0.5212	0.477922			
2 nm	580 nm / 10 nm	530.444	0.521128	0.477992	0.06	0.014	0.015
2 nm/10 nm	700 nm / 10 nm	4.259882	0.734524	0.265381			
2 nm	700 nm / 10 nm	4.265975	0.734506	0.265367	0.14	0.002	0.005