RTS Improvements and New Uncertainty Budget

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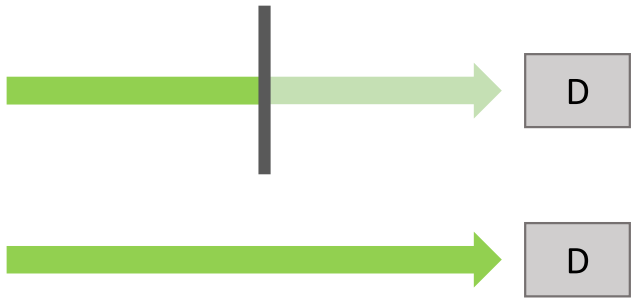
National Institute of Standards and Technology
U.S. Department of Commerce

Regular Spectral Transmittance



$$\tau = \frac{\Phi_t}{\Phi_i}$$

Stakeholders:

- Standard/certified reference material producers (e.g. MML)
- Optics/photonics/instrument manufacturers
- Pharmaceutical and healthcare industries
- Coatings manufacturers
- Remote sensing community
- Military standards laboratories

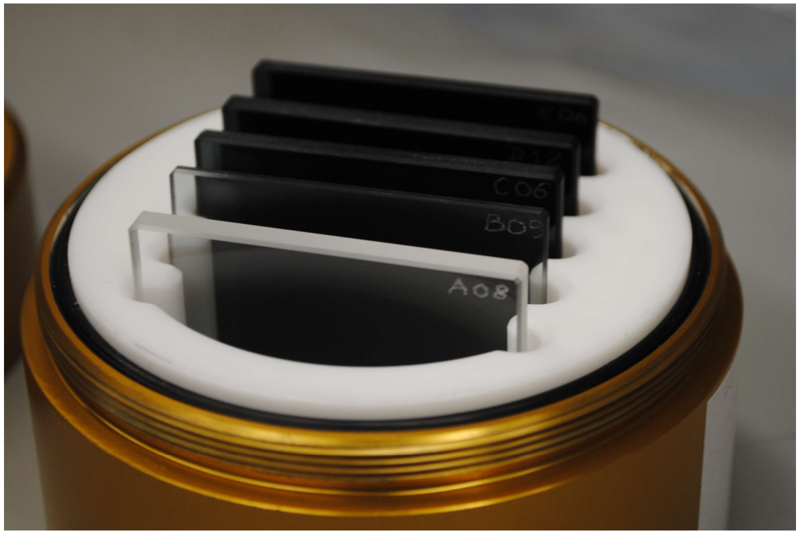
Calibration Service

Green Filter Transmittance (38020C):

- Copper-green glass filter
- 380 nm to 770 nm at 10 nm intervals

Special Tests of Transmittance (38061S):

- Neutral or colored, non-fluorescent glass filters
- 250 nm to 2500 nm

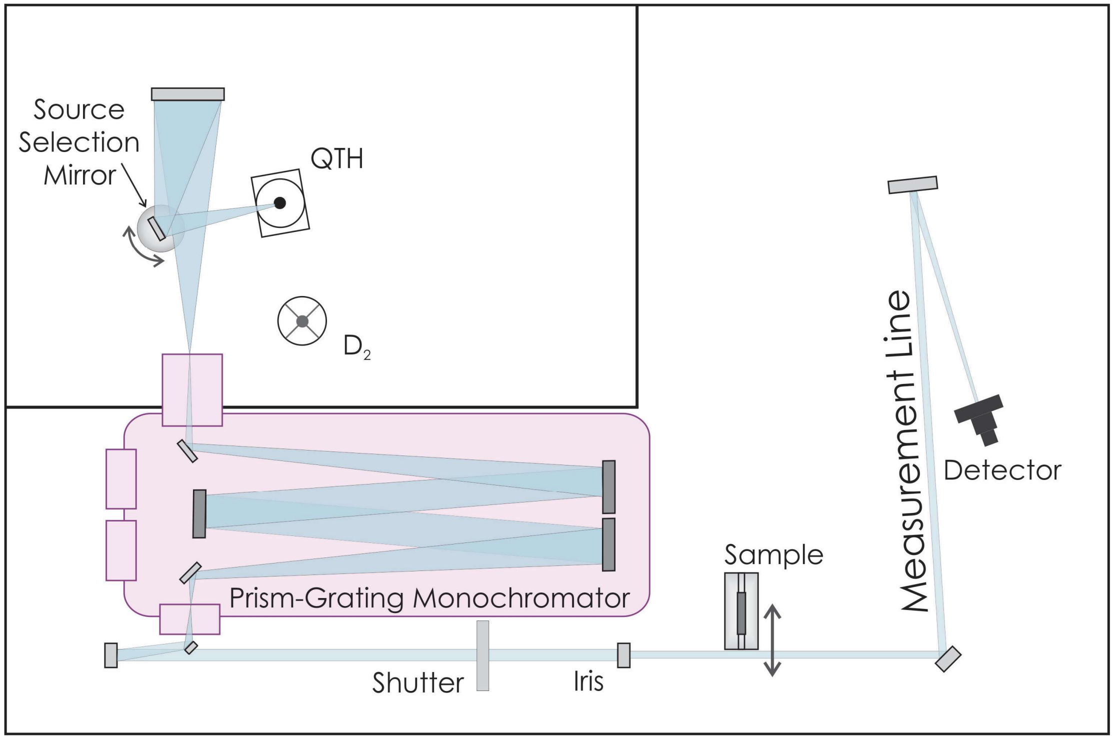


NIST Measurement Services: Regular spectral transmittance
NIST Special Publication 250-69
Allen DW, Early EA, Tsai BK, Cooksey CC (2011)

Reference Transmittance Spectrophotometer (RTS)

Sources:
- Deuterium (D_2) for UV
- QTH for visible

Measurement Line:
- PMT for UV
- Si for visible



2011

Reference Transmittance Spectrophotometer (RTS)

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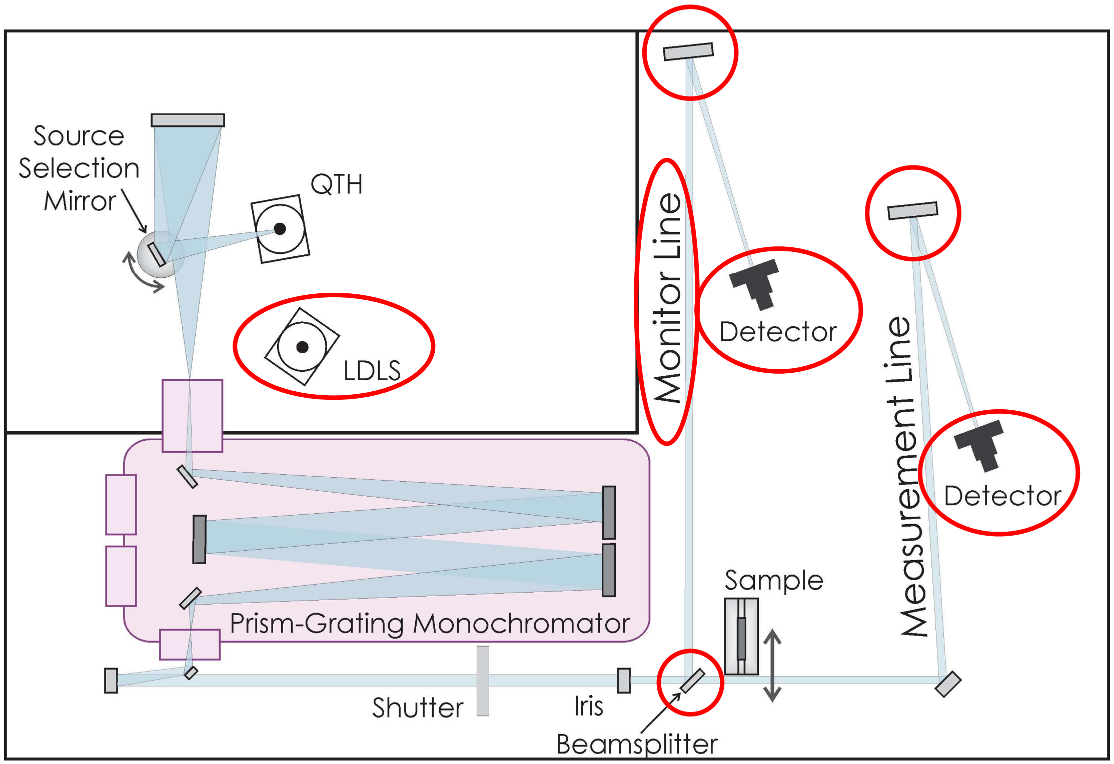
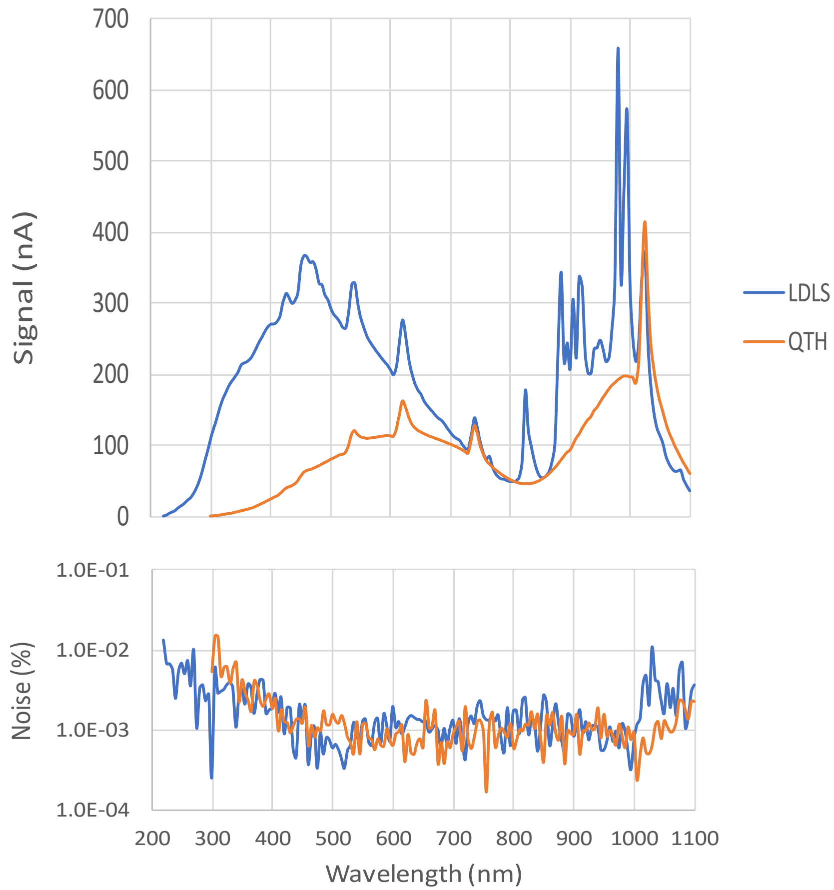
Sources:
- LDLS (EQ-99) for UV
- QTH for visible

Measurement and Monitor Lines:
- 50% beam splitter
- New, identical optics, Si photodiodes, and electronics



2021

LDLS and QTH Signals



Signal Measurement

The detection system collects ***n* voltage readings** at each wavelength λ, position (Sample or Clear), and shutter condition (Open or Closed).

For each set of *n* voltage readings, **average voltage** is

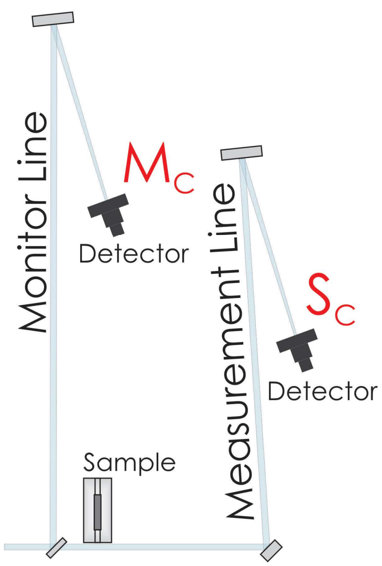
$$V = \frac{1}{n}\sum_{i=1}^{n} V_i$$

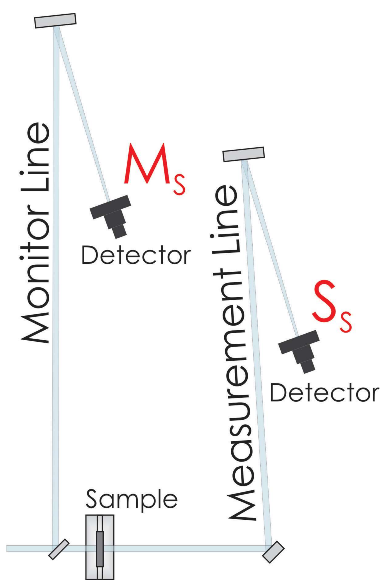
The average voltages are then converted to **currents *I*(*V*)** using

$$I(V) = \frac{1}{G_m}(V - b)$$

Where G_m is the gain of the amplifier and b is the offset voltage of the amplifier.

Signal Measurement





Signal variable (A)	Line	Position	Shutter condition
S_s	Measurement	Sample	Open
$S_{s,d}$	Measurement	Sample	Closed (dark)
S_c	Measurement	Clear	Open
$S_{c,d}$	Measurement	Clear	Closed (dark)
M_s	Monitor	Sample	Open
$M_{s,d}$	Monitor	Sample	Closed (dark)
M_c	Monitor	Clear	Open
$M_{c,d}$	Monitor	Clear	Closed (dark)

Transmittance Measurement

Net signal at each wavelength λ and position (Sample or Clear) is the difference between the signal measured when the shutter is open and when it is closed

$$S_i^{NET} = S_i - S_{i,d}$$

$$M_i^{NET} = M_i - M_{i,d}$$

Transmittance at each wavelength λ

$$\tau(\lambda) = \left[\frac{S_s^{NET}(\lambda)}{S_c^{NET}(\lambda)}\right]\left[\frac{M_c^{NET}(\lambda)}{M_s^{NET}(\lambda)}\right]$$

where S_s^{NET} and S_c^{NET} are the net signals obtained from the measurement line and M_s^{NET} and M_c^{NET} are the net signals obtained from the monitor line.

Uncertainty Analysis

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Source of Uncertainty	Effect: Systematic	Effect: Random	Sample: Independent	Sample: Dependent
Stray Light	X			X
Inter-reflections	X			X
Wavelength	X			X
Signals				
DVM Accuracy	X		X	
Voltage Accuracy	X		X	
Amplifier Gain	X		X	
Amplifier Offset Voltage	X		X	
Random Fluctuations		X	X	

Step 2: Stray Light, Inter-reflections, Wavelength

Step 1: Signals (DVM Accuracy, Voltage Accuracy, Amplifier Gain, Amplifier Offset Voltage, Random Fluctuations)

Step 1: Signal Uncertainty

Formal measurement equation:

$$I(V) = \frac{1}{G_m}[(V + c_{DVM} + c_R) - b]$$

Calibration factors:

c_{DVM} - Accuracy of the digital voltmeter (DVM)

c_R - Random fluctuations in the voltage measurements

c_{DVM} = c_R = 0, but their uncertainty values (non-zero) contribute to the overall signal uncertainty

Combined standard uncertainty for each signal

$$u(S_i) = u(M_i) = \sqrt{[u_{DVM}(V)]^2 + [u_R(V)]^2 + [u_V(V)]^2 + [u_b(V)]^2 + [u_{Gm}(V)]^2}$$

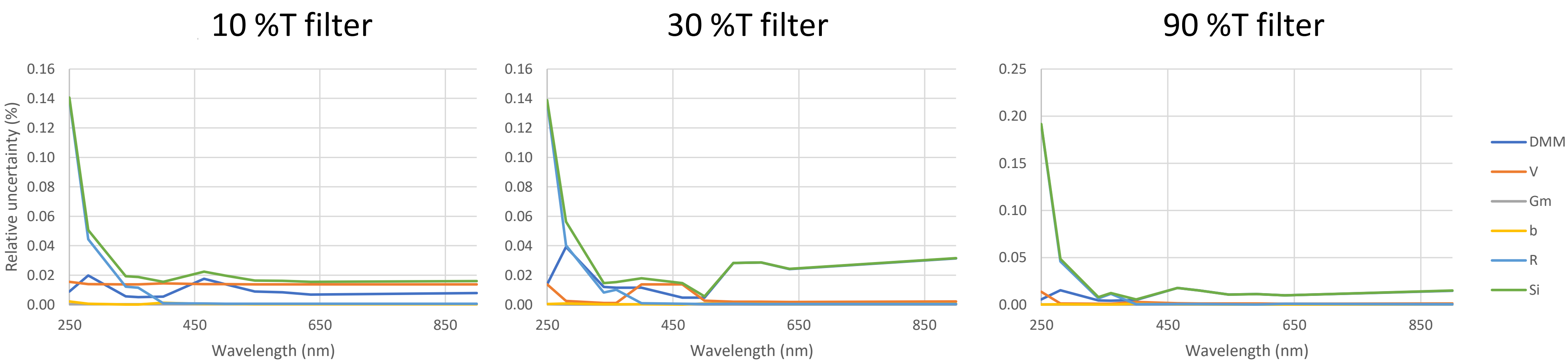
Step 1: Signal Uncertainty

Example uncertainty contributions and combined signal uncertainties for S_S = 1.4e-8 A

Source of Uncertainty	Standard Uncertainty	Relative Unc. Contribution
DVM Accuracy	400 μV	0.03%
Voltage Accuracy	2.8e-5 V	0.002%
Amplifier Gain	175 V/A	0.0002%
Amplifier Offset Voltage	8.5e-6 V	0.0006%
Random Fluctuations	7.4e-6 V	0.0005%
		Combined Uncertainty
		0.03%

Step 1: Signal Uncertainty

Example uncertainty contributions and combined signal uncertainties for S_S



Major contributors:

- Random fluctuations below approx. 350 nm
- DVM accuracy in visible for 30 %T and 90 %T filters

Step 2: Transmittance Uncertainty

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Formal measurement equation:

$$\tau(\lambda) = c_{SL} c_{IR} \left[\frac{S_S^{NET}(\lambda)}{S_C^{NET}(\lambda)}\right] \left[\frac{M_C^{NET}(\lambda)}{M_S^{NET}(\lambda)}\right]$$

Calibration factors:

c_{SL} - Out-of-band stray light

c_{IR} - Inter-reflections

c_{SL} = c_{IR} = 1, but their uncertainty values (non-zero) contribute to the overall signal uncertainty

Combined standard uncertainty for transmittance

$$u_\tau(\lambda) = \sqrt{(u_{SL})^2 + (u_{IR})^2 + (u_\lambda)^2 + \left(u_{S_S^{NET}}\right)^2 + \left(u_{S_C^{NET}}\right)^2 + \left(u_{M_S^{NET}}\right)^2 + \left(u_{M_C^{NET}}\right)^2}$$

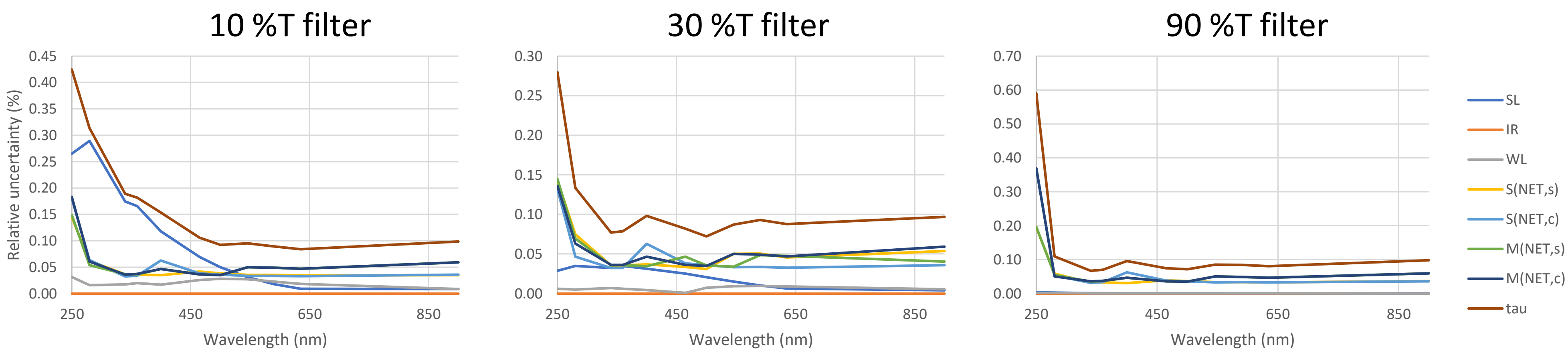
Step 2: Transmittance Uncertainty

Example uncertainty contributions and combined transmittance uncertainties for τ_{nominal} = 0.3

Source of Uncertainty	250 nm ≤ λ ≤ 360 nm		400 nm ≤ λ ≤ 900 nm	
	Standard Uncertainty	Relative Unc. Contribution	Standard Uncertainty	Relative Unc. Contribution
Stray Light	0.04%	0.03%	0.01%	0.02%
Wavelength	0.13 nm	0.01%	0.13 nm	0.01%
Signals				
Influx (S_S^{NET})	5.9e-12 A	0.07%	3.6e-12 A	0.04%
Efflux (S_C^{NET})	1.1e-11 A	0.06%	5.7e-11 A	0.04%
Monitor (M_S^{NET}, M_C^{NET})	6.3e-12 A	0.07%	3.9e-12 A	0.04%
		Exp. Unc. (k = 2)		Exp. Unc. (k = 2)
		0.2%		0.1%

Step 2: Transmittance Uncertainty

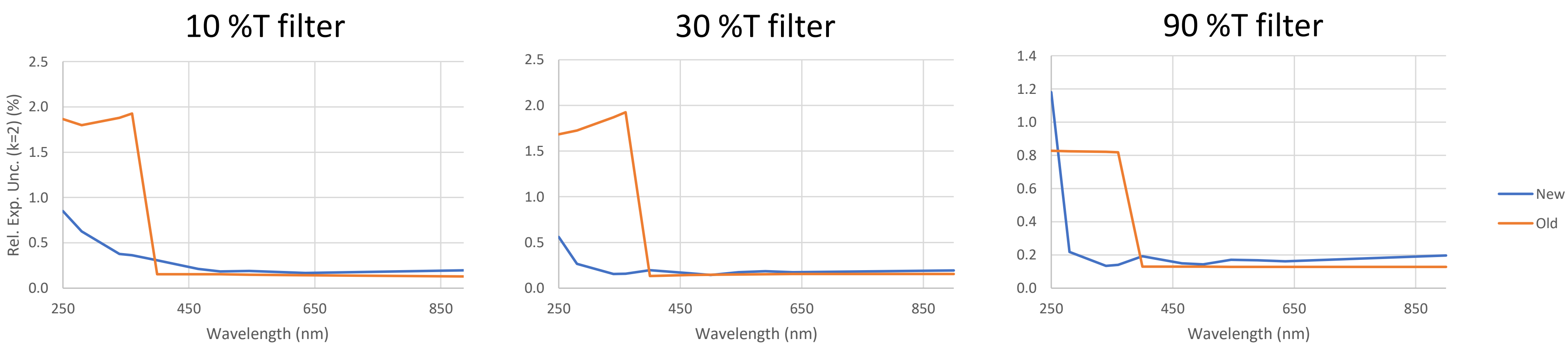
Example uncertainty contributions and combined transmittance uncertainties for τ



Major contributors:
- Net signals for 30 %T and 90 %T filters
- Stray light in UV for 10 %T filter

Uncertainty Budget Comparison

Example comparison of expanded uncertainty

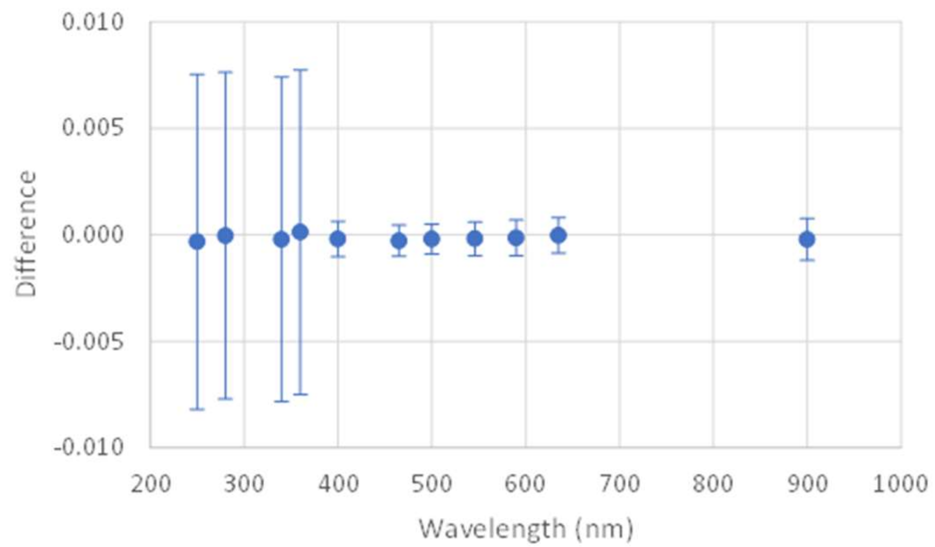


Results:

- Overall improvement in UV
- Uncertainties remain the same in visible

Instrument Validation

Example of difference between τ measured with the upgraded RTS and historical values



Results:

- Upgraded RTS agrees with historical measurements within the combined *k* = 2 uncertainties

Conclusions

Hardware Upgrades:
- LDLS for UV illumination
- Measurement and Monitor Lines
- New detection system

New Uncertainty Budget:
- Reduction of UV uncertainties by 70% or more

Bonus:
- Cut measurement time in half

Future Work

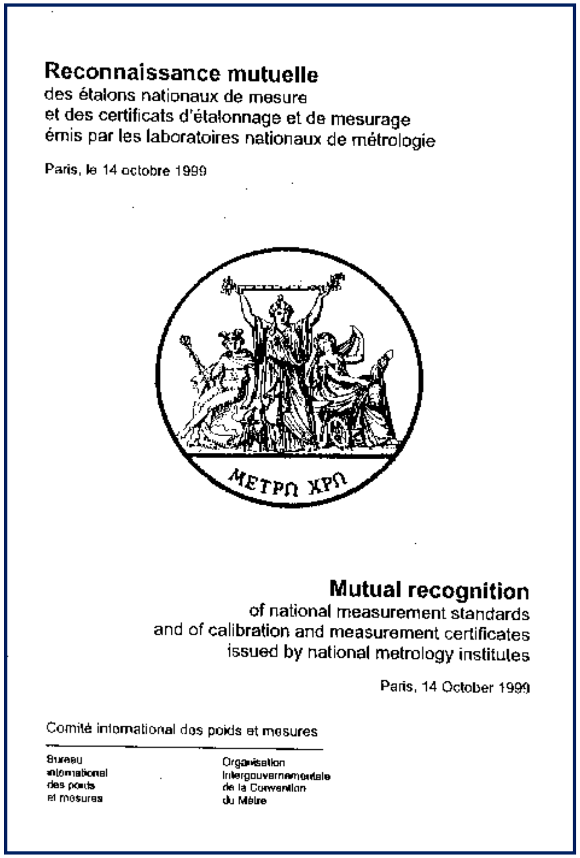
Short Term:
- Comparison measurements with NRC Canada

Near Term:
- Update Calibration and Measurement Capabilities (CMCs) for UV

Long Term:
- Incorporate polarization capability
- Update NIR detection system

CIPM Mutual Recognition Arrangement (MRA)

- Originally signed by 38 member states in Oct. 1999
- Today, 102 institutes have signed, covering 102 institutes plus 155 designated institutes
- Provides open, transparent, and comprehensive scheme to assess:
  - Comparability of national metrology services
  - Technical basis for wider agreements for international trade, commerce, and regulatory affairs


Reconnaissance mutuelle
des étalons nationaux de mesure
et des certificats d'étalonnage et de mesurage
émis par les laboratoires nationaux de métrologie

Paris, le 14 octobre 1999

Mutual recognition
of national measurement standards
and of calibration and measurement certificates
issued by national metrology institutes

Paris, 14 October 1999

Comité international des poids et mesures

Bureau international des poids et mesures

Organisation intergouvernementale de la Convention du Mètre

CIPM Mutual Recognition Arrangement (MRA)

NIST

Objectives:

Establish degree of equivalence of national measurement standards

+

Provide for mutual recognition of calibration and measurement standards

→

Provide technical foundation for international trade, commerce, and regulatory agreements

CIPM Mutual Recognition Arrangement (MRA)

NIST

Calibration and Measurement Capabilities (CMCs):

Calibration and Measurement Capabilities

Photometry and Radiometry, United States, NIST (National Institute of Standards and Technology)

Calibration or Measurement Service			Measurand Level or Range			Measurement Conditions/Independent Variable		Expanded Uncertainty						
Quantity	Instrument or Artifact	Instrument Type or Method	Minimum value	Maximum value	Units	Parameter	Specifications	Value	Units	Coverage factor	Level of Confidence	Is the expanded uncertainty a relative one?	Comments	NMI Internal Service Identifier
Luminous intensity	Tungsten lamp	Photometric bench	0.001	1	cd	Color temperature	2000 K to 3200 K	1.5 to 0.5, varies with measurand	%	2	95%	Yes	Services also available for sources other than tungsten lamps, with uncertainty evaluated for specific sources.	37010C and 37020S
Luminous intensity	Tungsten lamp	Photometric bench	1	10000	cd	Color temperature	2000 K to 3200 K	0.5	%	2	95%	Yes	Services also available for sources other than tungsten lamps, with uncertainty evaluated for specific sources.	37010C and 37020S
Illuminance responsivity, tungsten source	Illuminance meter	Photometric bench			A/lx or V/lx	Illuminance	0.001 lx to 0.1 lx	1.5 to 0.5 varies with illuminance	%	2	95%	Yes	Services also available for sources other than Illuminant A (e.g., LEDs of various colors), with uncertainty evaluated for specific sources.	37090S
						Color temperature	2856 K							
Illuminance responsivity, tungsten source	Illuminance meter	Photometric bench			A/lx or V/lx	Illuminance	0.1 lx to 1000 lx	0.5	%	2	95%	Yes	Services also available for sources other than Illuminant A (e.g., LEDs of various colors), with uncertainty evaluated for specific sources.	37090S
						Color temperature	2856 K							

Intercomparisons

Quality Management Systems

International Peer Reviews

Thank you!