**Appendix A.1 Description of measurement facility and measurement method**

Laboratory: NPL (National Physical Laboratory)

Indicate whether this table relates to Step 2 [ Yes ] or Step 4 [ -- ]

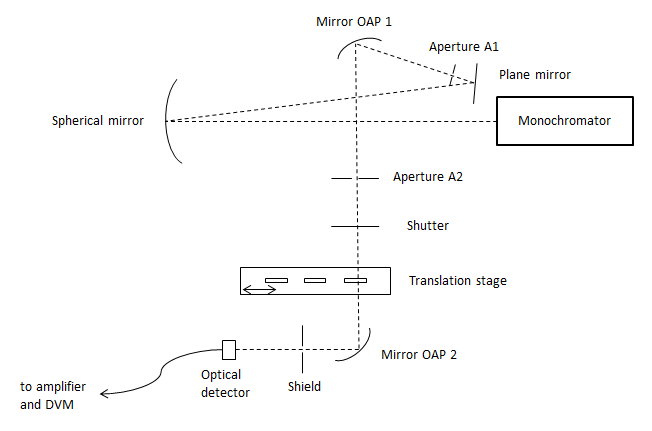
If the measurement setup has not changed from Step 2, check here [ ✓] and the following table does not need to be completed. Otherwise, please fill out the whole table.

Table A-1 Details of Measurement Setup for NPL round 1 and round 2 measurements

|  |  |
| --- | --- |
| Make and Type of Spectrophotometer | McPherson D330 double subtractive monochromator |
| Additional Stray Light Rejection | Light exiting the monochromator entered directly to a light tight enclosure. The filters (and all other optics) were located within the enclosure.  Order sorting filters were used at the entrance to the monochromator. |
| Source Drift Monitoring | None. Tests confirmed source stability was good and several sets of readings were made within each independent measurement run in order to minimise any residual drift effects. |
| Source | Tungsten strip lamp |
| Detector | Silicon |
| Temperature | Monitored by PRT located within the enclosure. Range of temperatures: 23.10 °C to 23.37 °C  (round 1) and 23.23 °C to 23.48 °C (round 2). |
| Humidity | Not monitored but controlled within the range 30 % RH to 60 % RH |
| Beam Size | 17 mm high x 16 mm wide, oval |
| Beam Collimation | Beam divergence < 0.15° |
| Measurement Sequence | At least 4 independent measurements were taken. Each measurement consisted of at least 8 sets of readings taken in the sequence: reference (i.e. no filter); filter 1; filter 2; filter 3. Each filter was rotated through 90° after each independent measurement. |
| Bandwidth | Approximately 1 nm |

**Description of measuring technique**

The filters were calibrated on the NPL primary spectral transmittance facility, shown in Figure 1 below.



**Figure 1: NPL Primary Spectral Transmittance Facility**

A quartz tungsten halogen source was imaged into the monochromator using mirrors. A McPherson model 2035 double subtractive Czerny-Turner monochromator was used, which had an f/number of f/4.8. The entrance and exit slits of each half of the monochromator were variable in both width and height; the slit width was adjusted to give a bandwidth of 1 nm (triangular), and the height was set to 2 mm. Built-in order sorting filters were located immediately before the entrance slit. The gratings installed in the monochromator for these measurements were blazed at 500 nm.

A spherical mirror was used to image the exit slit of the monochromator onto aperture A1, and an off-axis paraboloid mirror, OAP 1, was placed at its focal distance from this aperture so as to produce a collimated beam (divergence < 0.2°). A circular aperture A2, 16 mm in diameter, was placed in the collimated beam, to produce an irradiated area of the required size and shape at the position of the translation stage. The filters being measured were placed in holders on this translation stage and rotated slightly (2° to the normal) so that any reflected radiation was directed out of the light path. A second off-axis paraboloid mirror, OAP 2, was used to image the radiation passing through the filter onto the detector (a silicon photodiode).

The measurement side of the system (i.e. from the monochromator exit port onwards) was enclosed within a blackened, light-tight enclosure. The temperature within the enclosure was monitored using a platinum resistance thermometer (PRT).

Measurements were automated. The sequence for each measurement scan was as follows:

1. Set the monochromator to the wavelength required.
2. Record the light and dark readings (made with the shutter open and closed respectively) with no filter in the beam and calculate the detector signal.
3. Repeat step 2 with each individual filter positioned in the beam in turn (up to 3 filters were measured in each scan).
4. Set the monochromator to the next wavelength required.
5. Repeat steps 2 and 3.
6. Repeat steps 4 and 5 until all required wavelengths have been measured.

Eight repeated scans were carried out to form one ‘independent measurement’. The mean and standard deviation of the scans forming each independent measurement were calculated. A number of independent measurements were carried out (generally 4, but up to 8) and these were averaged to obtain the final measurement result. The filters were rotated by 90° and realigned between each independent measurement.

**Uncertainties**

Uncertainties due to random effects

The standard uncertainties due to random effects for an individual determination of filter transmittance (i.e. for one ‘independent measurement’) was estimated as the standard error associated with the mean (SEOM) for the associated series of spectral scans, given by:

*σ*scan=*σ*/√*N* Equation 1

where *N* is the number of spectral scans (i.e. 8) and*σ* is the standard deviation of these scans. By its nature, the random error varied for each independent determination of filter transmittance. However, it was observed that for a given filter at a given wavelength, the SEOM was similar for each determination, and it was therefore reasonable to take the median value of SEOM from the 4 (sometimes more) independent measurements for the uncertainty budget. This was included in the uncertainty budget as ‘scan repeatability’ and, as noted below, also included any uncertainties due to source drift and fluctuation.

The filters were realigned and rotated by 90° for each independent measurement, as described in the description of the measuring technique, and this would be expected to result in some additional random variation in the results, beyond that determined from the SEOM of the repeated scans. This additional uncertainty, , was calculated using:

If ≤ then ,

Equation 2

otherwise

where is the standard error associated with the mean (SEOM) for the series of independent measurements. This was included in the uncertainty budget as ‘independent measurement repeatability’. As indicated below, this also included the uncertainties due to beam size, shape and position, since the filter was realigned (and re-orientated) for each independent measurement.

The combined Type A standard uncertainty *u*A, was then calculated from:

Equation 3

Non-linearity

The uncertainty due to non-linearity in the detectors and electronics was evaluated based on the measured linearity characteristics (determined using the NPL double aperture linearity facility) and the difference in signal levels obtained for measurements with the test filter in position and with no filter in the beam.

Temperature

The temperature of the filters was measured throughout the measurements using a PRT within the enclosure. The measured transmittance values were corrected to a temperature of 23.00 °C using the information on the temperature coefficients of the filters supplied by the pilot laboratory. The associated uncertainty was evaluated based on:

* The standard deviation of filter temperatures during the measurements, multiplied by the relevant temperature coefficient
* The difference between the mean filter temperature during measurements and the reference temperature of 23.00 °C, multiplied by the uncertainty in the temperature coefficient
* The uncertainty in the temperature recorded by the PRT (as given in the associated calibration certificates for the PRT and the DVM used to measure its resistance), multiplied by the relevant temperature coefficient

Wavelength

The standard uncertainty associated with the measured spectral transmittance of the comparison filters due to uncertainty in the wavelength scale of the monochromator was estimated to be [1]:

 Equation 4

where *S*T(*λ*)and *S*R(*λ*) arethe signals for no filter and the test filter respectively, and *u*(*λ*) is the semi-range for the wavelength scale uncertainty, estimated to be 0.1 nm. The differential term was estimated by:

 Equation 5

where *ϕ*(*λ*) =*S*T(*λ*)/*S*R(*λ*).

Stray light

The stray light performance of the monochromator had been estimated in the past using combinations of filters. As expected for a well-designed double monochromator, the stray light performance was found to be good, and to have negligible impact on the measurement uncertainty.

The effect of stray light arising from, for example, reflections in the sample enclosure, was evaluated by placing baffles at various positions in the beam and recording any change in signal. The results of these investigations showed that external stray light was negligible, but an uncertainty of 0.01 % of the filter transmittance was included in the uncertainty budget as a worst case allowance.

Beam size, shape and position

The beam size and shape was very close to that specified in the protocol and therefore the uncertainty due to beam size was considered to be negligible. The beam was positioned centrally on the filter for each measurement and each filter was measured at least 4 times (with the filter rotated by 90° between each measurement); thus the impact of any small shifts in the beam position on the filter was included as part of the Type A uncertainty associated with the repeat measurements and therefore no additional allowance for beam position was considered necessary in the uncertainty budget.

Inter-reflection effects

The filters were offset at an angle of 2° to the beam in order to minimise inter-reflections. An uncertainty of 0.01 % of the measured filter transmittance was included as a worst case estimate of the possible influence of any residual reflections.

Obliquity

As indicated above, the filters were offset at a small angle (2°) to the beam in order to minimise inter-reflections, and in addition the beam used was not perfectly collimated, but had a divergence of approximately 0.12°. A small correction was applied to the results to allow for these geometric conditions; this correction was calculated according to the approach given in [2], assuming a refractive index for the filters of 1.5. The associated uncertainty was estimated by combining (in quadrature) the following effects:

* The difference between the corrected results and those that would be obtained using a tilt of 2.2° to the beam (a worst case estimate)
* The difference between the corrected results and those that would be obtained using a refractive index of 1.52 (a worst case estimate)
* The difference between the corrected results and those that would be obtained using a beam divergence of 0.4° (a gross over-estimate, but this difference was negligible in any case)

Polarisation

Measurements showed that there was negligible polarisation of the radiation incident on the filters, so no correction was necessary to allow for this. The uncertainty due to polarisation was evaluated using the Fresnel reflectance error equations given in [2], comparing the results calculated for unpolarised radiation and those for 67 % S (or P) and 33 % P (or S) as a worst case estimate.

Source drift and fluctuation

The measurement procedure involved making 8 sets of repeated measurements in each independent measurement run and the associated Type A uncertainty was included in the uncertainty budget; this uncertainty included any effects due to source drift and fluctuation.

Bandwidth

### Measurements were made using a bandwidth of 1 nm, in accordance with the protocol, and therefore it was not necessary to apply any bandwidth correction to the results. Nevertheless, the shape of the spectral transmittance profiles meant that the influence of bandwidth on the results had to be considered in the evaluation of the measurement uncertainty. The uncertainty due to bandwidth was estimated by calculating the size of the bandwidth correction (the correction to be applied to obtain the ‘true’ value for infinitely narrow bandwidth) using a 3-point correction method and assuming a triangular bandpass function [1] i.e. using:

Equation 6

where *C*0 is the corrected value for the wavelength being considered, *Δ* is the bandwidth, *δ* is the measurement step interval and *M*0, *M*-1 and *M*+1 are, respectively, the measured values at the wavelength being considered, the wavelength point one below this and the wavelength point one above this. The difference between *C*0 and *M*0 was found to be very small in all cases, but as a highly conservative estimate the uncertainty due to bandwidth was taken as being equal to the size of the resultant bandwidth correction ; this had negligible impact on the final measurement uncertainty.

Detector electronics

The uncertainty associated with the electronics (dvm and amplifier) was estimated based on the associated electrical calibration uncertainties, historical data relating to drift in the calibration values over time, and manufacturer’s data.

Filter instability

The uncertainty associated with filter instability was taken from the information provided by MSL (pooled estimate of uncertainty due to filter instability).

System reproducibility

For a small number of measurement points, the absolute difference in measured transmittance for the two rounds of measurements at NPL was greater than two times the total uncorrelated uncertainty. An additional uncertainty was therefore added for these measurements, which was set to be large enough to ensure consistency between the two measurements.

[1] Woolliams, E.R., Baribeau, R., Bialek, A., and Cox, M. G., *Spectrometer bandwidth correction for generalized bandpass functions.* Metrologia, 2011, **48**: 164–172

If any damage, contamination or cleaning of the filters was carried out, please give details.

[2] Mielenz, K. D. and R. Mavrodineanu., *Reflection correction for high-accuracy transmittance measurements on filter glasses*. Journal of Research of the National Bureau of Standards, 1973, **77A(6)**: 699-703

**Appendix A.2 Measurement Results (Round 1)**

All results are quoted in terms of absolute transmittance.

Laboratory: NPL Filter Identifier: A

Table A-2i Measurement Results (Round 1)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Wavelength  (nm) | 380 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
| Spectral Transmittance | 9.1299E-01 | 9.1455E-01 | 9.1706E-01 | 9.1848E-01 | 9.1921E-01 | 9.2033E-01 | 9.2068E-01 | 9.2119E-01 |
| Number of Measurements | 8 | 4 | 5 | 5 | 5 | 5 | 4 | 5 |
| Temperature | 23.23 | 23.25 | 23.21 | 23.21 | 23.21 | 23.21 | 23.17 | 23.21 |
| Type A Uncertainty | 4.31E-05 | 2.69E-05 | 2.53E-05 | 1.68E-05 | 3.74E-05 | 5.04E-05 | 1.50E-05 | 3.19E-05 |
| Type B Uncertainty | 1.79E-04 | 1.77E-04 | 1.69E-04 | 1.58E-04 | 1.65E-04 | 1.49E-04 | 1.50E-04 | 1.50E-04 |
| Total Uncertainty | 1.84E-04 | 1.79E-04 | 1.71E-04 | 1.59E-04 | 1.69E-04 | 1.57E-04 | 1.51E-04 | 1.54E-04 |
| Degrees of Freedom | >1000 | >1000 | >1000 | >1000 | >1000 | 484 | >1000 | >1000 |

Table A-2ii Type B Uncertainty Budget(Round 1)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Wavelength  (nm) | 380 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
| Nonlinearity | 3.65E-05 | 2.29E-05 | 1.83E-05 | 1.84E-05 | 1.84E-05 | 1.84E-05 | 1.38E-05 | 9.21E-06 |
| Temperature | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Wavelength | 1.14E-05 | 3.94E-06 | 9.00E-07 | 1.61E-06 | 1.54E-06 | 2.78E-07 | 4.89E-07 | 1.99E-06 |
| Stray Light | 9.13E-05 | 9.15E-05 | 9.17E-05 | 9.18E-05 | 9.19E-05 | 9.20E-05 | 9.21E-05 | 9.21E-05 |
| Beam Size & Position | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Inter-reflection | 9.13E-05 | 9.15E-05 | 9.17E-05 | 9.18E-05 | 9.19E-05 | 9.20E-05 | 9.21E-05 | 9.21E-05 |
| Obliquity | 1.51E-06 | 1.48E-06 | 1.44E-06 | 1.42E-06 | 1.42E-06 | 1.41E-06 | 1.41E-06 | 1.41E-06 |
| Polarization | 3.96E-05 | 3.96E-05 | 3.97E-05 | 3.98E-05 | 3.98E-05 | 3.99E-05 | 3.99E-05 | 3.99E-05 |
| Source Drift & Fluctuation | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Bandwidth | 2.45E-07 | 3.15E-06 | 5.28E-07 | 1.64E-08 | 1.60E-06 | 1.27E-06 | 5.86E-07 | 3.45E-06 |
| Detector electronics | 9.13E-06 | 9.15E-06 | 9.17E-06 | 9.18E-06 | 9.19E-06 | 9.20E-06 | 9.21E-06 | 9.21E-06 |
| Filter instability | 1.10E-04 | 1.12E-04 | 9.89E-05 | 7.87E-05 | 6.81E-05 | 5.57E-05 | 6.11E-05 | 6.16E-05 |
| System reproducibility | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.00E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Total Type B Uncertainty | 1.79E-04 | 1.77E-04 | 1.69E-04 | 1.58E-04 | 1.65E-04 | 1.49E-04 | 1.50E-04 | 1.50E-04 |
| Degrees of Freedom | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |

**Signature :** Teresa Goodman **Date : 20 April 2015**

Laboratory: NPL Filter Identifier: B

Table A-2i Measurement Results (Round 1)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Wavelength  (nm) | 380 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
| Spectral Transmittance | 4.0714E-01 | 6.0721E-01 | 6.2077E-01 | 6.0848E-01 | 6.3583E-01 | 5.7517E-01 | 4.9981E-01 | 4.5136E-01 |
| Number of Measurements | 8 | 4 | 5 | 5 | 5 | 5 | 4 | 5 |
| Temperature | 23.23 | 23.25 | 23.21 | 23.21 | 23.21 | 23.21 | 23.17 | 23.21 |
| Type A Uncertainty | 1.43E-04 | 2.12E-05 | 2.29E-05 | 1.75E-05 | 2.64E-05 | 1.81E-05 | 9.79E-06 | 1.92E-05 |
| Type B Uncertainty | 9.83E-04 | 2.08E-04 | 1.75E-04 | 1.32E-04 | 1.34E-04 | 1.68E-04 | 1.35E-04 | 9.96E-05 |
| Total Uncertainty | 9.94E-04 | 2.09E-04 | 1.76E-04 | 1.33E-04 | 1.37E-04 | 1.69E-04 | 1.36E-04 | 1.01E-04 |
| Degrees of Freedom | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 |

Table A-2ii Type B Uncertainty Budget(Round 1)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Wavelength  (nm) | 380 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
| Nonlinearity | 8.14E-05 | 9.11E-05 | 6.21E-05 | 6.08E-05 | 6.36E-05 | 5.75E-05 | 4.00E-05 | 2.26E-05 |
| Temperature | 3.33E-08 | 5.86E-08 | 2.70E-08 | 6.03E-08 | 3.39E-08 | 2.21E-08 | 1.97E-08 | 2.77E-08 |
| Wavelength | 9.08E-04 | 8.46E-05 | 1.15E-05 | 6.56E-06 | 2.30E-05 | 8.39E-05 | 6.41E-05 | 3.16E-05 |
| Stray Light | 4.07E-05 | 6.07E-05 | 6.21E-05 | 6.08E-05 | 6.36E-05 | 5.75E-05 | 5.00E-05 | 4.51E-05 |
| Beam Size & Position | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Inter-reflection | 4.07E-05 | 6.07E-05 | 6.21E-05 | 6.08E-05 | 6.36E-05 | 5.75E-05 | 5.00E-05 | 4.51E-05 |
| Obliquity | 1.92E-05 | 1.47E-05 | 1.43E-05 | 1.47E-05 | 1.37E-05 | 1.57E-05 | 1.77E-05 | 1.87E-05 |
| Polarization | 1.76E-05 | 2.63E-05 | 2.69E-05 | 2.64E-05 | 2.75E-05 | 2.49E-05 | 2.16E-05 | 1.96E-05 |
| Source Drift & Fluctuation | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Bandwidth | 2.78E-04 | 5.29E-05 | 8.45E-07 | 8.96E-07 | 2.66E-06 | 1.23E-06 | 5.78E-07 | 1.15E-06 |
| Detector Electronics | 8.14E-06 | 1.21E-05 | 1.24E-05 | 1.22E-05 | 1.27E-05 | 1.15E-05 | 1.00E-05 | 9.03E-06 |
| Filter instability | 2.31E-04 | 1.29E-04 | 1.33E-04 | 7.16E-05 | 6.53E-05 | 1.02E-04 | 8.21E-05 | 4.80E-05 |
| System reproducibility | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 3.50E-05 |
| Total Type B Uncertainty | 9.83E-04 | 2.08E-04 | 1.75E-04 | 1.32E-04 | 1.34E-04 | 1.68E-04 | 1.35E-04 | 9.96E-05 |
| Degrees of Freedom | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |

**Signature :** Teresa Goodman **Date : 20 April 2015**Laboratory: NPL Filter Identifier: C

Table A-2i Measurement Results (Round 1)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Wavelength  (nm) | 380 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
| Spectral Transmittance | 2.1496E-02 | 9.5668E-02 | 9.2044E-02 | 7.7085E-02 | 1.6136E-01 | 1.5011E-01 | 1.0281E-01 | 7.6531E-02 |
| Number of Measurements | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Temperature | 23.15 | 23.15 | 23.18 | 23.18 | 23.18 | 23.18 | 23.17 | 23.18 |
| Type A Uncertainty | 1.36E-05 | 1.08E-05 | 9.39E-06 | 6.00E-06 | 9.83E-06 | 8.39E-06 | 4.19E-06 | 4.56E-06 |
| Type B Uncertainty | 2.59E-04 | 1.07E-04 | 4.46E-05 | 2.71E-05 | 1.51E-04 | 6.60E-05 | 4.90E-05 | 2.52E-05 |
| Total Uncertainty | 2.59E-04 | 1.08E-04 | 4.56E-05 | 2.78E-05 | 1.52E-04 | 6.66E-05 | 4.92E-05 | 2.56E-05 |
| Degrees of Freedom | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 |

Table A-2ii Type B Uncertainty Budget(Round 1)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Wavelength  (nm) | 380 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
| Nonlinearity | 8.60E-06 | 2.87E-05 | 1.84E-05 | 1.54E-05 | 3.23E-05 | 3.00E-05 | 1.54E-05 | 7.65E-06 |
| Temperature | 6.41E-09 | 3.77E-08 | 1.86E-08 | 3.43E-08 | 3.12E-08 | 1.88E-08 | 1.31E-08 | 1.34E-08 |
| Wavelength | 2.49E-04 | 9.90E-05 | 3.62E-05 | 2.03E-05 | 1.48E-04 | 5.35E-05 | 3.80E-05 | 1.53E-05 |
| Stray Light | 2.15E-06 | 9.57E-06 | 9.20E-06 | 7.71E-06 | 1.61E-05 | 1.50E-05 | 1.03E-05 | 7.65E-06 |
| Beam Size & Position | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Inter-reflection | 2.15E-06 | 9.57E-06 | 9.20E-06 | 7.71E-06 | 1.61E-05 | 1.50E-05 | 1.03E-05 | 7.65E-06 |
| Obliquity | 4.66E-06 | 1.25E-05 | 1.22E-05 | 1.10E-05 | 1.62E-05 | 1.57E-05 | 1.30E-05 | 1.10E-05 |
| Polarization | 9.30E-07 | 4.14E-06 | 3.99E-06 | 3.34E-06 | 6.99E-06 | 6.50E-06 | 4.45E-06 | 3.31E-06 |
| Source Drift & Fluctuation | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Bandwidth | 6.41E-05 | 2.62E-05 | 2.05E-06 | 9.66E-07 | 6.67E-06 | 1.76E-07 | 1.15E-06 | 1.77E-07 |
| Detector electronics | 1.07E-06 | 4.78E-06 | 4.60E-06 | 3.85E-06 | 8.07E-06 | 7.51E-06 | 5.14E-06 | 3.83E-06 |
| Filter instability | 3.32E-05 | 2.61E-05 | 9.72E-06 | 7.39E-06 | 0.00E+00 | 2.64E-05 | 2.31E-05 | 1.17E-05 |
| System reproducibility | 0.00E+00 | 0.00E+00 | 1.50E-05 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Total Type B Uncertainty | 2.59E-04 | 1.07E-04 | 4.46E-05 | 2.71E-05 | 1.51E-04 | 6.60E-05 | 4.90E-05 | 2.52E-05 |
| Degrees of Freedom | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |

**Signature :** Teresa Goodman **Date : 20 April 2015**

Laboratory: NPL Filter Identifier: D

Table A-2i Measurement Results (Round 1)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Wavelength  (nm) | 380 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
| Spectral Transmittance | 3.9133E-04 | 5.3736E-03 | 8.6947E-03 | 8.6000E-03 | 2.7136E-02 | 3.2955E-02 | 2.3098E-02 | 1.7138E-02 |
| Number of Measurements | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Temperature | 23.15 | 23.15 | 23.18 | 23.18 | 23.18 | 23.18 | 23.17 | 23.18 |
| Type A Uncertainty | 1.70E-05 | 4.61E-06 | 1.76E-06 | 1.51E-06 | 2.66E-06 | 3.84E-06 | 2.69E-06 | 1.15E-06 |
| Type B Uncertainty | 8.45E-06 | 1.79E-05 | 4.62E-06 | 6.21E-06 | 3.67E-05 | 1.57E-05 | 1.27E-05 | 6.43E-06 |
| Total Uncertainty | 1.90E-05 | 1.85E-05 | 4.94E-06 | 6.40E-06 | 3.68E-05 | 1.62E-05 | 1.30E-05 | 6.53E-06 |
| Degrees of Freedom | 11 | >1000 | 321 | >1000 | >1000 | >1000 | >1000 | >1000 |

Table A-2ii Type B Uncertainty Budget(Round 1)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Wavelength  (nm) | 380 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
| Nonlinearity | 1.57E-07 | 1.61E-06 | 1.74E-06 | 1.72E-06 | 5.43E-06 | 6.59E-06 | 3.46E-06 | 1.71E-06 |
| Temperature | 2.49E-10 | 4.81E-09 | 3.55E-09 | 7.28E-09 | 1.07E-08 | 7.54E-09 | 4.90E-09 | 4.83E-09 |
| Wavelength | 8.22E-06 | 1.72E-05 | 2.44E-06 | 4.91E-06 | 3.51E-05 | 7.81E-06 | 9.12E-06 | 2.78E-06 |
| Stray Light | 3.91E-08 | 5.37E-07 | 8.69E-07 | 8.60E-07 | 2.71E-06 | 3.30E-06 | 2.31E-06 | 1.71E-06 |
| Beam Size & Position | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Inter-reflection | 3.91E-08 | 5.37E-07 | 8.69E-07 | 8.60E-07 | 2.71E-06 | 3.30E-06 | 2.31E-06 | 1.71E-06 |
| Obliquity | 1.75E-07 | 1.59E-06 | 2.34E-06 | 2.32E-06 | 5.52E-06 | 6.34E-06 | 4.91E-06 | 3.94E-06 |
| Polarization | 1.69E-08 | 2.32E-07 | 3.76E-07 | 3.72E-07 | 1.17E-06 | 1.43E-06 | 1.00E-06 | 7.42E-07 |
| Source Drift & Fluctuation | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Bandwidth | 1.96E-06 | 2.51E-06 | 2.31E-07 | 1.64E-07 | 8.99E-07 | 1.67E-07 | 7.20E-08 | 8.90E-08 |
| Detector electronics | 3.91E-08 | 5.37E-07 | 8.69E-07 | 8.60E-07 | 2.71E-06 | 3.30E-06 | 2.31E-06 | 1.71E-06 |
| Filter instability | 0.00E+00 | 3.63E-06 | 2.09E-06 | 1.95E-06 | 5.60E-06 | 8.26E-06 | 4.91E-06 | 2.41E-06 |
| System reproducibility | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Total Type B Uncertainty | 8.45E-06 | 1.79E-05 | 4.62E-06 | 6.21E-06 | 3.67E-05 | 1.57E-05 | 1.27E-05 | 6.43E-06 |
| Degrees of Freedom | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |

**Signature :** Teresa Goodman **Date : 20 April 2015**

Laboratory: NPL Filter Identifier: E

Table A-2i Measurement Results (Round 1)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Wavelength  (nm) | 380 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
| Spectral Transmittance |  | 3.4968E-04 | 9.6411E-04 | 1.0308E-03 | 5.1582E-03 | 9.8744E-03 | 8.6137E-03 | 7.2887E-03 |
| Number of Measurements |  | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Temperature |  | 23.15 | 23.18 | 23.18 | 23.18 | 23.18 | 23.17 | 23.18 |
| Type A Uncertainty |  | 5.99E-06 | 2.28E-06 | 9.54E-07 | 1.85E-06 | 4.75E-06 | 2.13E-06 | 7.08E-07 |
| Type B Uncertainty |  | 2.09E-06 | 6.02E-07 | 1.01E-06 | 9.72E-06 | 4.18E-06 | 4.05E-06 | 3.53E-06 |
| Total Uncertainty |  | 6.34E-06 | 2.36E-06 | 1.39E-06 | 9.90E-06 | 6.33E-06 | 4.58E-06 | 3.60E-06 |
| Degrees of Freedom |  | 9 | 8 | 31 | >1000 | 22 | 149 | >1000 |

Table A-2ii Type B Uncertainty Budget(Round 1)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Wavelength  (nm) | 380 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
| Nonlinearity |  | 1.05E-07 | 1.93E-07 | 2.06E-07 | 1.03E-06 | 1.97E-06 | 1.29E-06 | 7.29E-07 |
| Temperature |  | 4.86E-10 | 5.85E-10 | 1.28E-09 | 3.00E-09 | 3.14E-09 | 2.33E-09 | 3.16E-09 |
| Wavelength |  | 2.05E-06 | 3.48E-07 | 8.64E-07 | 9.46E-06 | 9.42E-07 | 2.18E-06 | 2.46E-07 |
| Stray Light |  | 3.50E-08 | 9.64E-08 | 1.03E-07 | 5.16E-07 | 9.87E-07 | 8.61E-07 | 7.29E-07 |
| Beam Size & Position |  | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Inter-reflection |  | 3.50E-08 | 9.64E-08 | 1.03E-07 | 5.16E-07 | 9.87E-07 | 8.61E-07 | 7.29E-07 |
| Obliquity |  | 1.59E-07 | 3.81E-07 | 4.04E-07 | 1.54E-06 | 2.58E-06 | 2.32E-06 | 2.03E-06 |
| Polarization |  | 1.51E-08 | 4.17E-08 | 4.46E-08 | 2.23E-07 | 4.27E-07 | 3.73E-07 | 3.15E-07 |
| Source Drift & Fluctuation |  | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Bandwidth |  | 6.50E-08 | 3.28E-08 | 2.93E-08 | 1.02E-07 | 7.25E-08 | 2.07E-08 | 5.27E-08 |
| Detector electronics |  | 6.99E-08 | 1.93E-07 | 2.06E-07 | 1.03E-06 | 1.97E-06 | 1.72E-06 | 1.46E-06 |
| Filter instability |  | 3.38E-07 | 0.00E+00 | 7.14E-08 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 6.87E-07 |
| System reproducibility |  | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 2.00E-06 |
| Total Type B Uncertainty |  | 2.09E-06 | 6.02E-07 | 1.01E-06 | 9.72E-06 | 4.18E-06 | 4.05E-06 | 3.53E-06 |
| Degrees of Freedom |  | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |

**Signature :** Teresa Goodman **Date : 20 April 2015**

**Appendix A.3 Measurement Results (Round 2)**

Laboratory: NPL Filter Identifier: A

Table A-3i Measurement Results (Round 2)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Wavelength  (nm) | 380 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
| Spectral Transmittance | 9.1285E-01 | 9.1462E-01 | 9.1704E-01 | 9.1850E-01 | 9.1948E-01 | 9.2025E-01 | 9.2063E-01 | 9.2102E-01 |
| Number of Measurements | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Temperature | 23.36 | 23.36 | 23.36 | 23.36 | 23.36 | 23.36 | 23.38 | 23.38 |
| Type A Uncertainty | 2.70E-05 | 2.02E-05 | 1.00E-05 | 6.64E-06 | 7.09E-06 | 7.30E-06 | 2.03E-05 | 1.69E-05 |
| Type B Uncertainty | 1.79E-04 | 1.77E-04 | 1.69E-04 | 1.58E-04 | 1.65E-04 | 1.49E-04 | 1.50E-04 | 1.50E-04 |
| Total Uncertainty | 1.81E-04 | 1.79E-04 | 1.69E-04 | 1.58E-04 | 1.65E-04 | 1.49E-04 | 1.52E-04 | 1.51E-04 |
| Degrees of Freedom | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 |

Laboratory: NPL Filter Identifier: B

Table A-3i Measurement Results (Round 2)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Wavelength  (nm) | 380 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
| Spectral Transmittance | 4.0711E-01 | 6.0709E-01 | 6.2053E-01 | 6.0840E-01 | 6.3593E-01 | 5.7497E-01 | 4.9965E-01 | 4.5119E-01 |
| Number of Measurements | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Temperature | 23.36 | 23.36 | 23.36 | 23.36 | 23.36 | 23.36 | 23.38 | 23.38 |
| Type A Uncertainty | 7.53E-05 | 3.96E-05 | 1.98E-05 | 1.53E-05 | 1.46E-05 | 1.22E-05 | 2.03E-05 | 1.24E-05 |
| Type B Uncertainty | 9.83E-04 | 2.08E-04 | 1.75E-04 | 1.32E-04 | 1.34E-04 | 1.68E-04 | 1.35E-04 | 9.96E-05 |
| Total Uncertainty | 9.86E-04 | 2.12E-04 | 1.76E-04 | 1.33E-04 | 1.35E-04 | 1.69E-04 | 1.37E-04 | 1.00E-04 |
| Degrees of Freedom | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 | >1000 |

Laboratory: NPL Filter Identifier: C

Table A-3i Measurement Results (Round 2)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Wavelength  (nm) | 380 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
| Spectral Transmittance | 2.1550E-02 | 9.5618E-02 | 9.1993E-02 | 7.7058E-02 | 1.6138E-01 | 1.5005E-01 | 1.0276E-01 | 7.6496E-02 |
| Number of Measurements | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Temperature | 23.36 | 23.36 | 23.36 | 23.36 | 23.36 | 23.36 | 23.38 | 23.38 |
| Type A Uncertainty | 1.43E-05 | 1.98E-05 | 7.48E-06 | 9.29E-06 | 1.14E-05 | 5.85E-06 | 7.52E-06 | 5.78E-06 |
| Type B Uncertainty | 2.60E-04 | 1.11E-04 | 4.82E-05 | 3.12E-05 | 1.55E-04 | 7.25E-05 | 5.14E-05 | 2.63E-05 |
| Total Uncertainty | 2.60E-04 | 1.13E-04 | 4.88E-05 | 3.25E-05 | 1.55E-04 | 7.27E-05 | 5.19E-05 | 2.69E-05 |
| Degrees of Freedom | >1000 | >1000 | >1000 | 427 | >1000 | >1000 | >1000 | >1000 |

Laboratory: NPL Filter Identifier: D

Table A-3i Measurement Results (Round 2)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Wavelength  (nm) | 380 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
| Spectral Transmittance | 3.6812E-04 | 5.3725E-03 | 8.6949E-03 | 8.6000E-03 | 2.7146E-02 | 3.2944E-02 | 2.3095E-02 | 1.7131E-02 |
| Number of Measurements | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Temperature | 23.39 | 23.39 | 23.39 | 23.36 | 23.39 | 23.39 | 23.39 | 23.39 |
| Type A Uncertainty | 1.38E-05 | 6.78E-06 | 8.82E-07 | 6.69E-07 | 1.54E-06 | 2.50E-06 | 2.35E-06 | 3.25E-06 |
| Type B Uncertainty | 7.95E-06 | 1.79E-05 | 4.62E-06 | 6.21E-06 | 3.67E-05 | 1.57E-05 | 1.27E-05 | 6.43E-06 |
| Total Uncertainty | 1.60E-05 | 1.92E-05 | 4.70E-06 | 6.25E-06 | 3.67E-05 | 1.59E-05 | 1.29E-05 | 7.20E-06 |
| Degrees of Freedom | 12 | 463 | >1000 | >1000 | >1000 | >1000 | >1000 | 64 |

Laboratory: NPL Filter Identifier: E

Table A-3i Measurement Results (Round 2)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Wavelength  (nm) | 380 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
| Spectral Transmittance |  | 3.4290E-04 | 9.6232E-04 | 1.0308E-03 | 5.1610E-03 | 9.8706E-03 | 8.6122E-03 | 7.2835E-03 |
| Number of Measurements |  | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Temperature |  | 23.39 | 23.39 | 23.36 | 23.39 | 23.39 | 23.39 | 23.39 |
| Type A Uncertainty |  | 6.01E-06 | 7.68E-07 | 5.27E-07 | 1.84E-06 | 2.38E-06 | 1.54E-06 | 7.58E-07 |
| Type B Uncertainty |  | 2.05E-06 | 6.01E-07 | 1.01E-06 | 9.73E-06 | 4.18E-06 | 4.05E-06 | 3.53E-06 |
| Total Uncertainty |  | 6.35E-06 | 9.75E-07 | 1.14E-06 | 9.90E-06 | 4.81E-06 | 4.33E-06 | 3.61E-06 |
| Degrees of Freedom |  | 9 | 18 | 153 | >1000 | 129 | 440 | >1000 |

Table A-3ii Type B Uncertainty Budget(Round 2)

If the uncertainty budget has not changed from Step 2 (Table A-2ii), check here [ ✓] and only the Correlation Coefficient column of the following table needs to be filled out. Otherwise, please fill out the whole table.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Wavelength  (nm) | 380 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 | Correlation Coefficient |
| Nonlinearity |  |  |  |  |  |  |  |  | 1.0 |
| Temperature |  |  |  |  |  |  |  |  | 1.0 |
| Wavelength |  |  |  |  |  |  |  |  | 1.0 |
| Stray Light |  |  |  |  |  |  |  |  | 1.0 |
| Beam Size & Position |  |  |  |  |  |  |  |  | 1.0 |
| Inter-reflection |  |  |  |  |  |  |  |  | 1.0 |
| Obliquity |  |  |  |  |  |  |  |  | 1.0 |
| Polarization |  |  |  |  |  |  |  |  | 1.0 |
| Source Drift & Fluctuation |  |  |  |  |  |  |  |  | 1.0 |
| Bandwidth |  |  |  |  |  |  |  |  | 1.0 |
| Detector Electronics |  |  |  |  |  |  |  |  | 1.0 |
| Filter instability |  |  |  |  |  |  |  |  | 0.0 |
| System reproducibility |  |  |  |  |  |  |  |  | 0.0 |
| Total Type B Uncertainty |  |  |  |  |  |  |  |  |  |
| Degrees of Freedom |  |  |  |  |  |  |  |  |  |

**Signature :** Teresa Goodman **Date : 20 April 2015**