

Report on the long-term stability of filter radiometers developed in the previous (98- 01) optical programme

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Report on the long-term stability of filter radiometers developed in the
previous (98-01) optical programme

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Quality of Life Division

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ABSTRACT

This report presents the findings of an investigation into the long-term stability of two types of filter radiometer, one type based on a high specification custom 800 nm interference optical bandpass filter and the other on a proprietary single glass 710 nm bandpass filter. Spectral responsivity measurements made over a three-year period showed that the 800 nm filter radiometers exhibited excellent long-term stability, of the order of the spectral responsivity measurement uncertainty of ± 0.1 %. This, combined with their high out-of-band blocking, makes these 800 nm filter radiometers a notable improvement on the 800 nm NPL primary filter radiometers used previously. Unfortunately, high spatial non-uniformity and low optical transmission of the 710 nm glass filters resulted in insufficient measurement accuracy to reliably evaluate their long-term stability.

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Contents

1. Introduction	1
1.1 Filter radiometer components	2
1.1.1 Aperture	2
1.1.2 Detector	3
1.1.3 Filter	3
1.1.4 Housing and electronics	5
1.2 Calibration of filter radiometers	6
2. Long-term stability measurement results	8
2.1 800 nm interference filter radiometers	8
2.2 710 nm glass filter radiometers	14
3. Conclusions	18
4. References	18

Figure index

Figure 1: The standard NPL filter radiometer (not to scale).	2
Figure 2: Schematic of the NPL laser-based primary filter radiometer calibration facility	7
Figure 3: Representative absolute spectral responsivity curves for the new type 800 nm filter radiometer (top), and plotted with a logarithmic ordinate scale (bottom).	9
Figure 4: Changes in spectral responsivity, over a three year period, for a 800 nm filter radiometer (serial number 800W50S1337A).	10
Figure 5: Changes in spectral responsivity, over a three year period, for the older type of 800 nm filter radiometer (serial number 800W20THE).	11
Figure 6: Comparison of old (800W20THE) and new (800W50S1227D) type of 800 nm filter radiometers' spectral responsivity, plotted with a logarithmic scale.	12

Figure 7: Changes in spectral responsivity, over a three year period, for a 800 nm filter radiometer (serial number 800W50S1337C).	13
Figure 8: Changes in spectral responsivity, over a three year period, for a 800 nm filter radiometer (serial number 800W50S1337D).	14
Figure 9: Representative absolute spectral responsivity curves for the 710 nm glass type filter radiometer (top), and plotted with a logarithmic ordinate scale (bottom).....	15
Figure 10: Compares spectral responsivity changes of two 710 nm filter radiometers (serial number 710W50S5227D and E) over approximately two years. Representaive spectral responsivity data is also plotted.	16
Figure 11: Spatial uniformity of transmission of a 710 nm glass optical bandpass filter.....	17

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For project QR0113 Milestone 5

1. Introduction

A filter radiometer is a device that measures a specific spectral band from a broad band electromagnetic radiation source. For example, a suitable filter radiometer could be used to measure the amount of Ultra Violet (UV) light emitted from a white light source. Filter radiometry forms the cornerstone of optical radiation measurement. The use of filter radiometers in industry is widespread, finding application in areas such as direct optical radiation measurement (for instance solar UV measurement, or continuous flow pollution monitoring), radiation temperature measurement, colorimetry, and photometry. Furthermore, filter radiometers are the underpinning technology behind the dissemination of detector-based spectral scales, and in the establishment at NPL of source-based scales [1].

Currently one of the main limitations in filter radiometry is the long-term ageing of the optical filters used, both in terms of the stability of their absolute transmittance and their relative spectral profile. Development of filter radiometers with improved stability will allow less frequent re-calibration and more robust and stable industrial meters and process monitoring instruments.

Potentially any part of the filter radiometer can contribute to its ageing and these components are discussed below, in §1.1. In practice, for most applications the optical bandpass filter is the most critical component in filter radiometer's ageing. This report examines the long-term stability of filter radiometers developed in the 98-01 optical programme. Two types of filter radiometers were investigated, the first type is based on an interference filter with a centre wavelength of 800 nm and the second type employs a 710 nm centre wavelength glass filter.

1.1 Filter radiometer components

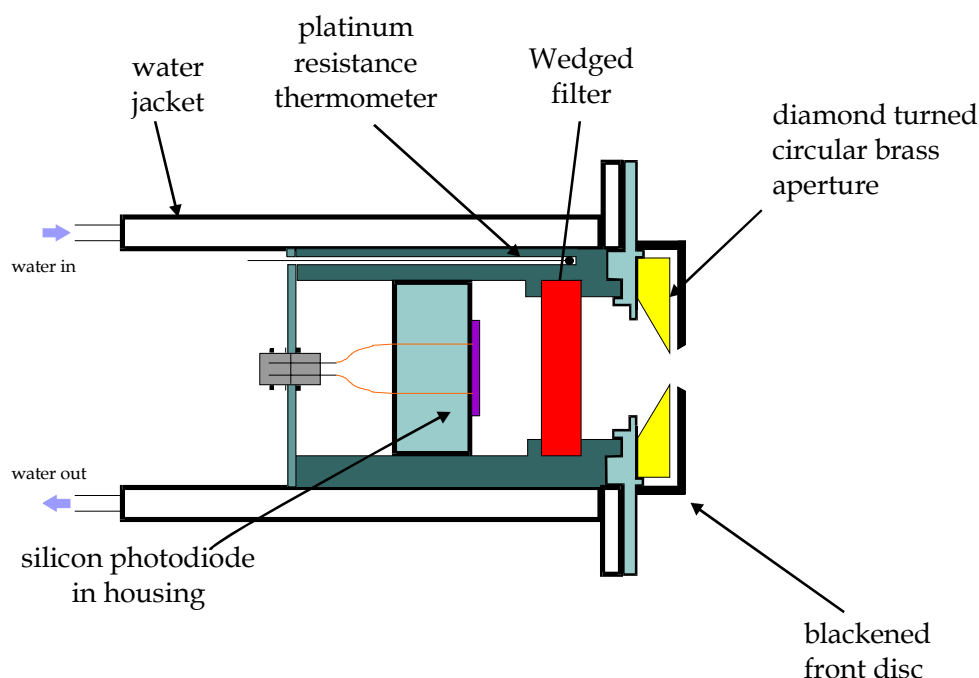


Figure 1: The standard NPL filter radiometer (not to scale).

The basic components of any filter radiometer are a light detector, such as a silicon photodiode, an optical filter, for example coloured glass, and a precision aperture, which is used to define the measurement geometry. A schematic of the current standard NPL filter radiometer is shown in Figure 1. Due to the temperature dependant characteristics of most optical bandpass filters, a water jacket is used to maintain the filter radiometer at a constant temperature.

1.1.1 Aperture

For the filter radiometers reported here precision diamond turned, brass apertures were used. With good housekeeping, such as using aperture covers when the filter radiometer is not in use, the aperture area should not change with time. Repeat aperture area measurement performed at NPL over several years has confirmed this to within the area measurement uncertainty of around 0.002 % [2]. However, reductions in aperture area of up to 0.3 % have been observed at NPL before and after cleaning.

Possible causes for such changes are exposure to oil vapour and other contaminants and aperture growth. In addition, mishandling can cause burrs on the defining edge of the aperture.

1.1.2 Detector

The detector used in filter radiometers is normally a solid-state device, such as the widely used and well-developed silicon photodiode. For the filter radiometers investigated here, Hamamatsu S1337 and S1227 (IR suppressed version of the S1337) silicon photodiodes were chosen. These detectors have been shown to be one of the best commercially available Si photodiodes in terms of stability [3] and spatial uniformity of response. Typically, such photodiodes exhibit an annual drop in responsivity of less than 0.05 % over the spectral range 400 nm – 950 nm [4].

1.1.3 Filter

The heart of the filter radiometer is the optical bandpass filter, which provides a well-defined spectral transmission band. The filter may possess a narrow spectral bandpass, or pass a somewhat larger wavelength range, as for instance in a photometer which have a full width half maximum (FWHM) bandwidth of 100 nm. Currently two main types of filter technology are employed in filter radiometers, namely coloured glass and interference filters. Interference filters consist of a substrate coated by multi-layers of thin films [5]. These films enhance the transmission of radiation of the required wavelength by constructive interference and reduce that of unwanted radiation by destructive interference or reflection. By varying the thickness, number and chemical composition of these layers and the substrate, filters can be produced with varying success across most of the spectral range from 200 nm to 2.5 μm and beyond. The technology that is used to fabricate them has been well developed, and this allows filters with very narrow transmission bands (as small as 0.1 nm) to be made while retaining a reasonable level of transmission. This is the major advantage of interference filters.

A disadvantage of interference filters is that they tend to have fine structure, which can make them difficult to calibrate accurately. In addition, they have properties that are dependent on the nature of the optical radiation, for example angle of incidence, polarisation, and coherence. Interference filters can also be highly sensitive to temperature changes ($> 0.1 \text{ nm}/^{\circ}\text{C}$ shift in centre wavelength) and to humidity changes. Potential moisture dependence is reduced if the filter is manufactured using high-energy techniques, such as ion-beam assisted deposition [6], which leads to high packing densities.

The other form of filter technology that is used in filter radiometers is coloured absorptive blocking glasses. Glass filters remove unwanted radiation by absorption or scattering. The spectral properties are tailored by the materials added to the molten glass during manufacture, and/or by the choice of the host glass. It is more difficult to produce very small bandwidth devices using coloured glass filters, and as such glass filters are more suited for use in filter radiometers that are to have a large spectral bandpass ($> 50 \text{ nm}$). Glass filters can be used in combination, either as an optical filter sandwich or in a mosaic combination, to give narrower transmission profiles or specific spectral profiles, for example $V(\lambda)$ profile [7].

Some glasses can exhibit spatial non-uniformities in transmission caused by impurities in the glass or in-homogeneities introduced during manufacture and some can suffer from spectral and transmission changes associated with UV induced solarisation. However, in general, the major attraction of glass filters over interference filters is their insensitivity to the nature of the illuminating light and to their environment. For example, measurements made at NPL have shown the temperature sensitivity of the observed signal from a filter radiometer, when viewing a tungsten halogen source, constructed using an 800 nm interference filter to be 30 times that when using a 710 nm glass bandpass filter. Another advantage of glass filters is that they can be made in very large sizes.

In addition to spectral coverage, stability, robustness and spatial uniformity, other important properties of bandpass filters include fluorescence, and the amount of light that is transmitted outside the desired spectral region, which is referred to as the out-of-band transmission. Particularly under UV illumination, some filters can exhibit fluorescence, and such filters should not generally be used for radiometry. Out-of-band transmission can be most significant when the spectral range the detector has response in, is much wider than the desired spectral bandpass of the filter. Out-of-band transmission can vary dramatically depending on the specific filter type, manufacturing process used, the presence of pinholes and of course, on the spectral content of the source that is being measured. For glass bandpass filters, by their very nature, high out-of-band blocking comes at the expense of throughput, for example by using very thick filters or high concentrations of absorbing dopants.

A wide range of interference based optical bandpass filters, of varying degrees of quality, are commercially obtainable as "off-the-shelf" items. Fabrication of customised filters is also available but at significantly greater costs. There is dramatically less availability of off-the-shelf glass bandpass filters, however the costs associated with manufacturing glasses, of known recipes, is less than those associated with interference filters.

In conclusion, it is clear that the choice of filter technology is the most critical factor in the design of filter radiometers and should be made by in association with the intended application. In general, for applications requiring a narrow bandpass (< 50 nm), interference filters are a clear first choice, while for broad bandpass applications coloured glass filters can offer superior robustness.

1.1.4 Housing and electronics

The remaining components of a filter radiometer are its housing, and in some cases integrated temperature control apparatus and an integrated current to voltage amplifier. The filter radiometers reported here follow the design shown in Figure 1

and do not contain any integrated electronics. Temperature stabilisation is achieved using a water jacket and water circulator, which can maintain the filter radiometer temperature to within ± 0.2 °C. Separate, calibrated, photo-current to voltage transimpedance amplifiers were used. For repeatable and accurate measurements, it is essential that the individual components of any filter radiometer are held fixed in space by a rigid housing. Additionally, the housing will shield the detector from stray light and help protect the components from the environment. Blackened aperture covers were used to reduce interreflections between the source (and any optics) and the filter radiometer. Both anodising and black paint can age and as such, if the measurement set-up is sensitive to interreflections, black coatings should be reapplied as appropriate. The housing should be fitted with an aperture cover when not in use to protect the components from the ingress of dust. The build up of contaminants, for example on the filter, can contribute to the ageing of the filter radiometer.

1.2 Calibration of filter radiometers

The majority of techniques developed for filter radiometer characterisation are based on comparative scale transfer. The response of the filter radiometer to light at a particular wavelength (or more realistically, wavelength band) is directly compared to the response of a calibrated detector exposed to the same radiation. This comparison is done at each wavelength interval across the response range of the filter radiometer. In this way the spectral responsivity, that is responsivity (amps per watt) as a function of wavelength, of the filter radiometer can be determined.

The filter radiometers investigated for this report were calibrated using the NPL primary filter radiometer calibration facility [8], which is illustrated in Figure 2. This facility utilizes highly monochromatic, tuneable, laser light as the source of optical radiation. A number of different laser sources are often required to generate sufficient wavelength coverage to calibrate broadband filter radiometers.

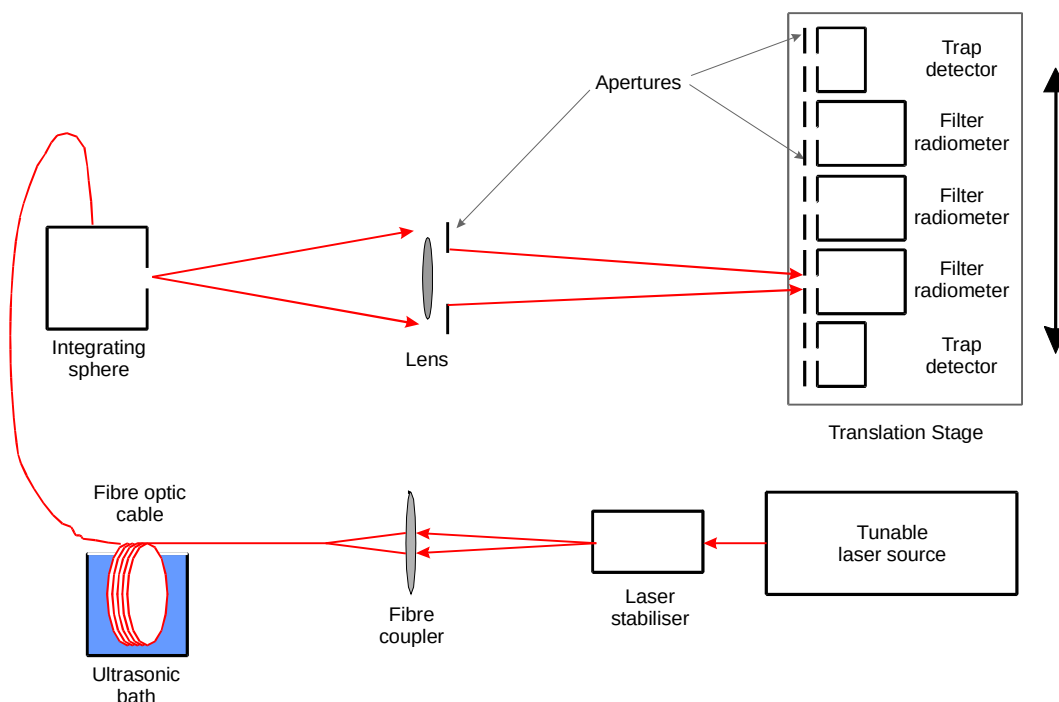


Figure 2: Schematic of the NPL laser-based primary filter radiometer calibration facility

This comparative calibration technique requires the intensity of the light source to remain constant between measurements made on the filter radiometer and reference (trap) detectors. The laser stabiliser unit monitors the signal from a photodiode mounted in the integrating sphere and continuously adjusts the voltage applied to a Pockel cell in order to maintain a constant light output. To effectively remove (over the response timescales of the detectors used) the "speckle" pattern of the laser light, which is due to the light's temporal coherence, the laser beam is passed through a (multi-mode) fibre optic that is agitated in an ultrasonic bath. The output of the fibre optic is connected to an integrating sphere, which generates a near ideal (Lambertian) source with the added advantage of scrambling the laser light's polarisation. The resultant light is finally imaged onto an orthogonal translation stage, which systematically positions the trap and filter radiometer detectors in front of the light beam. This facility can provide spectral responsivity measurements with an uncertainty of $\pm 0.05\%$.

2. Long-term stability measurement results

The long-term stability of a selection of filter radiometers of the two types (800 nm interference and 710 nm glass) was monitored in two ways. Firstly, by periodic calibration using the NPL primary filter radiometer calibration facility, as described in §1.2. Secondly, by measurements of a reference source, namely a copper fixed point black body. The complete re-calibration of a filter radiometer provides full spectrally resolved information on how the responsivity of the filter radiometer has changed, and at the highest accuracy when using the laser based primary calibration facility. However, this process attracts relatively high costs. A quicker, "spot check" on filter radiometer ageing can be obtained from repeat measurements of a fixed-point black body source. In this case the measured signal correlates to the overlap of the integrated spectral responsivity and the (fixed) black body spectral output. A series of measurements of the copper point black body source were made using the filter radiometers under investigation. Unfortunately, the initial measurements did not have sufficient accuracy to be of use for comparison with later, repeat, measurements. More reliable and higher accuracy black body measurements can now be made by using the Absolute Radiation Thermometer (ART) facility [9]. The accuracy of black body measurements made using the 710 nm filter radiometers was limited by signal-to-noise, due to the low throughput of the glass filter.

2.1 800 nm interference filter radiometers

Figure 3 shows representative absolute spectral responsivity data, measured on the NPL primary filter radiometer calibration facility, for the 800 nm interference filter radiometers investigated.

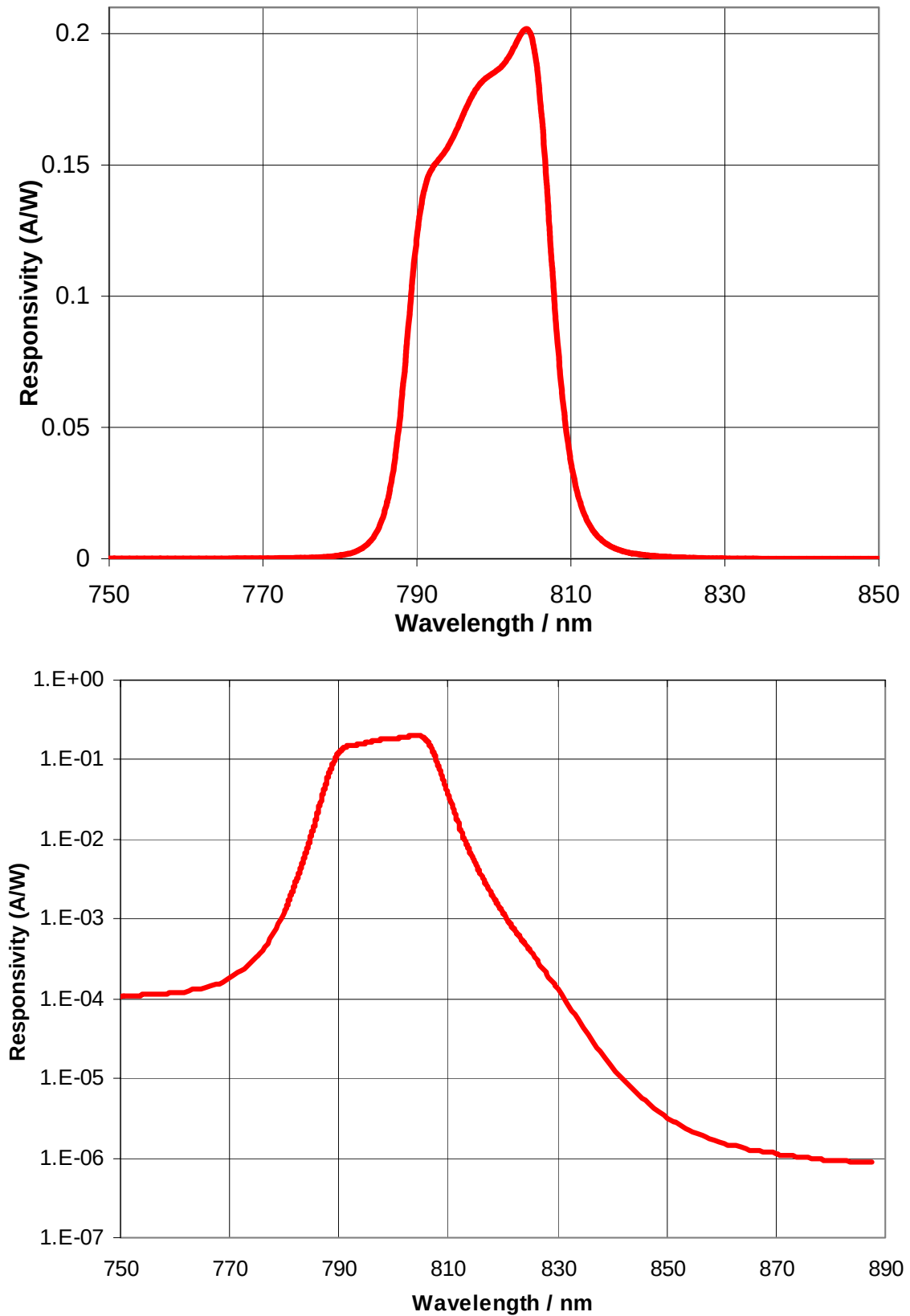


Figure 3: Representative absolute spectral responsivity curves for the new type 800 nm filter radiometer (top), and plotted with a logarithmic ordinate scale (bottom).

The spectral responsivity of a set of the new 800 nm filter radiometers was measured over a three-year period. Figure 4 shows the spectral responsivity measurements of one such filter radiometer (serial number 800W50S1337A) made in November 2000, August 2002 and December 2003. With the scale used no discernable change in responsivity can be seen by eye. However, also plotted in Figure 4 is the percentage change in spectral responsivity of the Aug-02 and Dec-03 measurements compared to the Nov-00 results. Because each calibration was performed at slightly different wavelength points, interpolation (cubic spline) was used to allow direct comparison of the responsivity data at identical wavelengths. It is anticipated that the uncertainty added to the comparison, due to this interpolation, will be small. An additional uncertainty, in determining the change in filter radiometer spectral responsivity due to ageing, arises from any temperature variations between measurements. For the results presented here, filter radiometer temperature variations were kept to within ± 0.5 °C.

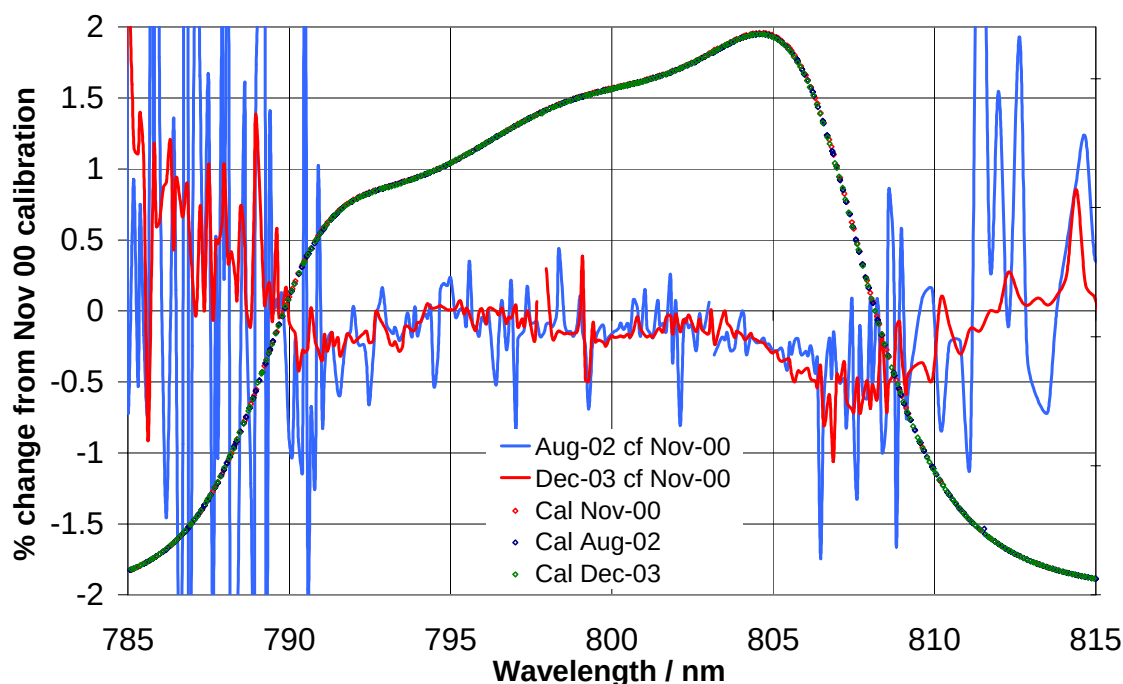


Figure 4: Changes in spectral responsivity, over a three year period, for a 800 nm filter radiometer (serial number 800W50S1337A).

The Aug-02 calibration exhibits higher than normal noise, which should not be mistaken for spectral responsivity drift of the filter radiometer. The results presented in Figure 4 demonstrate the exceptional long-term stability of the new 800 nm filter radiometer, being within a few tenths of a percent (over the spectral bandpass region) over a three-year period. Moreover, there was no discernable drift in spectral responsivity between Aug-02 and Dec-03 measurements. Between calibrations the filter radiometers were used for measurements and underwent transportation by airfreight. The noticeable increase in the degree of responsivity drift at wavelengths along the edges of the spectral bandpass reflects the increased sensitivity to any shift in the centre wavelength of the filter, for example due to ageing or temperature changes. For wavelengths outside the bandpass the responsivity measurement uncertainty increases with increasing signal-to-noise.

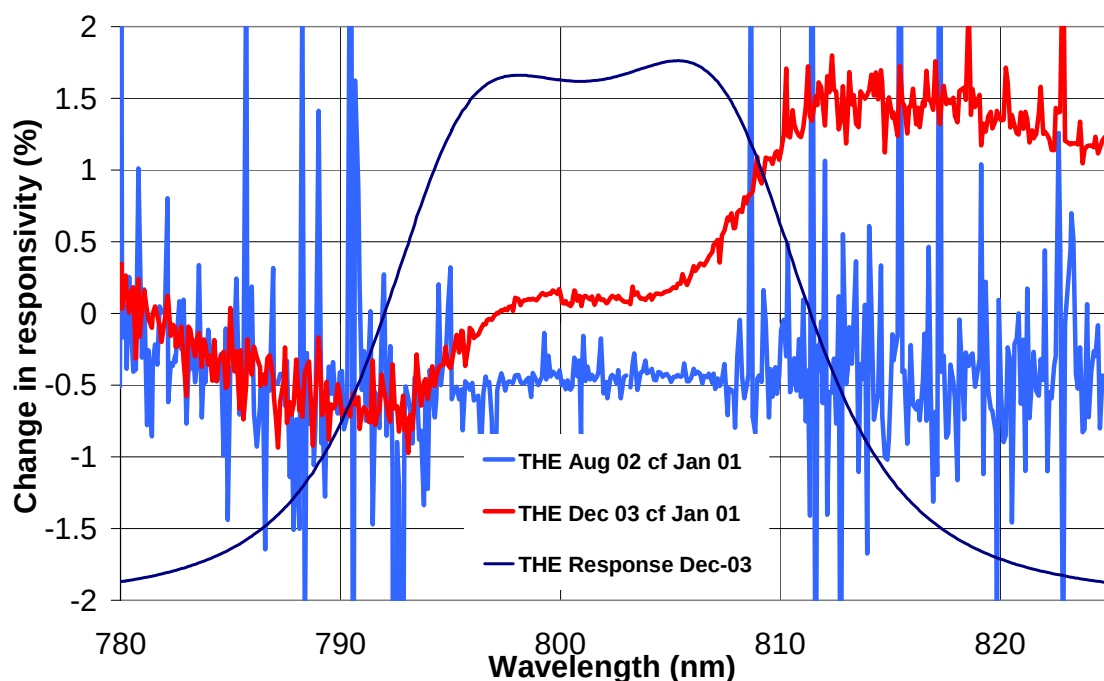


Figure 5: Changes in spectral responsivity, over a three year period, for the older type of 800 nm filter radiometer (serial number 800W20THE).

For comparison with the previously used 800 nm filter radiometer type, spectral responsivity measurements were made of such a filter radiometer (serial number

800W20THE) at the same time as those of 800W50S1337A, and are shown in Figure 5. No obvious ageing trend can be seen in the spectral responsivity data, however it is evident that new type of 800 nm filter radiometer exhibits superior stability. It should also be noted that the new 800 nm filter radiometers exhibited significantly higher out-of-band blocking, as can be seen in Figure 6.

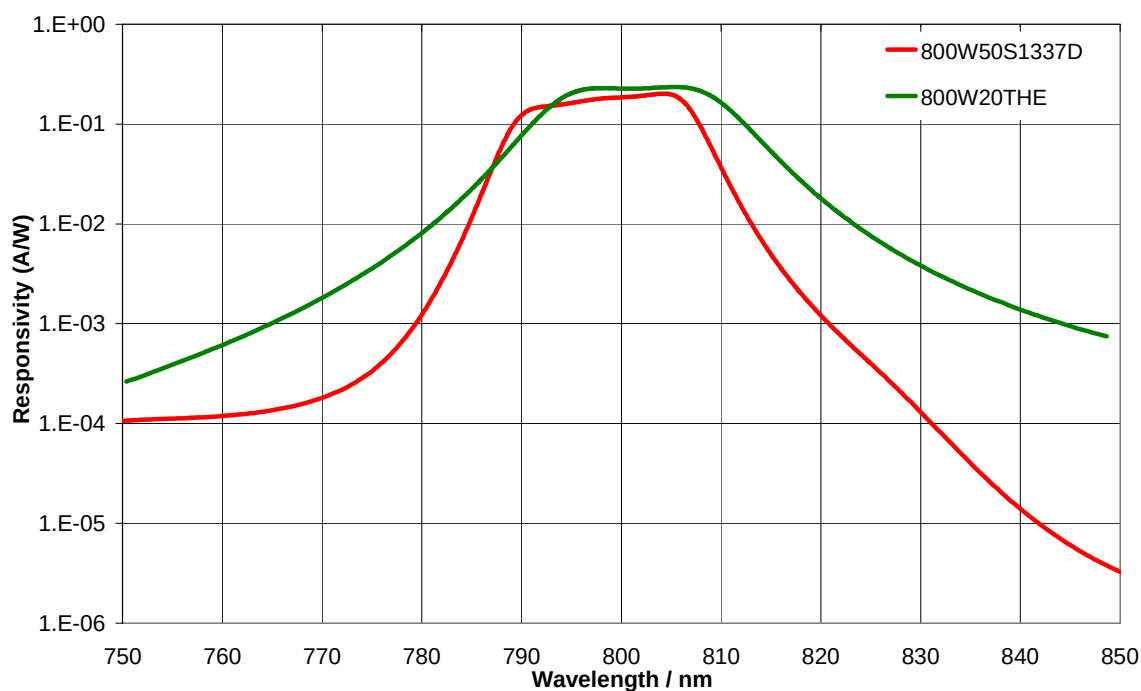


Figure 6: Comparison of old (800W20THE) and new (800W50S1227D) type of 800 nm filter radiometers' spectral responsivity, plotted with a logarithmic scale.

Long-term spectral responsivity measurements for a further two of the new type 800 nm filter radiometers, 800W50S1337C and D, are shown respectively in Figure 7 and Figure 8. The change in their spectral responsivity measured in Jan-03 compared to that measured in Nov-00 was similar to that observed for 800W50S1337A, and at a level comparable to the measurement uncertainty (0.1 %). However, the most recent measurements (Jan-04) of both filter radiometers (C and D) show a disproportionately large drop in responsivity of approximately 0.3 %. Given that these two filter radiometers were calibrated at the same time, a possible alternative explanation to that of filter radiometer ageing is measurement error.

The changes in responsivity shown by all the new type of 800 nm filter radiometers have a near identical spectral shape, that is an initial increase in responsivity with time for wavelengths either side of the bandpass, which later (after 1-2 years) ceases. From the data presented in this report it could be tempting to trace this trend to uncertainties in the original Nov-00 calibration, however, data on a fourth filter radiometer (800W50S1337B) calibrated in Jan-01 and re-measured in Dec-03 also displayed the same spectral trend. This suggests the observed spectral trend in filter radiometer responsivity ageing is real.

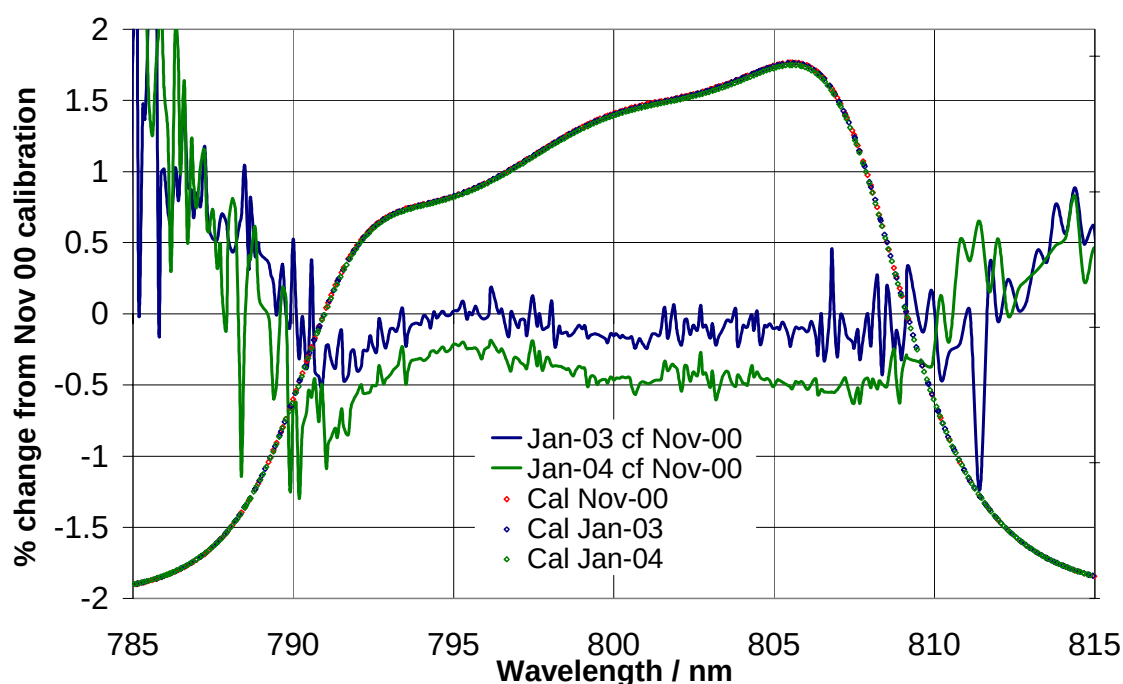


Figure 7: Changes in spectral responsivity, over a three year period, for a 800 nm filter radiometer (serial number 800W50S1337C).

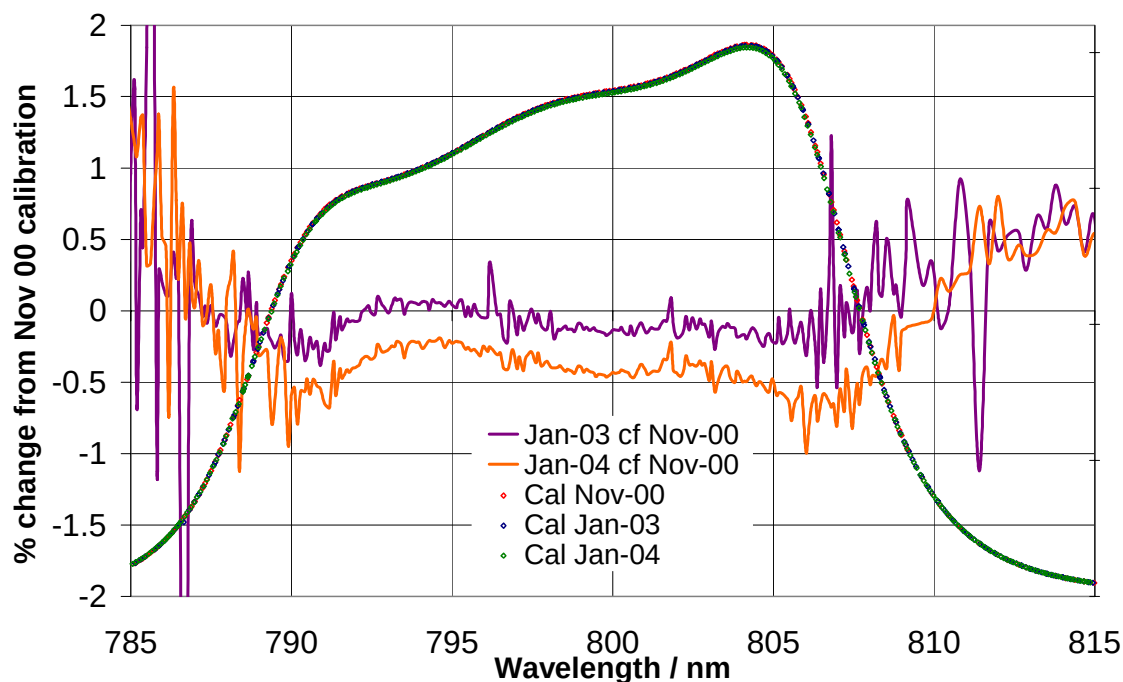


Figure 8: Changes in spectral responsivity, over a three year period, for a 800 nm filter radiometer (serial number 800W50S1337D).

For the application of radiometric thermodynamic temperature measurement, it is integrated change in the spectral responsivity of the filter radiometer that is important. The calculated temperature difference that results from using the Nov-00, compared to the Jan-03, calibration data for filter radiometer 800W50S1337C (or D) when measuring an ideal 3000 K black body source, is only -0.3 K (0.01 %).

2.2 710 nm glass filter radiometers

Figure 9 shows representative absolute spectral responsivity data, measured on the NPL primary filter radiometer calibration facility, for the 710 nm glass filter radiometers investigated.

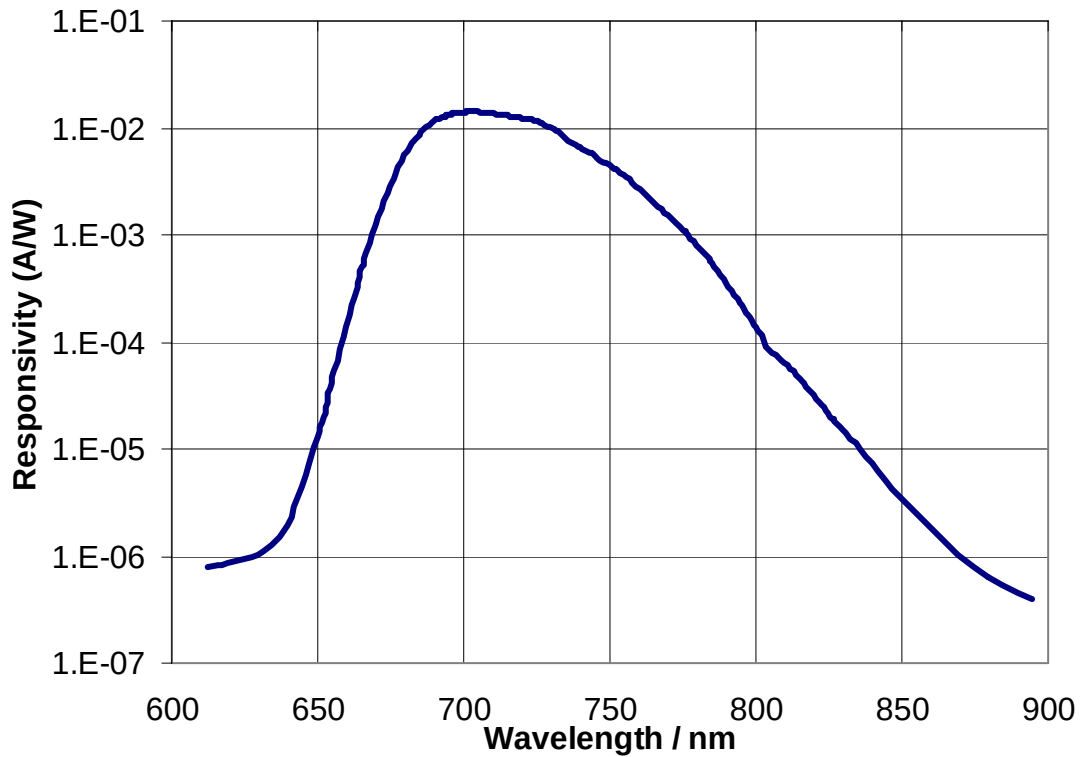
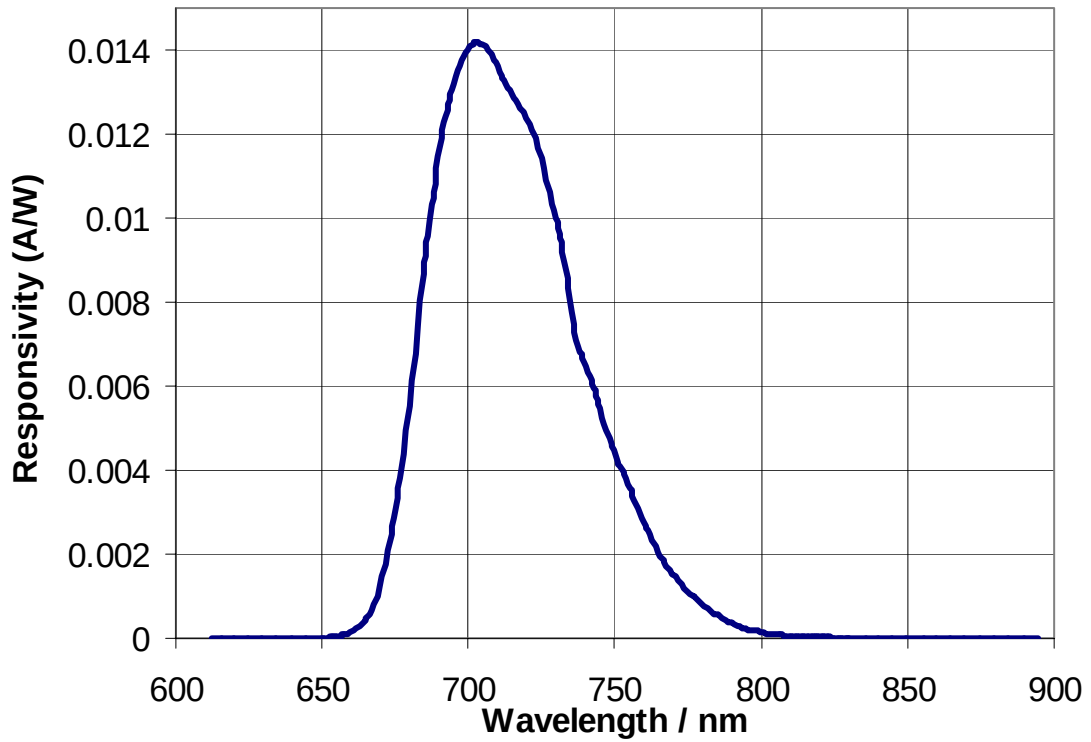


Figure 9: Representative absolute spectral responsivity curves for the 710 nm glass type filter radiometer (top), and plotted with a logarithmic ordinate scale (bottom).

From comparison of Figure 9 with Figure 3 it is immediately apparent that the spectral responsivity of the 710 nm glass filter based radiometers is much broader and smoother than the 800 nm interference filter based filter radiometers. The low transmission of the glass filter ($\sim 10\%$ at peak wavelength) results in the responsivity of the 710 nm filter radiometers being ten times lower than that of the 800 nm filter radiometers.

In an identical manner to the 800 nm filter radiometer spectral responsivity drift analysis, interpolation was used to allow comparison of the 710 nm filter radiometer responsivity data shown in Figure 10.

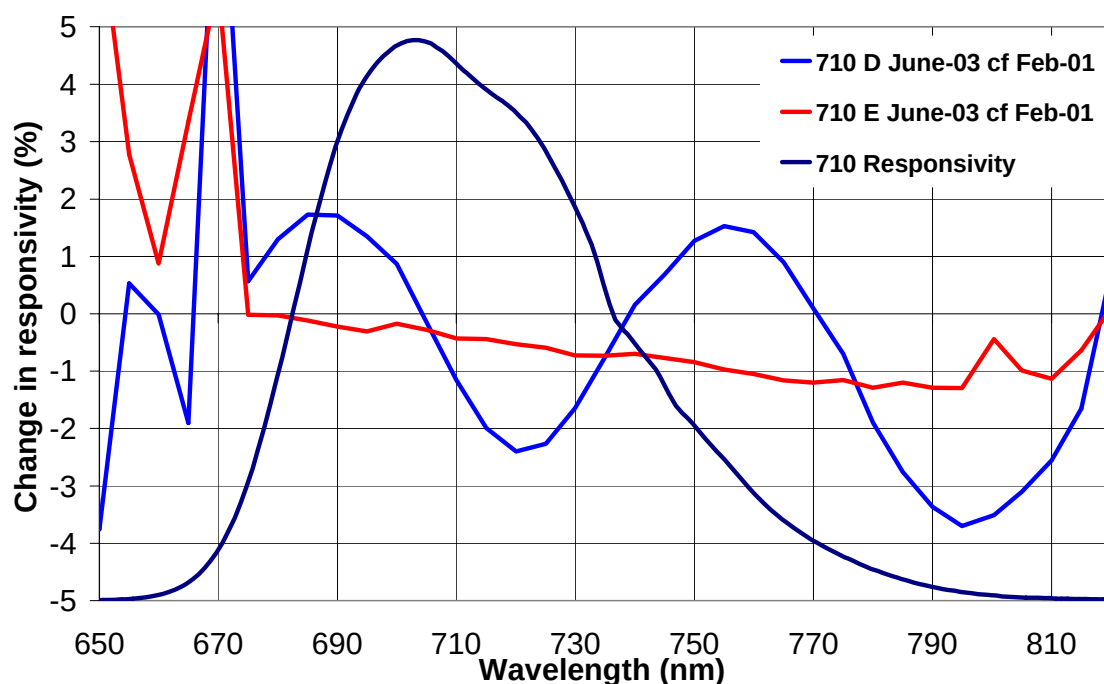


Figure 10: Compares spectral responsivity changes of two 710 nm filter radiometers (serial number 710W50S5227D and E) over approximately two years. Representative spectral responsivity data is also plotted.

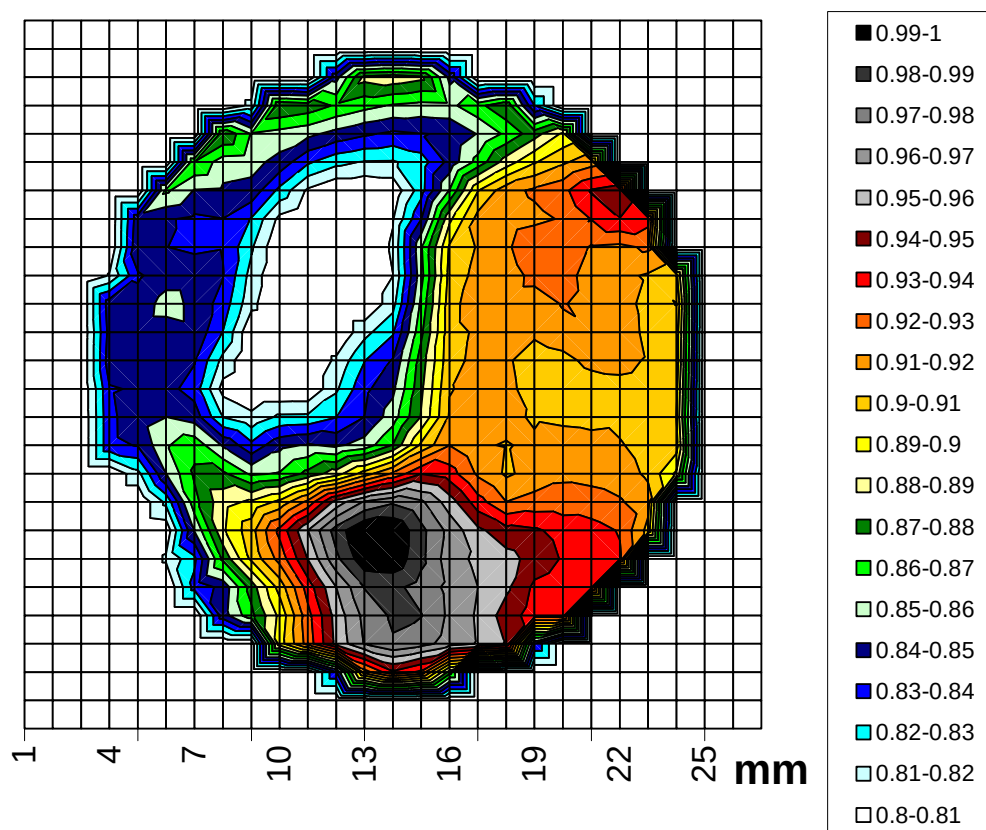


Figure 11: Spatial uniformity of transmission of a 710 nm glass optical bandpass filter.

The significant (up to 2 % level) change in the responsivity of the 710 nm filter radiometers shown in Figure 10 is attributed more to measurement uncertainty, resulting from the very high (up to 20 %) spatial non-uniformity of the glass filters (Figure 11) and low signal-to-noise due to low filter transmission, than to actual filter radiometer ageing. The 710 nm glass filter uniformity of transmission measurements were made using a broadband light source, which was focused to a 2 mm spot with a beam geometry of $f/20$. For comparison, the measured spatial non-uniformity of the 800 nm interference filters was < 2 %. New 710 nm glass filters with significantly improved uniformity have since been developed as part of the current (01-04) optical programme, and their evaluation is left for a future report. The calculated temperature difference between temperature measurements of an ideal 3000 K black body source using the Feb-01 compared to the June-03 calibration data is respectively -0.9 K and -2 K (0.03 % and 0.07 %) for filter radiometers 710W50S5227D and E.

3. Conclusions

This investigation set out to monitor the long-term stability of two types of filter radiometer, one type based on a high specification custom 800 nm interference optical bandpass filter and the other on a proprietary single glass 710 nm bandpass filter. Spectral responsivity measurements made over a three-year period showed that the 800 nm filter radiometers exhibited excellent long-term stability, of the order of the spectral responsivity measurement uncertainty of ± 0.1 %. This, combined with their high out-of-band blocking, makes these 800 nm filter radiometers a notable improvement on the 800 nm NPL primary filter radiometers used previously. Unfortunately, high spatial non-uniformity and low optical transmission of the 710 nm glass filters resulted in insufficient measurement accuracy to reliably evaluate their long-term stability.

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