

The NPL high temperature radiation thermometry calibration facility

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ABSTRACT

The NPL high temperature radiation thermometry calibration facility consisting of high temperature blackbody sources and a standard transfer pyrometer is described. The performance of the system and the uncertainty budget for the scale realisation is given. It is shown that using a suitably calibrated transfer pyrometer, it is possible to realise and intercompare the ITS-90 above the silver point with a 2s uncertainty of better than 0.05% of temperature.

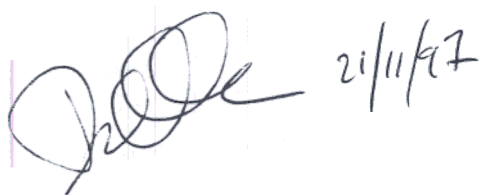
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Approved on behalf of the Managing Director, NPL
by D W Robinson, Head, Centre for Basic and Thermal Metrology

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The NPL High Temperature Radiation Thermometry Calibration Facility

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1. INTRODUCTION

Temperature scale realisation, dissemination and intercomparison at high temperatures (generally from 1000 °C to 1700 °C or 2200 °C) have traditionally been performed using high stability tungsten strip lamps [1, 2]. These sources have good long term stability but have a number of serious drawbacks, including a small target size (1.5-3 mm), a maximum radiance temperature of only 2200 °C and being limited for use only at a restricted range of wavelengths around their calibration wavelength (usually 660 ± 20 nm). It is true that blackbody lamps are available, but these have a source size of only 1 mm and are limited to a maximum temperature of 2650 °C.

With the advent of objective radiation thermometers the limitations of using tungsten strip lamps as calibration sources has become obvious. These thermometers generally have larger target sizes, larger temperature ranges and operate at longer wavelengths than lamps (though the latter restriction can be somewhat ameliorated by calibrating the lamps at a more suitable wavelength). These limitations render lamps generally unsuitable as calibration devices for such instruments. In addition, the processing of exotic refractory materials and the increasing use of materials such as carbon-carbon fibre composites has led to a demand for calibration standards in the 2500 °C to 3000°C range, above the range of operation of the lamps.

To overcome the difficulties encountered by using lamps to realise and disseminate the temperature scale several National Measurement Institutes (NMIs) have developed high temperature facilities that can meet the growing calibration requirement. Generally in these facilities the high stability lamp is replaced by a graphite blackbody with emissivity of order >0.99 with the scale being obtained from a calibrated high stability linear radiation thermometer calibrated directly in terms of the ITS-90.

The NPL high temperature calibration facility is centred around three pieces of equipment: one high quality transfer standard radiation thermometer and two high temperature blackbody sources. In the following report the NPL facility is described and its performance is discussed.

1.1 THE BLACKBODY CAVITIES

NPL has two high temperature blackbody sources, one manufactured to a design of IKE, Stuttgart [3] the other by Thermogage, USA [4]. For both cavities temperature control is performed using an integral radiation thermometer which views the rear of the back-wall of the blackbody cavity. The output of this thermometer is incorporated into a feedback loop controlling the power to the furnace.

The blackbodies are used as temporarily stable sources of radiation, but they do not maintain a calibration. At each point the temperature is measured using the linear pyrometer and the readings of other radiation thermometers can then be taken at that temperature.

The NPL IKE cavity is well described in the literature [3]. In brief, it consists of a directly heated graphite tube with a 15 mm nominal aperture and a maximum temperature of 2700 °C. The outer surface of the graphite tube is specially shaped to minimise temperature gradients within the system leading to an effective emissivity for the cavity of >0.999. It can be operated under vacuum or in an argon atmosphere. The vacuum chamber has two water free silica windows for viewing the blackbody from the front (for calibration) and rear (for control). At the NPL the system is always operated using argon. Calibrations are performed without the front window in place, thus eliminating the need to know the window transmission. The cavity's overall stability is generally ± 0.3 °C for a period of 1 hour.

The NPL Thermogage cavity [4] consists of a directly heated graphite cavity and has a 25 mm nominal aperture with a maximum temperature of 3000 °C. The effective emissivity of the cavity is >0.99. The cavity has no window, the protection of the graphite blackbody being afforded by a laminar flow of argon through the graphite tube. The blackbody is generally stable to ± 0.1 °C for periods of several hours.

The two cavities are affected by temperature gradients, both along the walls of the cavities and along the back-wall. Typical back-wall gradients for the IKE cavity are given in Figure 1 and for the Thermogage cavity in Figure 2.

When calculating calibration uncertainties the gradients described above must be taken into account as the standard pyrometer and the test pyrometer will view different sized areas on the back-wall of the blackbody cavity. This will lead to a difference in the temperatures measured by the two instruments. It is possible to ameliorate this effect by matching the target sizes of the two pyrometers by slight defocusing, this technique is described in [24].

1.2 THE STANDARD RADIATION THERMOMETER

The high temperature facility standard radiation thermometer is a highly linear, stable instrument known as the LP2. Its general characteristics are well described in the literature [5, 6]. In brief; the NPL LP2 has a temperature stabilised silicon

photodiode with three interference filters of 650 nm, 804 nm and 906 nm. The complete system has a temperature range of $\sim 500^\circ\text{C}$ to $\sim 3100^\circ\text{C}$.

Accurate realisation of the ITS-90 demands that the instrument has a well defined wavelength of operation and is calibrated against a defining fixed point. Implicit requirements are that the instrument has a low size of source effect (SSE), good stability and linearity (or at least that its linearity characteristics are known and can be corrected for.) In the following section the calibration and testing of the NPL LP2 is described.

1.2.1 Calibration of the interference filters

The interference filters are calibrated using a Chromex 500 SM, single pass monochromator, a continuum source and emission line sources. The calibration procedure is as follows: the LP2 is focused onto the exit slit of the monochromator, which is generally set to a width of 150 mm. A continuum source, generally a tungsten ribbon lamp, is focused onto the entrance slit (width of 150 mm) using an auxiliary lens. Extraneous light is excluded by shielding the optical path between the monochromator and the LP2. In addition, the room lights are turned off during the measurements. The monochromator is then scanned, under computer control, in steps of ~ 0.3 nm, through the transmission peak of the filter and measurements of the LP2 output are made at each wavelength. The scan is stopped periodically to introduce a line source to provide a calibration for the monochromator. After this scan a second scan (in the same direction) is performed without the interference filter in place (the filters are mounted on a wheel that has several empty spaces). Corrections are applied to the monochromator wavelength using the line source measurements. The ratio of the first scan to the second scan then gives the transmission curve of the interference filter, eliminating the detector response, the variation with wavelength of the monochromator throughput, the LP2 lens transmission and the emissivity effects of the radiance source. In addition to these measurements wider step scans are performed at both longer and shorter wavelengths to ensure that the out of band transmission of the filters are blocked to a satisfactory level.

This procedure is followed for the three interference filters of the LP2 (650 nm, 804 nm and 906 nm) the transmission curves of which are given in Figures 3a, 3b and 3c.

The peak of transmission of the interference filters generally shift to longer wavelengths with temperature. This effect was determined by increasing the temperature of the LP2 by several degrees (by increasing the room temperature) and repeating the above scans. It was found that the temperature coefficients for the filters were $0.027\text{ nm}/^\circ\text{C}$ for the 650 nm filter, $0.018\text{ nm}/^\circ\text{C}$ for the 804 nm filter, and $0.075\text{ nm}/^\circ\text{C}$ for the 906 nm filter. The effect of these coefficients are built into the uncertainty budget described below in Section 2.2.1.

The effective wavelength [7, 8] of the instrument was then calculated using the filter

transmission curve and the detector response curve supplied by the manufacturer of the LP2, with due allowance made for the refractive index of air [9, 10]. The effective wavelength was then calculated assuming a flat detector response to estimate the worst case error in measured detector response. The largest shift in effective wavelength by making this assumption, was 0.03 nm for the 804 nm filter, and less for the other two filters - which, even for precise pyrometric measurements, is so small that it can be safely neglected. Figures 4a, 4b and 4c show the effective wavelength, using the detector response, for the 650 nm, 804 nm and 906 nm filters respectively in 1994 and 1997. The shift in effective wavelength is small amounting to 0.01 nm for the 650 nm filter, 0.05 nm for the 804 nm filter and 0.12 nm for the 906 nm filter.

From the effective wavelength the mean effective wavelength was deduced [7,11]. These values are then used in the ITS-90 definition to derive radiance temperatures.

1.2.2 Linearity of the detector

The linearity of the LP2 is determined using the Thermogage blackbody cavity and a double aperture technique [12, 13].

The LP2 is aligned so as to lie on the optical axis of the Thermogage blackbody and focused on the back-wall. An anodised double aperture, with a knife edge, is attached to the front of the LP2 lens holder.

The Thermogage cavity is set to a given temperature and measurements made at factor of two increments in radiance. The laboratory lights are out during the measurement process to prevent stray light from causing errors. This procedure was repeated with increasing blackbody temperature until the whole of the allowable LP2 photocurrent range is covered ($\sim 1\text{E-}13$ A to $5\text{E-}8$ A). Repeat measurements were made to assess the repeatability. The results are shown in Figure 5. The average non-linearity is $0.022 \pm 0.025(1s)\%$.

1.2.3 Checking the consistency of the range ratios

The LP2 has several amplification ranges. It is important to check the consistency between the ranges i.e. the ratio between two consecutive ranges should be closely equal to a factor of 10.0 [14]. The measurements of linearity described in 1.2.2 should indicate if there is a problem. Generally, however, the range ratio values are checked using the LP2 and an external DVM as follows:-

A high quality DVM is connected to the analogue output of the LP2 control box. The LP2 is sighted onto the Thermogage cavity. The temperature of the cavity is increased until the LP2 signal level is $\sim 4\text{E-}12$ A. The photocurrent is measured and the range then switched to the next level giving a signal of $\sim 0.4\text{E-}11$ A. A ratio of

these two values should be $10.0 \pm 0.05\%$. If not, internal trim resistors are used to adjust the ratio to the required value.

Once this pair of ranges has been checked the Thermogage cavity is increased in temperature and the ratio checked for the next pair ($\sim 0.4\text{E-}10$ A and $\sim 4\text{E-}11$ A) and so forth until all pairs up to E-8 have been checked.

1.2.4 Determination of the LP2 size of source effect (the SSE)

The size of source effect of radiation thermometers is a well known phenomenon (15, 16, 17). For accurate measurements the SSE must be determined at regular intervals.

The SSE for the LP2 is determined using a sodium heatpipe blackbody [18] and a series of aperture plates with increasing diameters from 0.5 mm to 30 mm.

A water cooled aperture holder is placed in front of the blackbody cavity which is held at a temperature of $\sim 900^\circ\text{C}$. The plates are placed on the holder in turn. The LP2 is focused onto the front of the aperture plate, and aligned such that the centre of the aperture is at the centre of the field of view. For each aperture plate the signal from the LP2 and the output of the thermocouple monitoring the blackbody temperature are recorded, the latter to correct for any radiance drifts that might occur during the measurement. The change in emissivity of the cavity due to varying the aperture size has been calculated to be negligible for the purposes for these measurements, being at most <5 mK when varying the aperture from 0.5 mm to 30 mm.

The SSE is represented by the ratio of the signal at a given aperture, corrected for drift in blackbody temperature, to that of the maximum aperture. SSE results are given in Figure 6. As can be seen the SSE at 1.5 mm target size and beyond is a constant indicating that the LP2 has excellent optical characteristics and can be used for scale realisation and calibrations with target sizes of 1.5 mm and greater.

1.2.5 Determination of the reference photocurrent

The instrument is calibrated against the NPL gold point [19], one of the defining fixed points of the ITS-90, twice a year. The LP2 is focused on the defining 3 mm rhodium aperture of the gold point blackbody cavity and aligned within the centre of the cavity aperture. Generally three melts and freezes are performed for each possible filter and neutral density filter combination. A typical melt and freeze is shown in Figure 7. The average photocurrents for each interference filter and neutral filter combination are used as the reference.

2. SCALE REALISATION AND ANALYSIS OF SCALE REALISATION UNCERTAINTIES

2.1 SCALE REALISATION

This LP2 has been demonstrated to be linear, with a small size of source effect, well defined interference filters and with a highly stable detector and electronics. Using the mean effective wavelength and the reference photocurrent of the ITS-90 fixed points, one can then use this device to establish the temperature scale.

2.2 UNCERTAINTY ANALYSIS OF SCALE REALISATION

The realisation of the scale using a calibrated pyrometer is subject to certain uncertainties [20]. In brief the following contributions can be identified:

- (i) wavelength characterisation, u_1
- (ii) reference photocurrent determination, u_2
- (iii) residual non-linearity, u_{3a} and u_{3b}
- (iv) uncertainty in SSE determination, u_4
- (v) drift in reference photocurrent between calibrations, u_5 .

The analysis presented below has been performed for the 650 nm and the 906 nm filters.

These uncertainties fall into Type A and Type B as defined in the ISO guide [21]. The uncertainty contributions u_1 , u_{3b} and u_5 are Type B whereas u_2 , u_{3a} and u_4 are Type A because they are based on repeated measurements. The Type B contributions, assumed to have a rectangular distribution, are then divided by $\sqrt{3}$ to obtain one standard uncertainty.

2.2.1 Uncertainty in wavelength characterisation

The uncertainty in the wavelength characterisation propagates, with temperature, according to the following equation [20]:

$$u_1 = (T_{90} - T_{ref}) \left(\frac{T_{90}}{T_{ref}} \right) \frac{\delta\lambda}{\lambda}$$

where T_{90} is the ITS-90 temperature from Planck's law, T_{ref} is the ITS-90 fixed point blackbody reference temperature, $d\lambda$ the uncertainty in wavelength and λ is the wavelength of operation of the pyrometer.

The value of $d\lambda$ is comprised of the following contributions:

- (a) the disregarding the filter temperature coefficient. The interference filter temperature is stable to ± 2 °C of its calibration temperature. Using the filter temperature coefficients obtained using the method described in Section 1.2.1, one can calculate the maximum uncertainty caused by disregarding the temperature change in the interference filters
- (b) the uncertainty in calculating the effective wavelength (an integration error)
- (c) wavelength repeatability determined from several monochromator scans
- (d) the uncertainty in the correction of the monochromator wavelength, including the assumption that the correction is linear between emission lines
- (e) the drift in effective wavelength between tri-annual calibrations.

When these contributions are added together in quadrature the resulting values are $d\lambda=0.11$ nm for the 650 nm filter and $d\lambda=0.20$ nm for the 906 nm filter. The values of $d\lambda$ are given at the 1s confidence level.

2.2.2 Uncertainty in determining the reference photocurrent

The statistical uncertainty associated with the determination of the reference photocurrent propagates according to the following relation:

$$u_2 = \frac{\lambda T^2}{c_2} \frac{\delta I_{ref}}{I_{ref}}$$

where T is the radiance temperature, λ is the wavelength, dI_{ref}/I_{ref} is the fractional uncertainty in reference photocurrent and c_2 is the second radiation constant (0.014388mK). A typical value, obtained from repeated realisation of the fixed point, is $dI_{ref}/I_{ref} \approx 2 \times 10^{-4}$.

2.2.3 Uncertainty due to the non linearity

As no corrections for non-linearity are made, the average non-linearity value (0.022%) is used to generate this uncertainty. Further details can be found in Section 1.2.2.

The uncertainty, u_{3a} , due to the non-linearity propagates in the same way as u_2 with the difference that dI_{ref}/I_{ref} is replaced with the fractional non-linearity.

Note that the range ratio deviation from 10.0 can also be considered to be a contribution to non-linearity. It is assumed that this has an upper bound of $\pm 0.05\%$ and makes contribution, u_{3b} , to the uncertainty budget.

2.2.4 Uncertainty due to the determination of the SSE

The SSE for the LP2 is given in Figure 7. At and beyond a target size of 1.5 mm the SSE is not resolved within the sensitivity of the measurement. The standard deviation of the mean SSE (at values at and beyond 1.5 mm) is taken to represent the uncertainty associated with the determination of the LP2 SSE. This value is 1.0000 ± 0.0001 (1s).

Again the uncertainty, u_4 , propagates as u_2 but with dI_{ref}/I_{ref} being replaced with the fractional SSE, 10^{-4} .

2.2.5 Uncertainty due to the drift in reference photocurrent between bi-annual calibrations

No system is drift free. This uncertainty takes into account the drift rate of the LP2 between re-determinations of the reference photocurrents. This can be represented as a temperature and propagates according to the following equation:

$$u_5 = \left(\frac{T_{90}}{T_{ref}} \right)^2 \delta T_{ref}$$

Typically the LP2 drifts by an equivalent of ~ 0.1 °C, at the gold point, between bi-annual calibrations.

2.3 COMBINED UNCERTAINTY OF SCALE REALISATION

Tables 1a and 1b give the values for these uncertainties. The uncertainty contributions are then combined in quadrature, and multiplied by an expansion factor of 2 to obtain approximately 95% confidence limits on scale realisation. The total uncertainty of the LP2 at 650 nm and 906 nm is plotted in Figure 8.

3. SUMMARY OF RECENT INTERCOMPARISON RESULTS

The objective performance of any top level calibration system such as this can only be validated by intercomparisons with other NMIs which have similar capabilities. Currently four international intercomparisons have been performed using this system; these are listed in Table 2.

The intercomparison with NRLM in 1995 was, because of exchange of copper point blackbody and the use of a highly stable transfer radiation thermometer, the most precise. It indicates that the scale realisation uncertainties claimed for the NPL high temperature calibration facility are realistic and have been demonstrated by comparison.

4. CONCLUSION

The NPL high temperature calibration facility, along with the uncertainty in scale realisation has been described. In addition a summary of international intercomparisons has also been given. It has been demonstrated, by measurement, that it is now possible, with a calibrated radiation thermometer, to realise the ITS90 above the silver point to an accuracy of $<0.05\%$ of temperature.

REFERENCES

- [1] Lee, R.D., Kostkowski, H.J., Quinn, T.J., Chandler, P.R., Jones, T.P., Tapping, J., Kunz, H., *In Temperature: Its Measurement and Control in Science and Industry*. Volume 4., Part 1 p. 377-393, 1972
- [2] McEvoy, H.C., Raven, K.M., Pokhodoun, A.I., Matveyev, M.S., NPL report QU107, 1995
- [3] Groll, M., Neuer, G., *In Temperature: Its Measurement and Control in Science and Industry*, Volume 4, Pt 1, p449-456, 1972
- [4] Brookley, C.E., Llewellyn, W.E., *In Temperature: Its Measurement and Control in Science and Industry*, Volume 6, Pt 2, p1195-1199, 1992
- [5] Wörner, B., *In Temperature: Its Measurement and Control in Science and Industry*, Volume 5, Pt 2, p429-432, 1982
- [6] Screiber, E., Neuer, G., Wörner, B., *In Tempmeko 90, the 4th IMEKO Symposium on Temperature and Thermal Measurement in Industry and Science*, p.292-306, 1990
- [7] Kostkowski, H.J., Lee, R.D., *In Temperature: Its Measurement and Control in Science and Industry*, Volume 43, Pt 1, p449-481, 1962
- [8] Bezemer, J., *Metrologia*, **10**, p.47-52, 1974
- [9] Blevin, W.R., *Metrologia*, **8**, p.146, 1972
- [10] Quinn, T.J., *Metrologia*, **10**, p.115, 1974
- [11] Coates, P.B., *Metrologia*, **13**, p.1-5, 1977
- [12] Mielenz, K.D., Eckerle, K.L., *Applied Optics*, **11**, p. 2294-2303 1972
- [13] Jung, H.J., *Metrologia*, **15**, p.173-181, 1979
- [14] Screiber, E., *Private communication*
- [15] Ricolfi, T, Wang, Li, *In Tempmeko 93, the 5th IMEKO Symposium on Temperature and Thermal Measurement in industry and Science*, p 161-165, 1993
- [16] Ohtsuka, M., Bedford, R.E., *Measurement*, **7**, p1-6, 1989
- [17] Bloembergen, P., *Private communication* (but to be published in TEMPMEKO96 proceedings 1997)
- [18] Chu, B., Machin, G., *to be published in TEMPMEKO96 proceedings 1997*

- [19] Chu, B., McEvoy, H.C., Andrews, J.W., *Meas.Sci. Technol.*, **5**, p12-19, 1994
- [20] Preston-Thomas H., Bloembergen, P., Quinn, T.J., *Supplementary information for the International Temperature Scale of 1990*, p152-156, 1990
- [21] *Guide to the Expression of Uncertainty in Measurement*, ISO, ISBN 92-67-10188-9, 1993
- [22] Machin, G., Johnson, B.C., Gibson, C., Rusby, R.L., *J. Res. NIST*, **99**, p.731-736, 1994
- [23] Sakuma, T., Sakate, H., Johnson, B.C., Gibson, C., Machin, G., Ricolfi, T., Battuello, M., Fischer, J., Jung, H.J., *Metrologia*, **33**, p.241-248, 1996
- [24] Machin, G., Ricolfi, T., Battuello, M., Negro, G., Jung, H.J., Bloembergen, P., Bosma, R., Ivarsson, J., Weckström, T., *Metrologia*, **33**, p.197-206, 1996
- [25] Sakuma, F., Sakate, H., Johnson, B.C., Gibson, C., Machin, G., Ricolfi, T., Battuello, M., Fischer, J., *Proceedings of the International Conference of the Temperature and Thermal Measurements (TEMPBEIJING97)*, p.39-44, 1997.

TABLES

TABLE 1a

Uncertainty in ITS-90 realisation with the LP2 at 650 nm

$t/^{\circ}\text{C}$	$u_1/^{\circ}\text{C}$	$u_2/^{\circ}\text{C}$	$u_{3a}/^{\circ}\text{C}$	$u_{3b}/^{\circ}\text{C}$	$u_4/^{\circ}\text{C}$	$u_5/^{\circ}\text{C}$	Combined uncertainty/ $^{\circ}\text{C}$	$U(k = 2)$
900	-0.01	0.01	0.01	0.02	0.01	0.04	0.05	0.11
1000	-0.01	0.01	0.02	0.02	0.01	0.05	0.06	0.12
1100	0.00	0.02	0.02	0.02	0.01	0.06	0.07	0.14
1200	0.01	0.02	0.02	0.03	0.01	0.07	0.08	0.17
1300	0.03	0.02	0.02	0.03	0.01	0.08	0.10	0.19
1400	0.04	0.03	0.03	0.04	0.01	0.09	0.11	0.23
1500	0.06	0.03	0.03	0.04	0.01	0.10	0.13	0.26
1600	0.07	0.03	0.03	0.05	0.01	0.11	0.15	0.30
1700	0.09	0.04	0.04	0.05	0.02	0.13	0.17	0.35
1800	0.11	0.04	0.04	0.06	0.02	0.14	0.20	0.39
1900	0.13	0.04	0.05	0.06	0.02	0.15	0.22	0.44
2000	0.16	0.05	0.05	0.07	0.02	0.17	0.25	0.50
2100	0.18	0.05	0.06	0.07	0.02	0.18	0.28	0.55
2200	0.21	0.06	0.06	0.08	0.02	0.20	0.31	0.62
2300	0.23	0.06	0.07	0.09	0.03	0.21	0.34	0.68
2400	0.26	0.06	0.07	0.09	0.03	0.23	0.37	0.75
2500	0.29	0.07	0.08	0.10	0.03	0.25	0.41	0.82
2600	0.32	0.07	0.08	0.11	0.03	0.27	0.45	0.89
2700	0.36	0.08	0.09	0.12	0.04	0.29	0.49	0.97
2800	0.39	0.09	0.09	0.12	0.04	0.30	0.53	1.05
2900	0.43	0.09	0.10	0.13	0.04	0.33	0.57	1.14
3000	0.46	0.10	0.11	0.14	0.04	0.35	0.61	1.23

TABLE 1b**Uncertainty in ITS-90 realisation with the LP2 at 906 nm**

$t/^{\circ}\text{C}$	$u_1/^{\circ}\text{C}$	$u_2/^{\circ}\text{C}$	$u_{3a}/^{\circ}\text{C}$	$u_{3b}/^{\circ}\text{C}$	$u_4/^{\circ}\text{C}$	$u_5/^{\circ}\text{C}$	Combined uncertainty/ $^{\circ}\text{C}$	$U(k = 2)$
900	-0.02	0.02	0.02	0.03	0.01	0.04	0.06	0.12
1000	-0.01	0.02	0.02	0.03	0.01	0.05	0.07	0.14
1100	0.00	0.02	0.03	0.03	0.01	0.06	0.08	0.16
1200	0.02	0.03	0.03	0.04	0.01	0.07	0.09	0.19
1300	0.04	0.03	0.03	0.04	0.01	0.08	0.11	0.22
1400	0.05	0.04	0.04	0.05	0.02	0.09	0.13	0.26
1500	0.07	0.04	0.04	0.06	0.02	0.10	0.15	0.30
1600	0.10	0.04	0.05	0.06	0.02	0.11	0.18	0.35
1700	0.12	0.05	0.05	0.07	0.02	0.13	0.20	0.40
1800	0.15	0.05	0.06	0.08	0.02	0.14	0.23	0.46
1900	0.17	0.06	0.07	0.09	0.03	0.15	0.26	0.53
2000	0.20	0.07	0.07	0.09	0.03	0.17	0.30	0.59
2100	0.23	0.07	0.08	0.10	0.03	0.18	0.33	0.66
2200	0.27	0.08	0.08	0.11	0.03	0.20	0.37	0.74
2300	0.30	0.08	0.09	0.12	0.04	0.21	0.41	0.82
2400	0.34	0.09	0.10	0.13	0.04	0.23	0.45	0.91
2500	0.38	0.10	0.11	0.14	0.04	0.25	0.50	1.00
2600	0.42	0.10	0.11	0.15	0.05	0.27	0.54	1.09
2700	0.46	0.11	0.12	0.16	0.05	0.29	0.59	1.19
2800	0.51	0.12	0.13	0.17	0.05	0.30	0.64	1.29
2900	0.56	0.13	0.14	0.18	0.06	0.33	0.70	1.39
3000	0.60	0.13	0.15	0.19	0.06	0.35	0.75	1.50

TABLE 2

Summary of intercomparisons undertaken by NPL in the period 1992 to 1995

Date of comparison	Participating NMI	Range of comparison °C	Comparison results °C (unless indicated)
Aug 92	NIST, USA [22]	1000 - 2500	≤1
Aug 93	NRLM, Japan [23]	800 - 2500	<2 at 2500
1993/1994	IMGC, IT; INM, FR; PTB, DE; VSL, NL; SP, SE & CMA, FI [24]	800 - 2000	<0.2% of scale
Aug 95	NRLM, Japan [25]	900 - 2800	<0.2 at 1000 <1 at 2800

FIGURES

Figure 1 KE cavity backwall scans

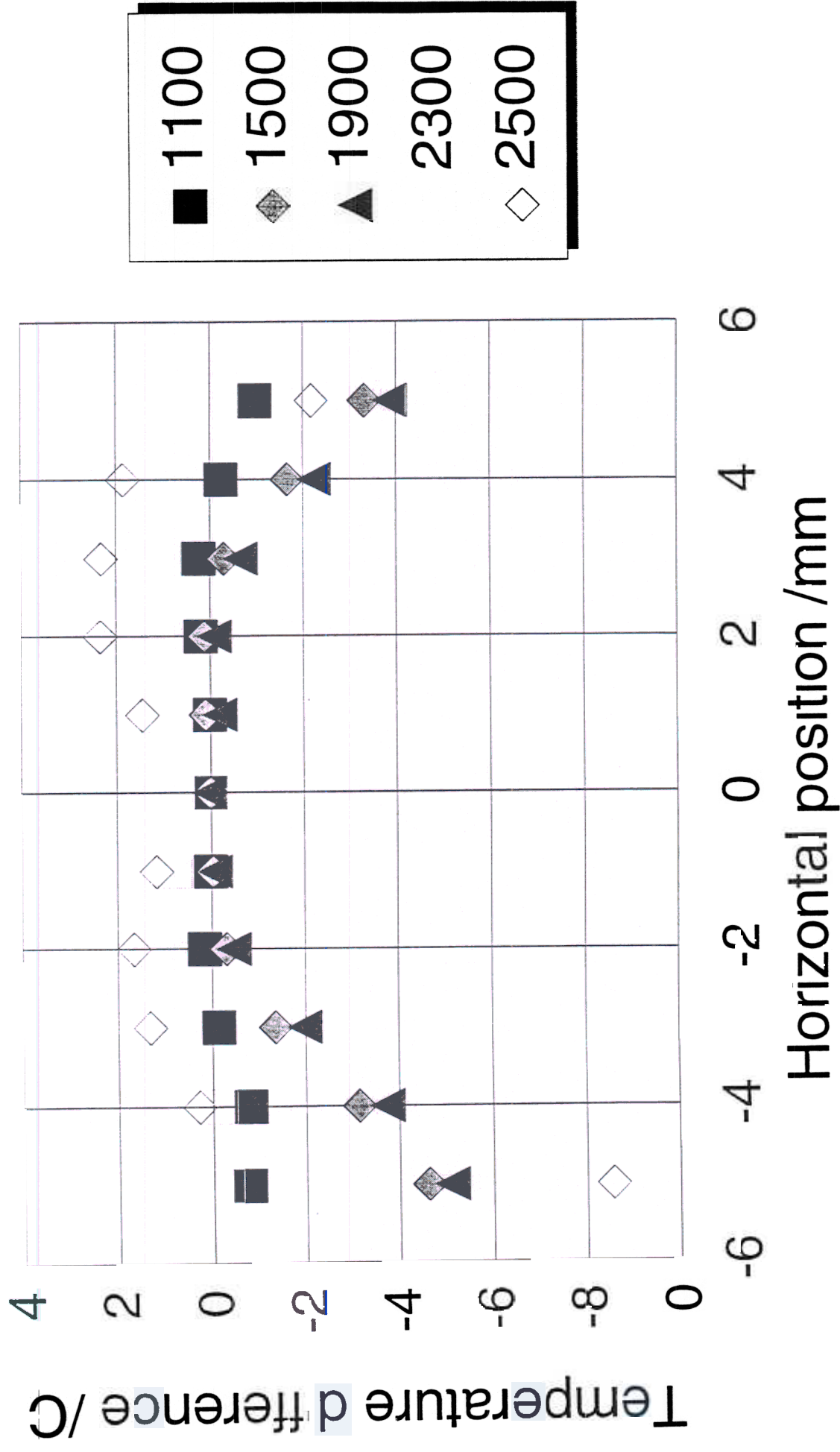


Figure 2: Thermogage cavity backwall scans

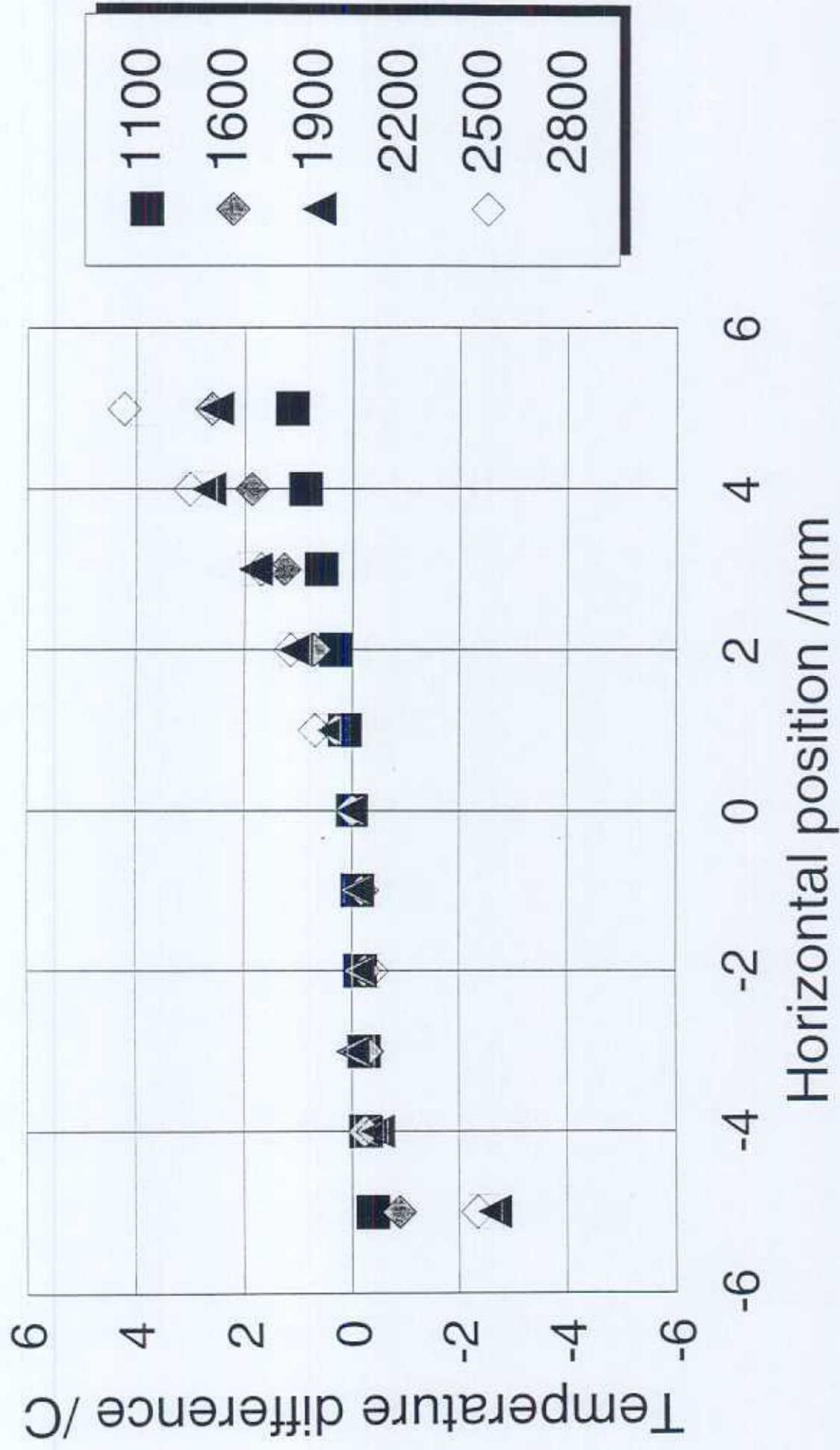


Figure 3a: LP2 650nm interference filter transmission

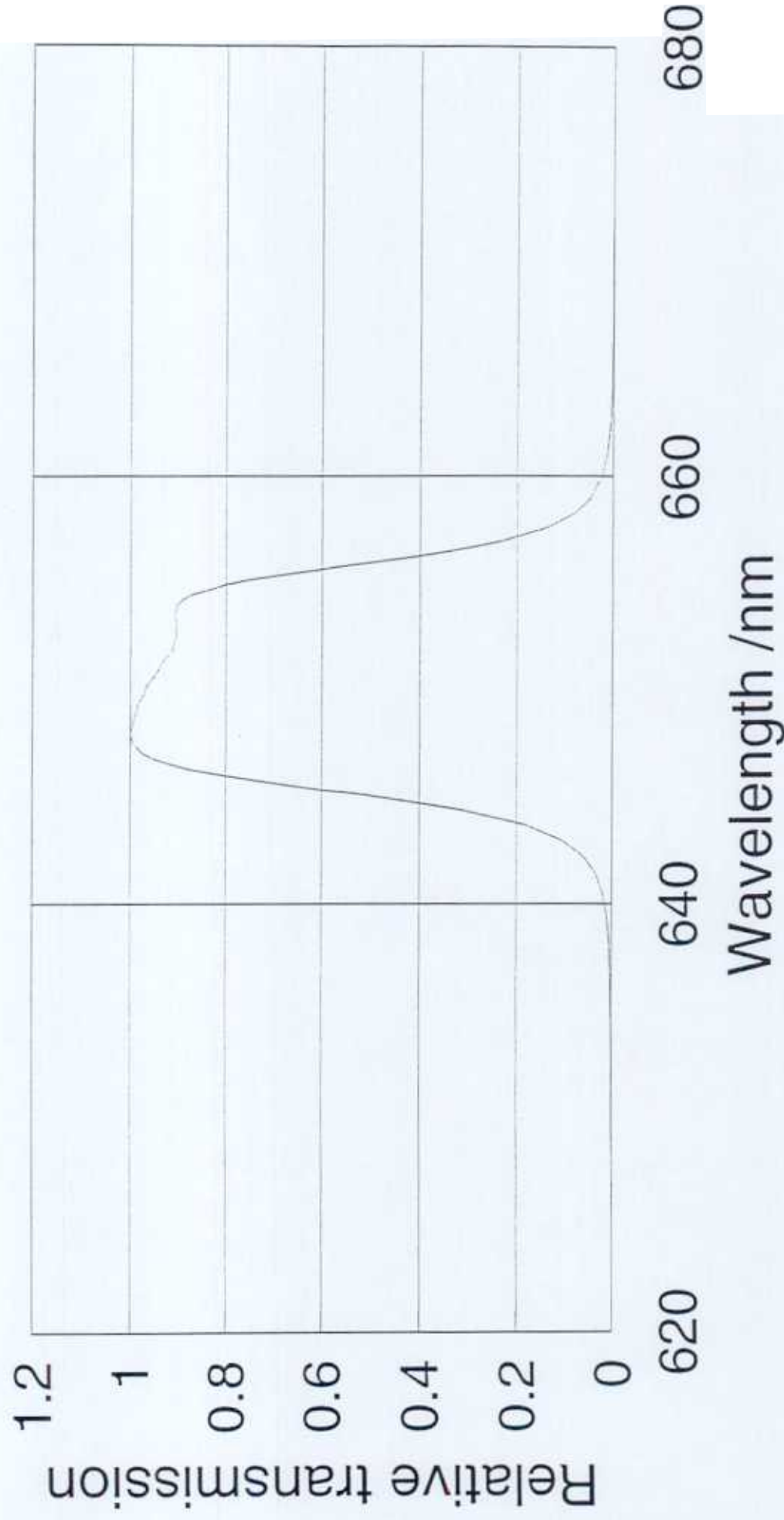


Figure 3b LP2 804nm interference filter
transmission

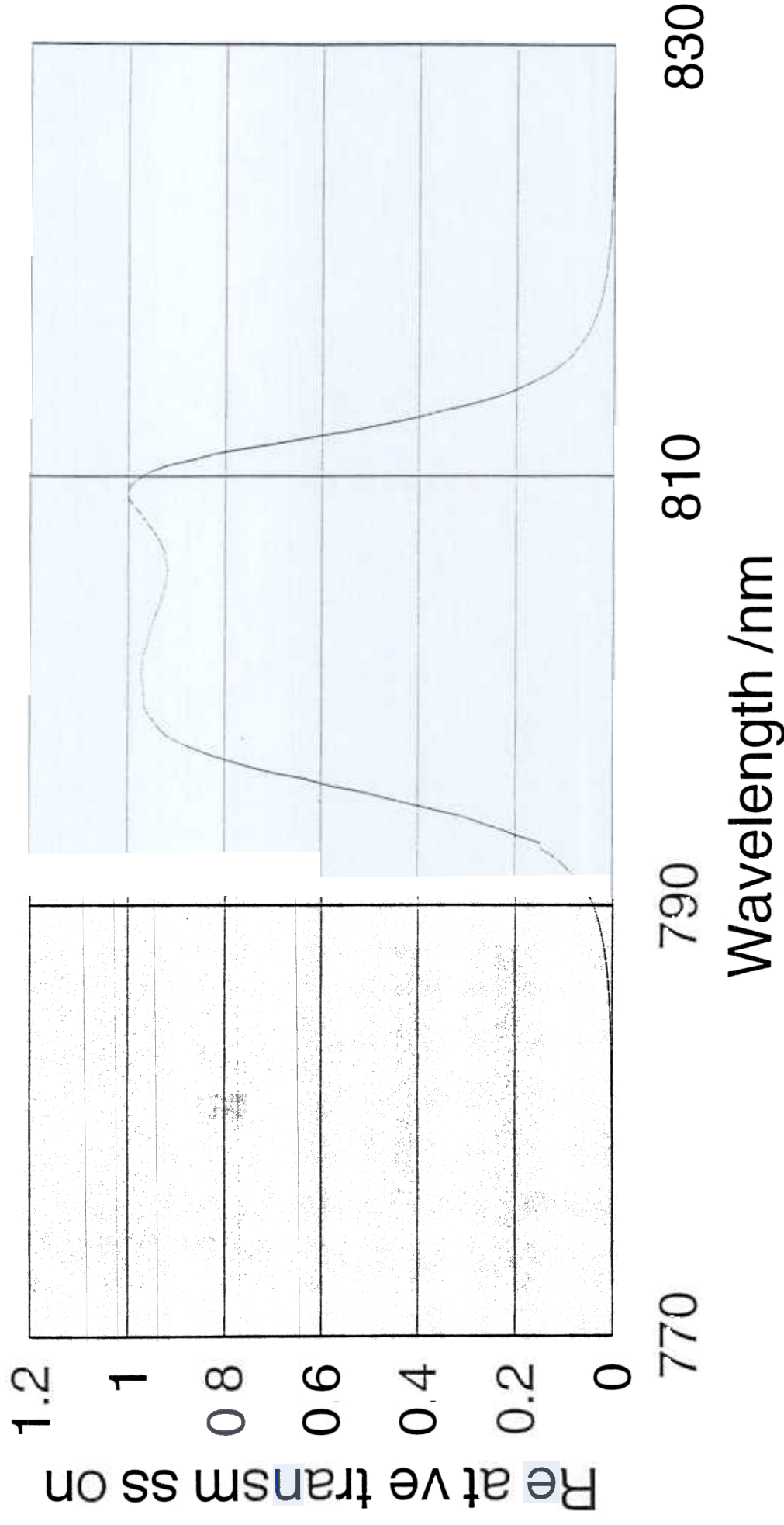


Figure 3c: LP2 906nm interference filter
transmission

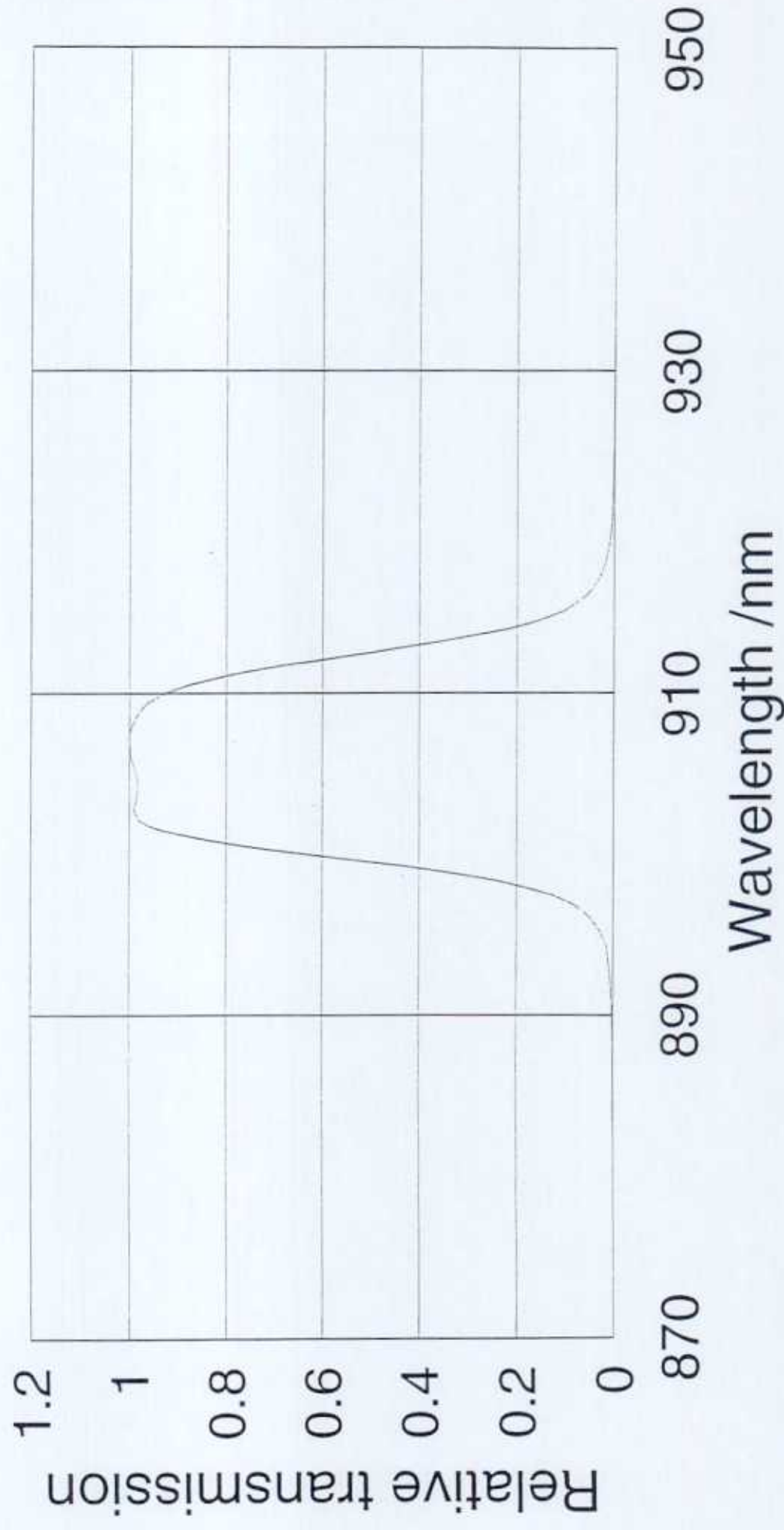


Figure 4a: Effective wavelength: 650 nm filter

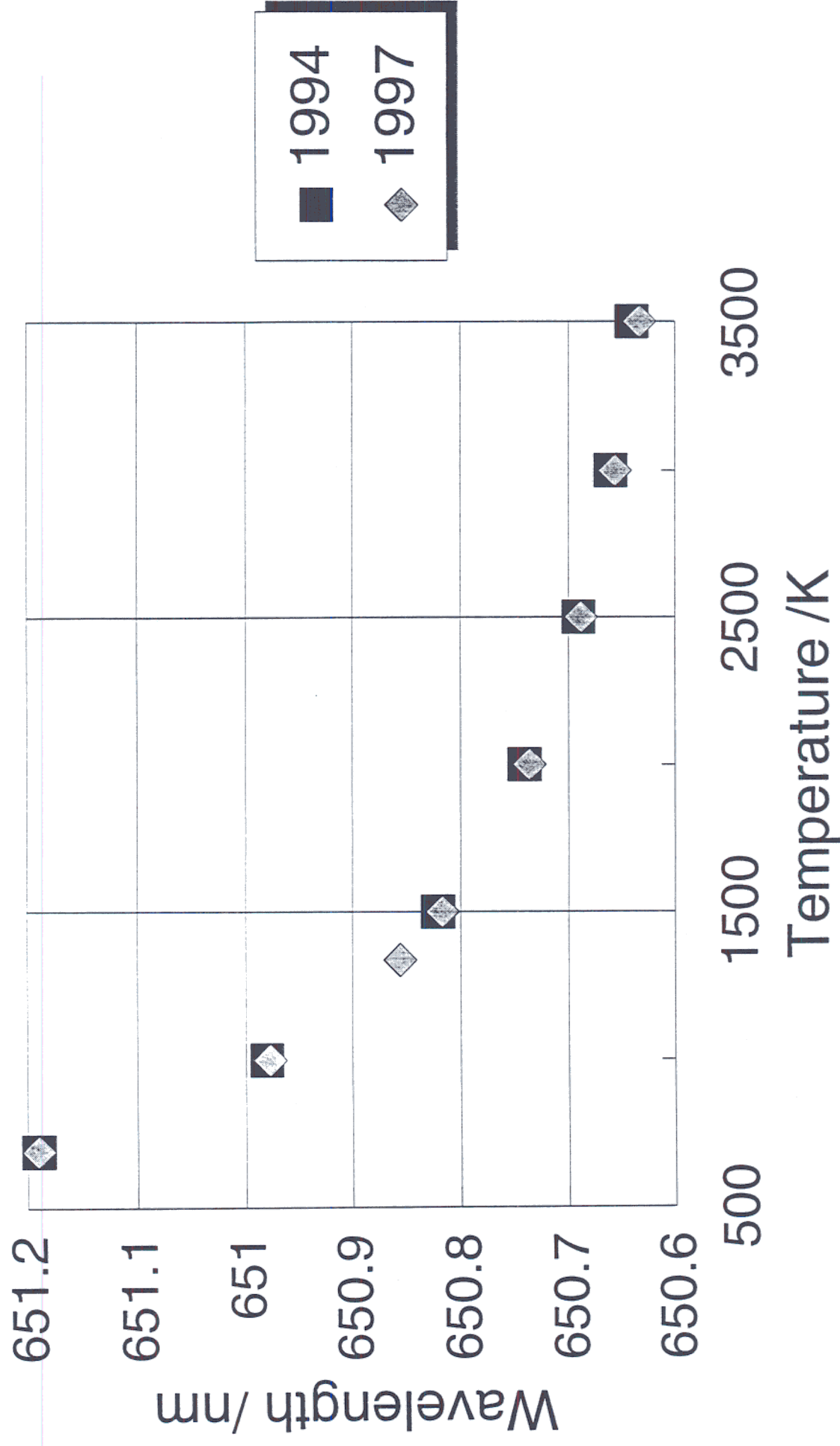


Figure 4b: Effective wavelength: 804 nm filter

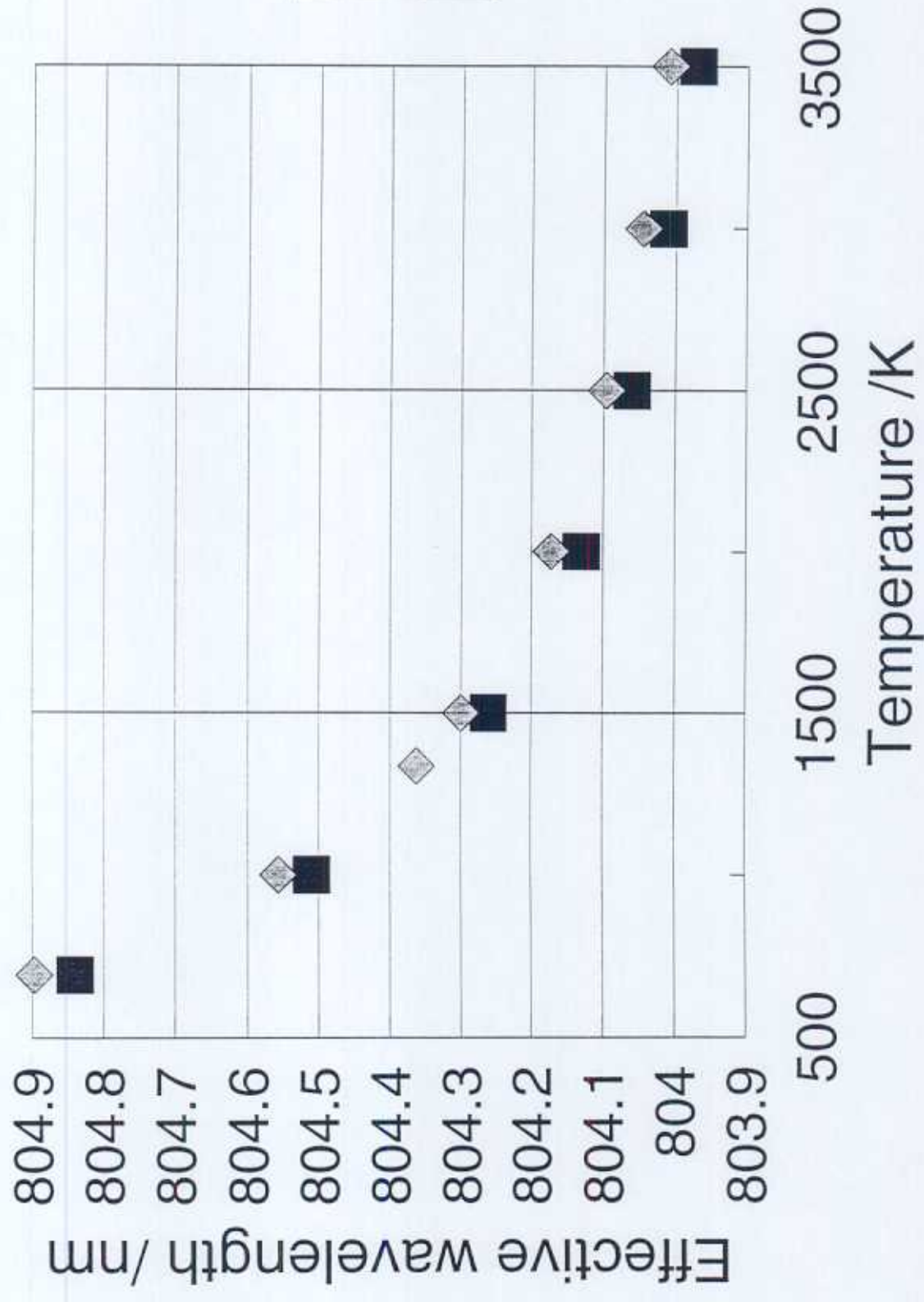


Figure 4c: Effective wavelength: 906 nm filter

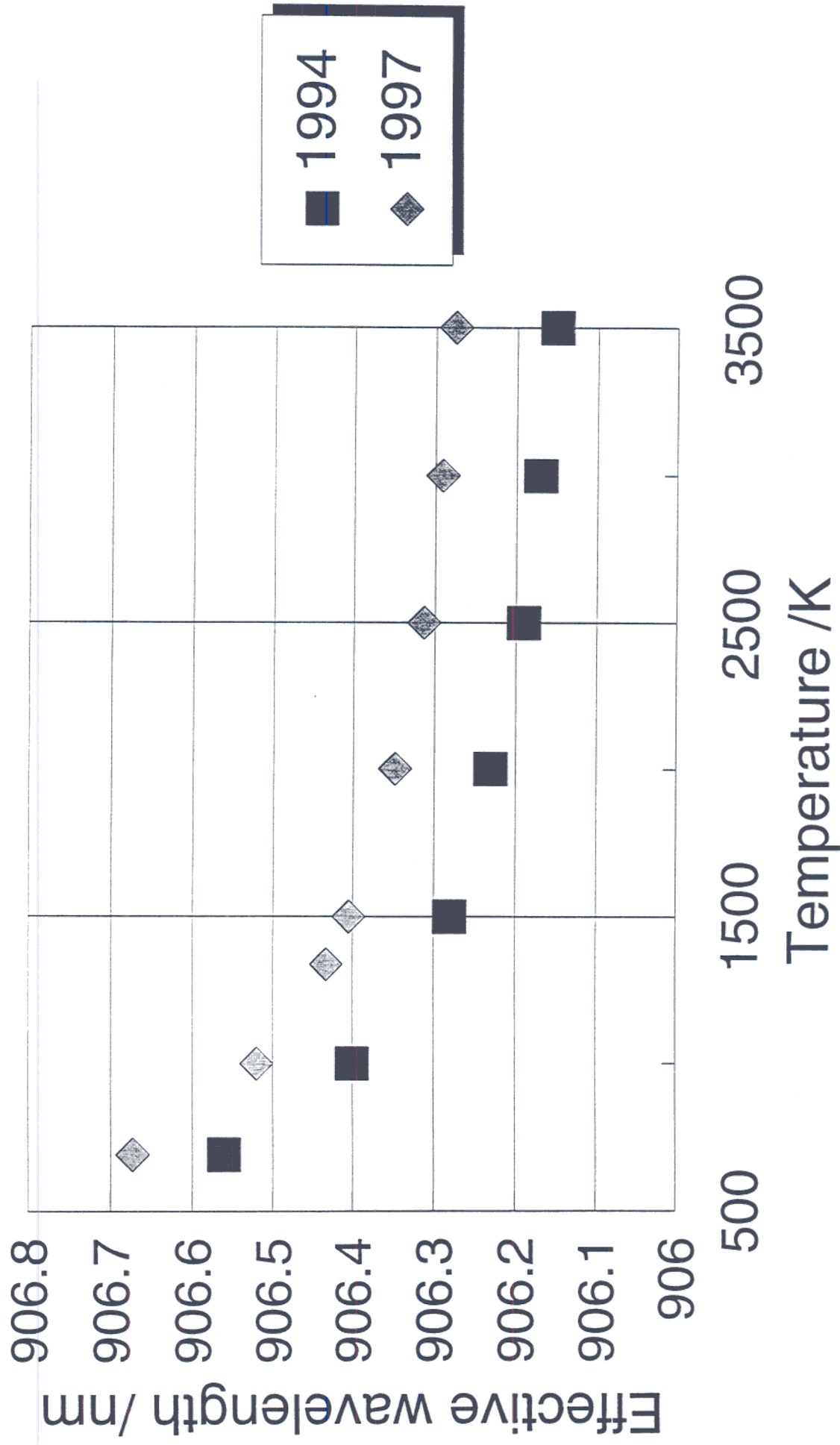


Figure 5: LP2 Non-linearity

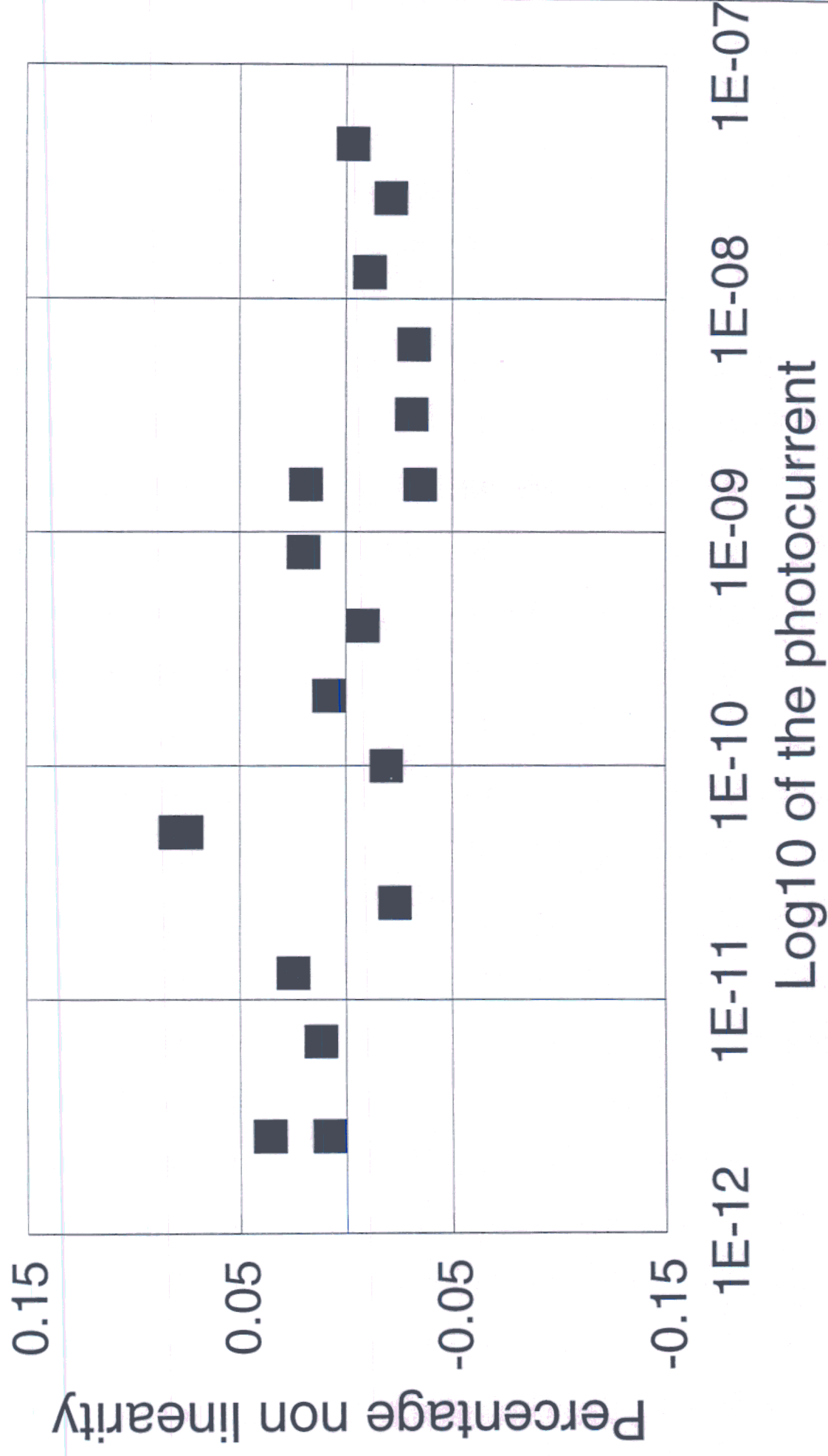


Figure 6: Size of Source of LP2

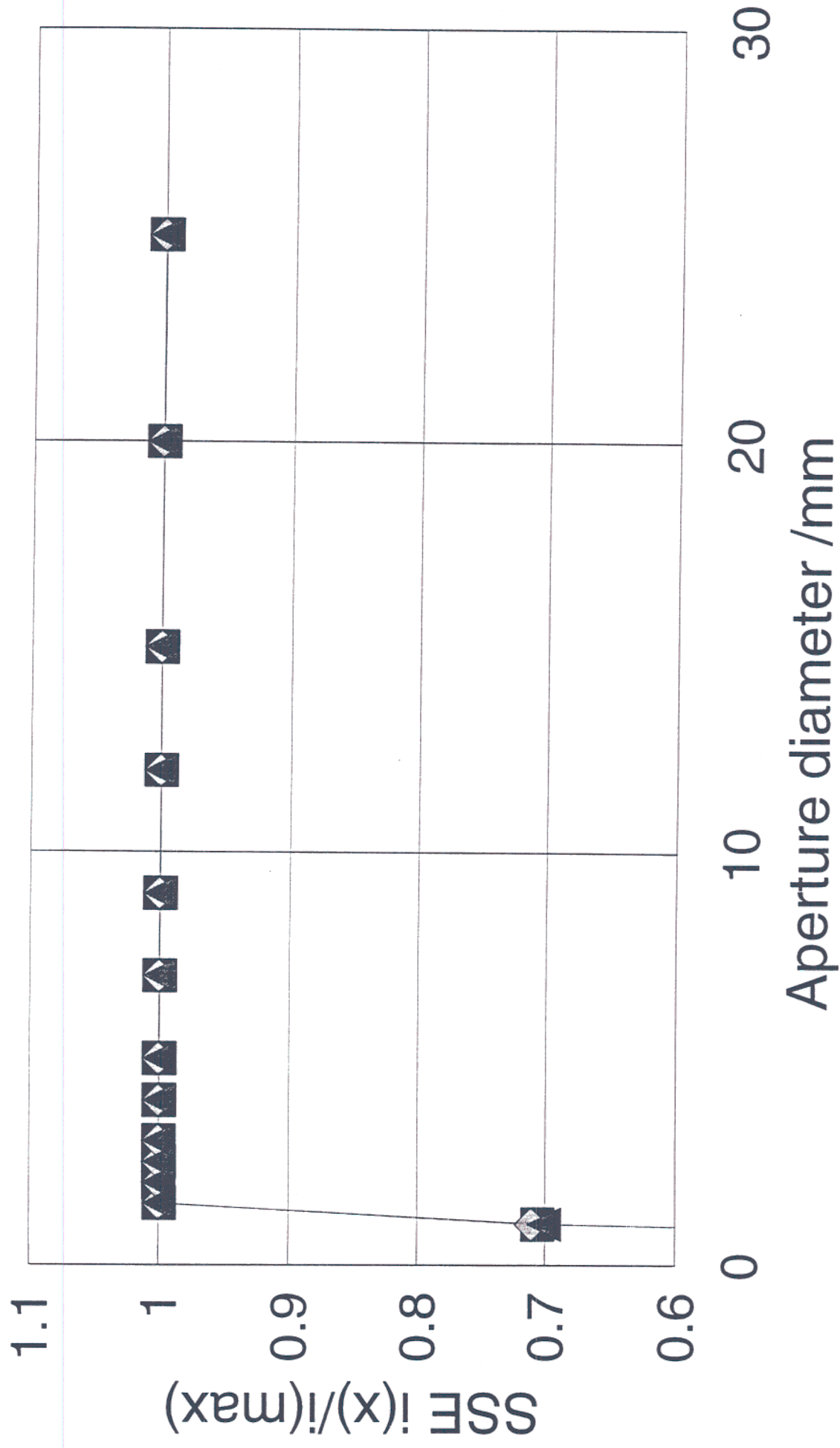


Figure 7: Typical gold melt and freeze plateaux



One division is $\sim 140\text{mK}$

Figure 8: Uncertainty in LP2 scale realisation

