

VISUAL ASSESSMENT
OF COLOUR RENDERING

BY

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ments for the degree of Master of Science in
Engineering at the University of Cape Town.

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In this thesis trade names are frequently used for convenient identification of the lamps chosen for testing. No conclusions should be drawn regarding the quality of various makes, particularly since the lamps tested were of different vintage and age.

M.R.V.C.

SYNOPSIS

The first part describes experimental work done which led to the construction of a portable pocket filter instrument which made it possible to assess the C.I.E. Colour Rendering Index for fluorescent lamps by a simple visual test. Research work was done on filter devices in the laboratory, and the results processed by digital computer.

The second part deals with a visual problem. Tests done using filter devices indicated two groups of observers with normal colour vision. After an experimental investigation on a few observers, this problem was overcome by using a pale yellow filter in the instrument.

Details of the computer programme and experimental details are described in appendices. Records are contained in a separate volume.

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SYMBOLS AND ABBREVIATIONS

(for definitions see S.A.B.S. 067 - 1958)

- $\tau(\lambda)$: Spectral transmission factor
 $\delta(\lambda)$: Optical density ($= -\log_{10} \tau(\lambda)$)
 $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$: C.I.E. spectral tristimulus values
 X, Y, Z : C.I.E. tristimulus values
 x, y : C.I.E. chromaticity co-ordinates
 R_a : C.I.E. General Colour Rendering Index
 R_i : C.I.E. Special Colour Rendering Index
 $P(\lambda)$: Spectral power distribution
 u, v : C.I.E.-Uniform Chromaticity Scale co-ordinates
 $(u, v)_T$: (u, v) co-ordinates of test field
 $(u, v)_{C, i}$: (u, v) co-ordinates of comparison field, index i , where $i = I, II, III$ and IV
 $u_{K_{Didy}}, v_{K_{Didy}}$: (u, v) co-ordinates of test field (didymium); see appendix 2, section 5
 F_i : Filter fields, index i , where $i = I, II, III$ and IV
 Filter "D" : Test field (called "didymium" in some Records)
 Filter "N" : Comparison field (called "neutral" in some Records)
 M.C. : Observer, the author
 H.E. : Observer, Dr H. D. Einhorn
 P32, 33 etc. : Philips lamp colours
 G.E. : General Electric lamps
 A.Td1 : Atlas Tropical Daylight lamp
 W.W., C.W., D.L. : Warm white, cool white and daylight lamps

Std., dlx : "Standard" and "de-luxe" lamps

UM. I, UM. II : "Universal" multi-comparison filter devices I and II

UNIV. : "Universal" filter devices

R_F : Reading with filter inserted in light beam

R_{NF} : Reading with filter removed from light beam

x : Wavelength scale setting (divs)

d : Width of entrance slit of spectroradiometer

D : Width of exit slit of spectroradiometer

Suffix K : Test lamp

Suffix o : Reference lamp

(See Appendix 2, section 5 for abbreviations used in computer programme)

1. INTRODUCTION

1.1 Summary of work performed

The practical need of assessing the colour rendering of fluorescent lamps often arises, and the aim of this task was to develop a portable pocket instrument with which it would be possible to assess, within reasonable limits, the C.I.E. Colour Rendering Index for the range of fluorescent lamps commonly used in practice.

The filter device finally constructed consisted of five filter fields, viz. a central section surrounded by four comparison fields, contained in a pocket-size holder. The lamp is viewed through the instrument, and the observer assesses nearest to which of the comparison fields the central section appears. A graduated scale next to these four fields enables the C.I.E. Colour Rendering Index for the lamp to be estimated to within 5 or 10 units of index.

The transmission curves for the various filter fields of the pocket instrument were obtained by spectroradiometry. The results of observations for the filter instrument on various fluorescent lamps were processed by digital computer. Other experimental filter devices were measured colorimetrically, and a new $(x,y) \rightarrow (u,v)$ nomogram was derived for their evaluation.

Differences in vision amongst observers with normal colour vision were found. Tests conducted in the short-wavelength region of the spectrum established that some observers were about ten times more sensitive than others to violet radiation of about 405 nm. This problem was overcome by using a pale yellow filter in the instrument, which absorbed most of the radiation below 430 nm.

1.2 Review of fundamentals and previous work

This research work was based on the work done at the National Physical Laboratory in Teddington, England⁽¹⁾. A pocket filter instrument was developed here which made it possible to assess the colour rendering properties of fluorescent lamps. This device consisted of a pair of metameric filters which appeared the same if a full radiator or a lamp of good colour rendering properties was viewed through it, but looked considerably different for a light source of poor colour rendering properties.

Further work was done in a B.Sc. thesis⁽²⁾ during which, amongst other things, transmission curves were obtained for existing filter instruments in use at that time.

If two light sources, compared side by side, appear identical they are said to have the same "colour appearance". If a wide variety of coloured surfaces are viewed under both sources, and they appear identical, then the sources are said to have the same "colour rendering". Now, any colour (except certain spectral ones) may be caused by an infinite number of spectra, and two colours which look the same but have different spectra are called metameric. Metameric light sources have the same "colour appearance", but different "colour rendering". Comparisons of the colour appearance of different light sources can be made by plotting their chromaticity co-ordinates (x,y) on the C.I.E. diagram⁽³⁾. The colour rendering properties of light sources can be specified by the C.I.E. Test-Colour Method⁽⁴⁾ which provides for the rating of a lamp in terms of a colour rendering index. This index, R , is based on the degree of colorimetric shifts of test objects under a test lamp in compari-

son to their colours under a reference lamp of the same, or nearly the same chromaticity. The rating consists of a General Index, R_a , based on a set of eight test-colour samples, supplemented by Special Indices, R_i , based on special purpose test samples.

Fluorescent lamps may generally be classified as:

- (a) those designed for high efficacy
- (b) those designed for good colour rendering
- (c) those falling in between the above categories.

However, these aims are conflicting. Computer studies⁽⁵⁾ have shown that for highest efficacy the emission in the yellow region round about 560 nm should be boosted at the expense of green and red radiation, while for good colour rendering, especially of faces and food, ample red radiation well above 600 nm is indispensable. Radiation, however, in the red region is of low efficacy, as can easily be seen from the $v(\lambda)$ curve⁽⁶⁾.

PART I

THE FILTER DEVICES

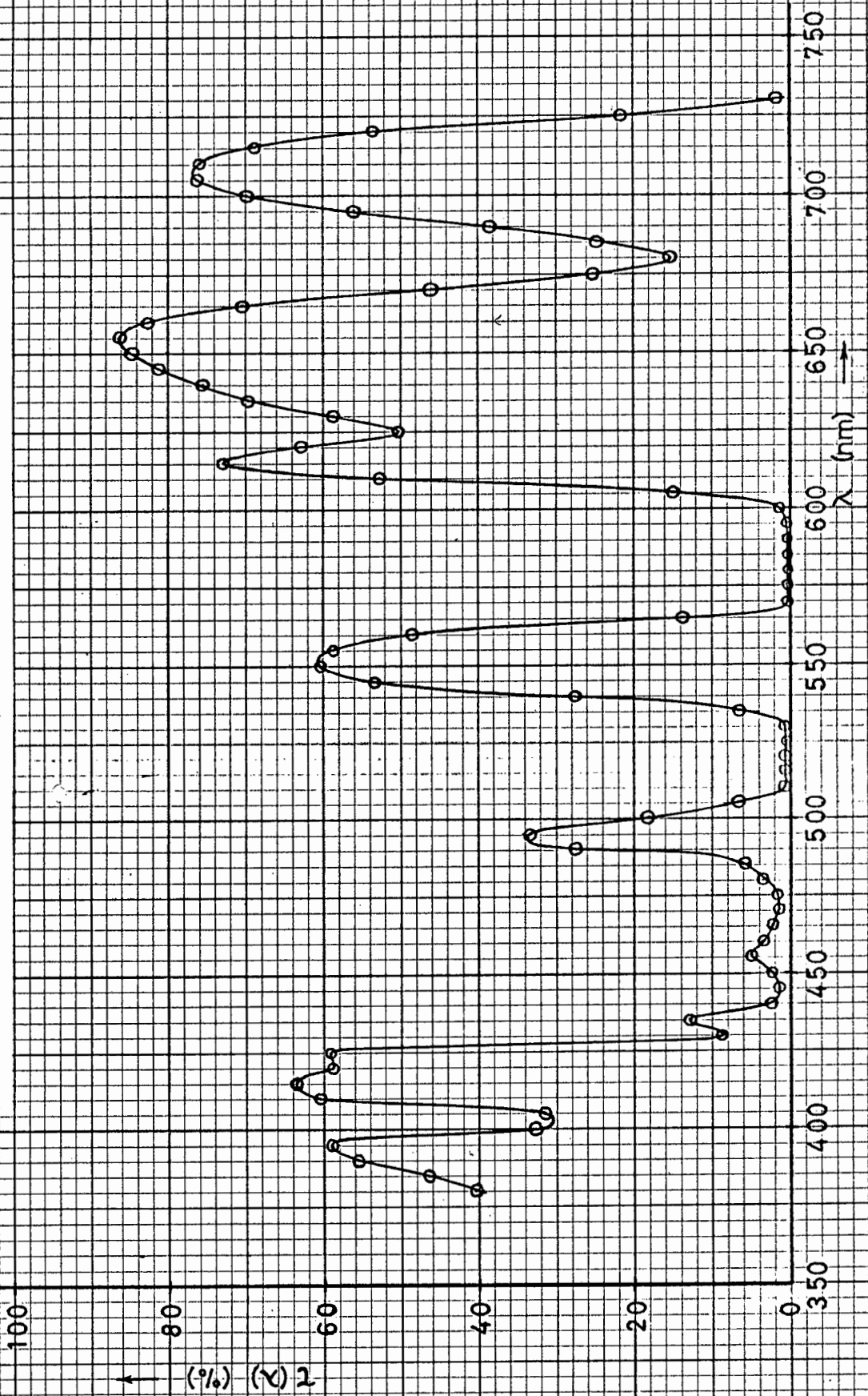
2. INITIAL SINGLE-COMPARISON FILTER DEVICES

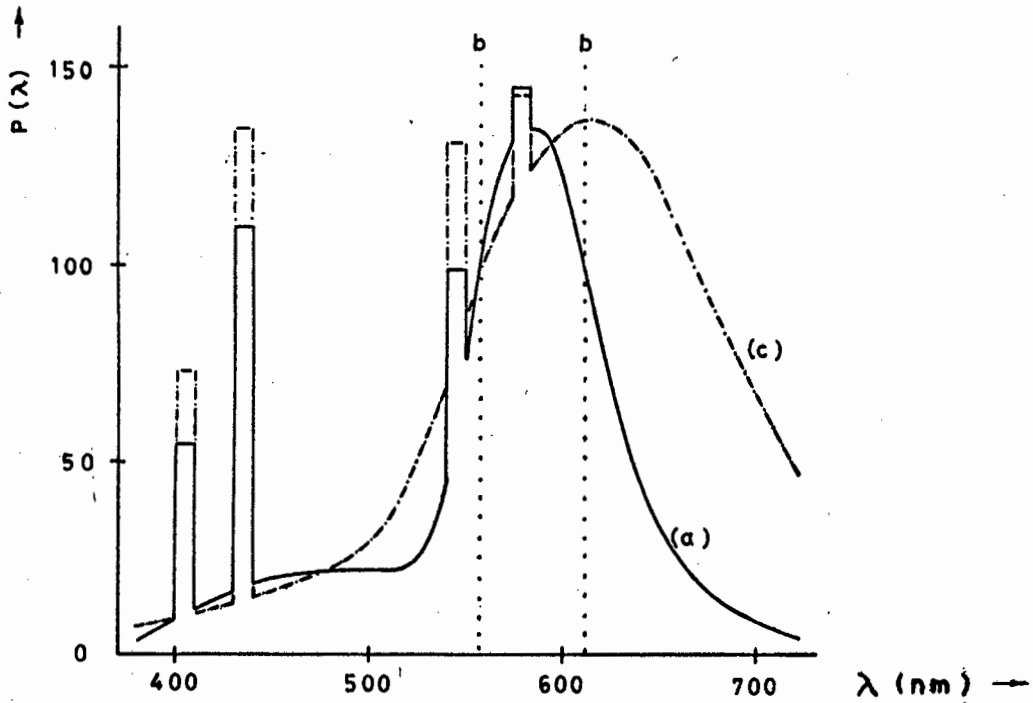
2.1 Design

The single-comparison filter instruments consisted of a pair of metameric filter fields, placed side by side, through which the lamp was sighted. The filter fields were chosen so that they looked substantially the same when a full radiator was viewed through them, but different for a light source of poor colour rendering properties - good colour rendering meaning a rendition similar to that of a full radiator.

These filter instruments made a check on the yellow boost in a lamp by absorbing this region using a suitable filter. Didymium glass, having a widely varying transmission curve which absorbs very strongly in the yellow region (Fig. 1), has the desired properties and was thus used in these filter devices. When a "standard" fluorescent lamp (Fig. 2, curve (a)) designed for high efficacy is viewed through the didymium, it appears a greenish colour, as a considerable portion of its spectrum has now been removed. The "standard" fluorescent lamp has a peak at about 580 nm, which is right in the centre of one of the regions where the didymium absorbs most strongly (Fig. 2, region b-b). When a "de-luxe" fluorescent tube (Fig. 2, curve (c)), designed for good colour rendering is observed, it is seen as a pinkish colour as proportionately less of its spectrum is removed than in the case of the "standard" fluorescent lamp. The "de-luxe" lamp has considerably more energy in the red region of the spectrum than the "standard" lamp, and as the didymium transmits strongly in the red region, the "de-luxe" lamp appears a reddish hue when observed through the didymium.

Fig. 1. $\tau(\lambda)$ for 5 mm thick Didymium glass - Schott BG 36.





- (a) : Warm white "standard" lamp
- (b) : Warm white "de-luxe" lamp
- (c) : Warm white "de-luxe" lamp
- b } : Principal absorption region of didymium glass
- b }

Fig. 2. Typical relative spectral power distribution curves for warm white lamps.

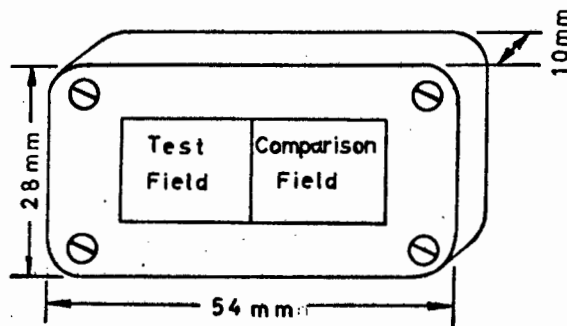


Fig. 3. Single-comparison filter device

During the research work, a number of different single-comparison filter instruments were constructed. Filter devices referred to in the results as H.E. I, H.E. II, the Large Demonstration filter device and the Original N.P.L. (National Physical Laboratory) filter device had been built during previous work to be metameric on a sunny cloud. A sunny cloud was used as a reference source having ideal colour rendering properties. Filter instruments M.C. I and M.C. II were constructed to be metameric on a sunny cloud, while M.C. III was designed to be very nearly metameric on either a good cool white de-luxe lamp such as the Philips Colour 37, or a good 6500K lamp such as the Philips Colour 57.

The symbol "M.C." refers to filter devices suited to the eyes of the author, and "H.E." to filter devices suited to the eyes of Dr H. D. Einhorn. The field containing the didymium glass has been called the test field (often referred to in the Records section as the "didymium" side), and the other field the comparison field (sometimes referred to in the Records as the "neutral" side).

Instruments H.E. I and II, and M.C. I, II and III were constructed in holders approximately 54 mm x 28 mm x 10 mm (Fig. 3), the other two in larger holders. The detailed composition of these filter instruments is described in Appendix 5.

2.2 Observations

Verbal statements were recorded on the chromaticities of various light sources as seen through these filter instruments, the observers being Dr H. D. Einhorn and the author (see Records, section R5.1).

The range of light sources used for these tests included the Philips Colour 29 - warm white (abbreviated P29 in the results), Philips Colour 32 - warm white de-luxe (P32), Philips Colour 33 - cool white (P33), Philips Colour 37 - cool white de-luxe (P37), Philips Colour 57 - daylight de-luxe (P57), Atlas Tropical Daylight (6500K) - abbreviated (A.Tdl), an incandescent lamp and a sunny cloud.

Analysis of these verbal statements showed that the greatest discrepancy of observation was that recorded when using a sunny cloud as a light source. This discrepancy in observation occurred in all filter instruments except with the N.P.L. Original and Large Demonstration models, in which a different make of didymium glass from the other filter instruments had been used. Table I summarizes a typical sunlight observation.

Table I. Sunlight Observations

Filter Instrument	H.E. I		M.C. I	
	H.E.	M.C.	H.E.	M.C.
Test field	grey	violet	greenish grey	violet
Comparison field	grey i.e. metameric	greenish grey	violet	violet i.e. metameric

Filter instrument M.C. I referred to in Table I was constructed with the test field having very nearly the same filter composition as that of filter device H.E. I.

It should be recorded that the colour vision of both observers was found to be normal, as far as could be determined from Ishihara tests. These tests consist of a series of plates used to find out, promptly and accurately, congenital colour-blindness - the most common form of colour blindness. A number of other observers (whose colour vision was first tested using the Ishihara tests) were asked to describe the colours of the filter devices H.E. I and M.C. I when looking at a cloudy sky. One group (called Group I) agreed with the description of observer M.C., and the other (called Group II) agreed with the statement made by observer H.E. There did not appear to be any observers with normal colour vision whose description of the colours seen lay somewhere "in between" those given by these two groups. A detailed investigation of this difference in vision amongst normal observers is discussed in Part II.

2.3 Colorimetric measurement of filter devices

To obtain some scientific correlation with these verbal statements, C.I.E. (x,y) chromaticity co-ordinates for different sources as seen through the filter devices were determined using a Tintometer. This method of measurement is described in Appendix 4. The transformation of these (x,y) values to the (u,v) U.C.S. co-ordinates was facilitated by use of the nomogram detailed in Appendix 1.

Measurements were made by observers H.E. and M.C. (both "Groups" of normal observers thus being represented) on various light sources (see Records, section R3). The U.C.S. co-ordinates were plotted for filter

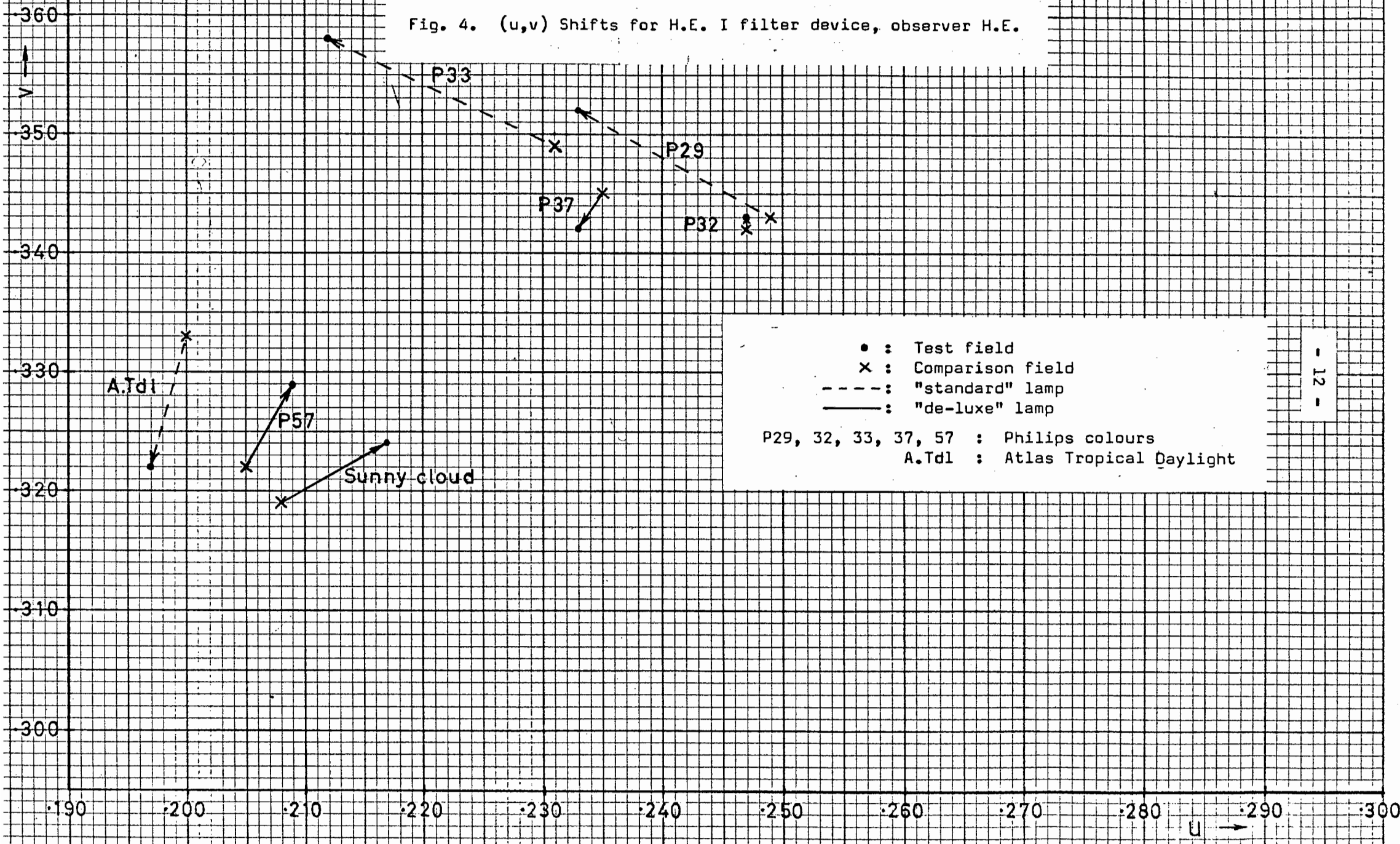
devices H.E. I, M.C. II and III, the N.P.L. Original filter and the Large Demonstration filter instrument. Figs. 4, 5, 7, 8, 10, 11, 13, and 14 show the (u,v) shifts for a particular filter device and observer on different lamps, while Figs. 6, 9 and 12 show observer differences for filter observations on various lamps.

In Fig. 15 repeat readings are plotted for both observers for observations on a number of filter instruments and several lamps. The results indicate that observers are on the average unable to reproduce measurements to within $0.005 \pm .001$ (u,v) units (see Records, section R3 for calculation). Thus when comparing observer differences in Figs. 6, 9 and 12, a difference of up to 0.005 (u,v) units between observations may be considered insignificant.

From Fig. 4 it may be seen that with filter device H.E. I observer H.E. sees de-luxe lamps almost metameric, while standard lamps give a greenish shift. Fig. 5 shows that observer M.C. finds it difficult to distinguish between the P57 and A.Td1, while the P33 does not give a very large shift using filter device H.E. I. Fig. 6 clearly shows that on a sunny cloud, observer M.C. sees the test field of device H.E. I as purple compared to the comparison field, while observer H.E. sees both sides almost metameric (test field slightly more yellowish).

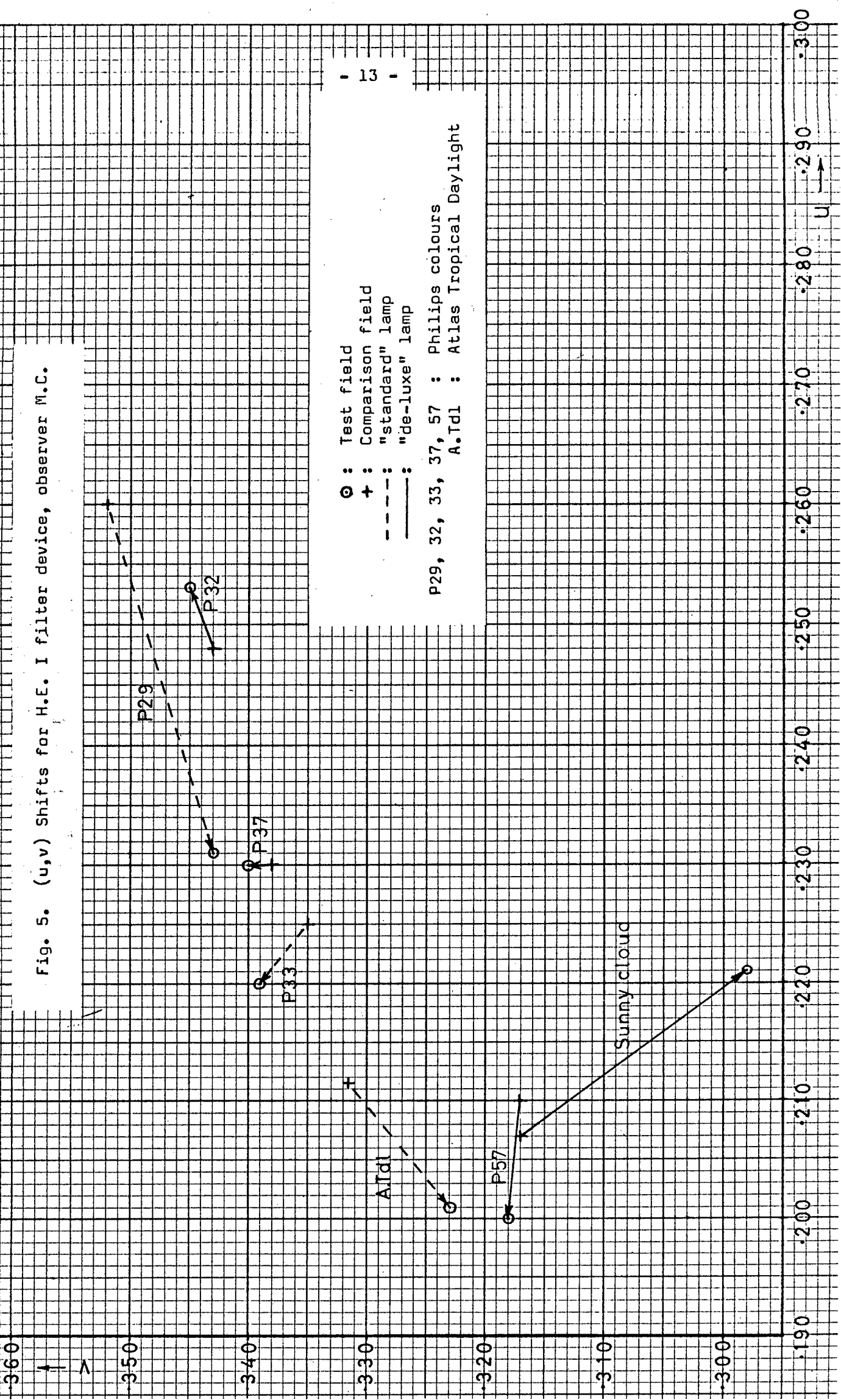
The (u,v) shifts in Figs. 7 and 8 signify that the N.P.L. Original filter works almost equally well for both observers, as the de-luxe lamps give small shifts and standard lamps appear greenish in both cases. The P32 tends to be assessed leniently by observer M.C., the test field appearing pinkish. From Fig. 9 it is apparent that observer M.C. sees a sunny cloud only slightly more purplish-pink than observer H.E.

Fig. 4. (u,v) Shifts for H.E. I filter device, observer H.E.



• : Test field
 x : Comparison field
 - - - : "standard" lamp
 — : "de-luxe" lamp
 P29, 32, 33, 37, 57 : Philips colours
 A.Td1 : Atlas Tropical Daylight

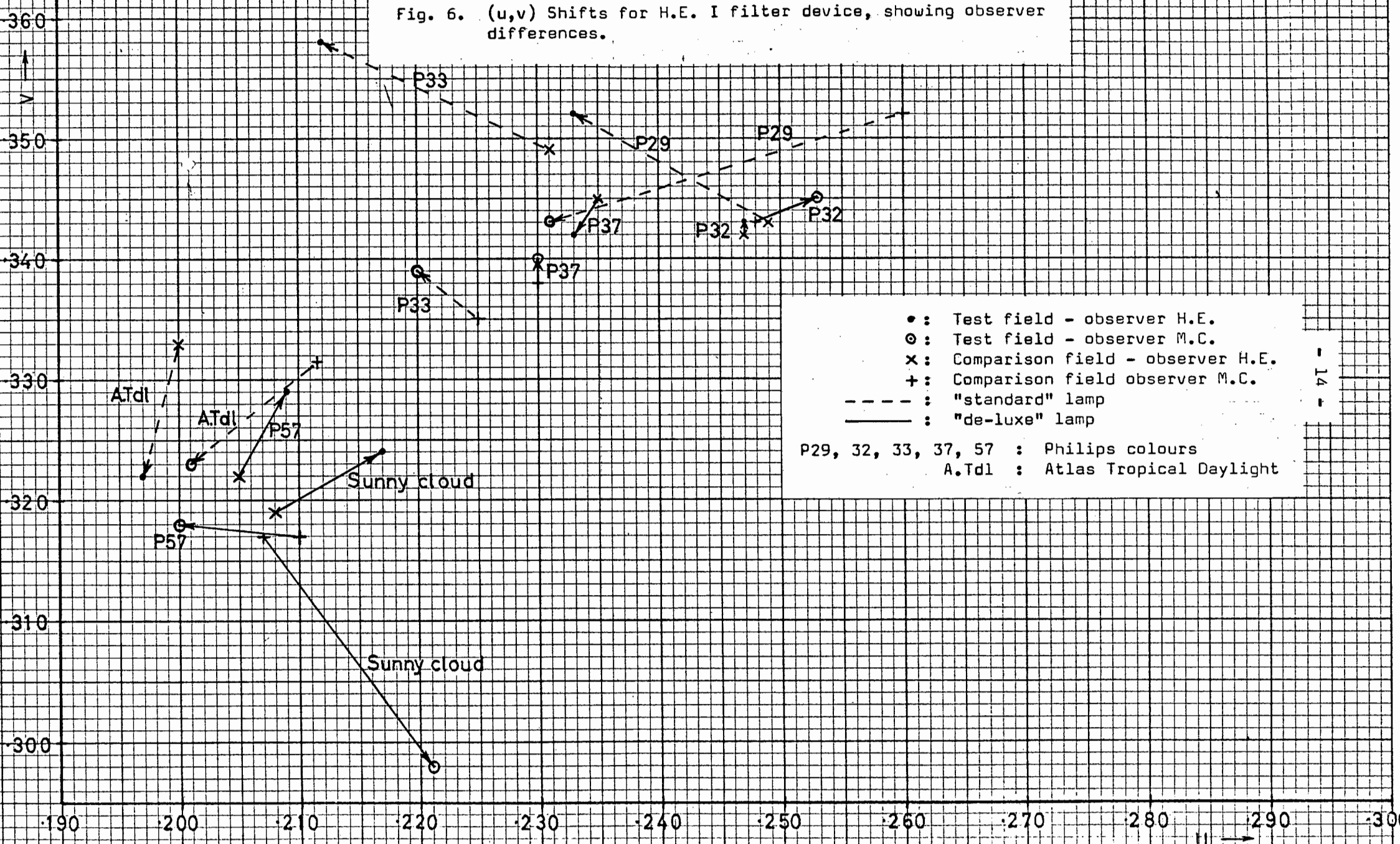
Fig. 5. (u,v) Shifts for H.E. I filter device, observer M.C.



⊙ : Test field
 + : Comparison field
 - - - : "standard" lamp
 — : "de-luxe" lamp

P29, 32, 33, 37, 57 : Philips colours
 A.TdI : Atlas Tropical Daylight

Fig. 6. (u,v) Shifts for H.E. I filter device, showing observer differences.



• : Test field - observer H.E.
 ⊙ : Test field - observer M.C.
 × : Comparison field - observer H.E.
 + : Comparison field observer M.C.
 - - - : "standard" lamp
 — : "de-luxe" lamp
 P29, 32, 33, 37, 57 : Philips colours
 A.Td1 : Atlas Tropical Daylight

Fig. 7. (u,v) Shifts for N.P.L. Original filter device, observer H.E.

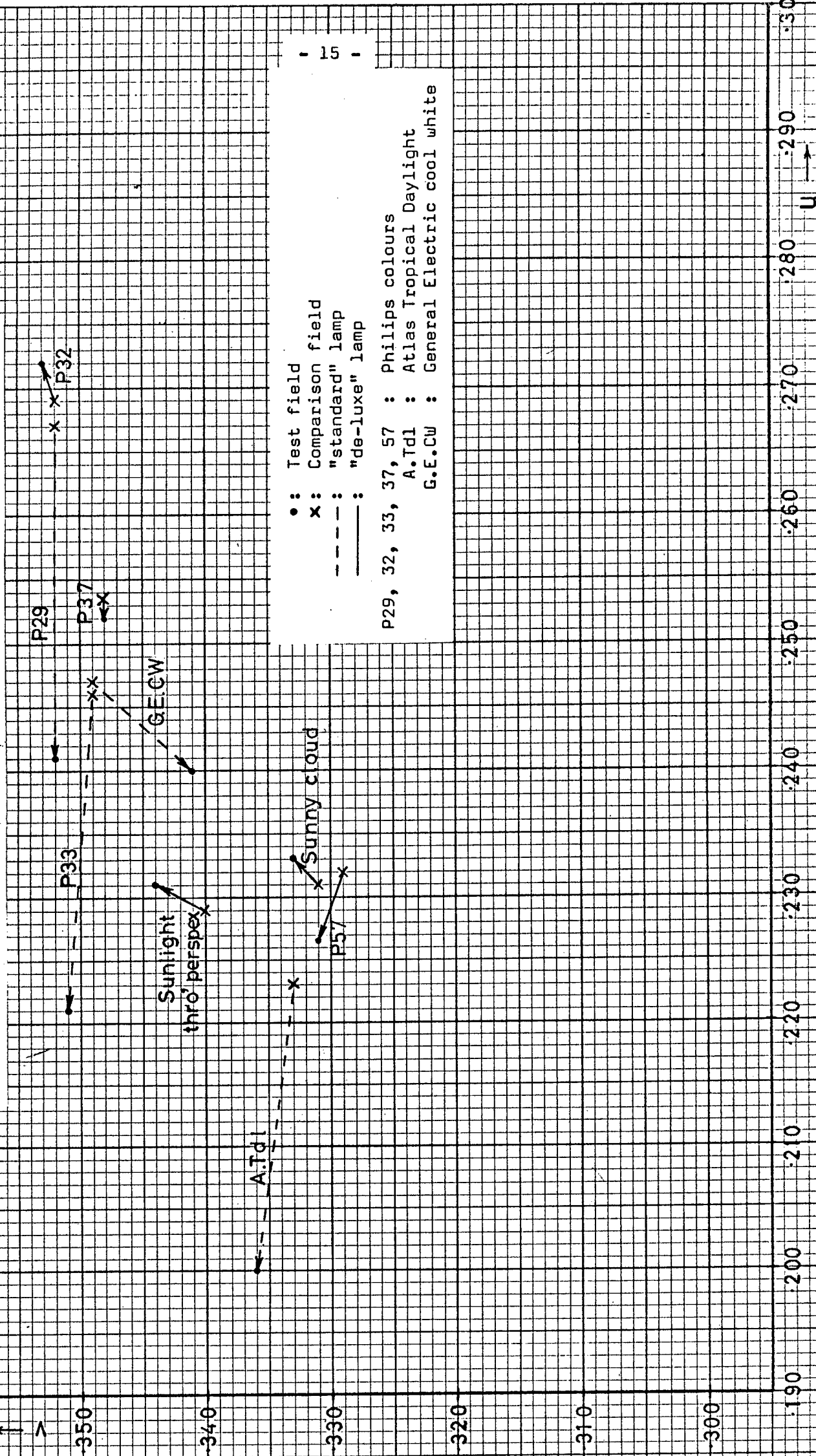


Fig. 8. (u,v) Shifts for N.P.L. Original filter device, observer M.C.

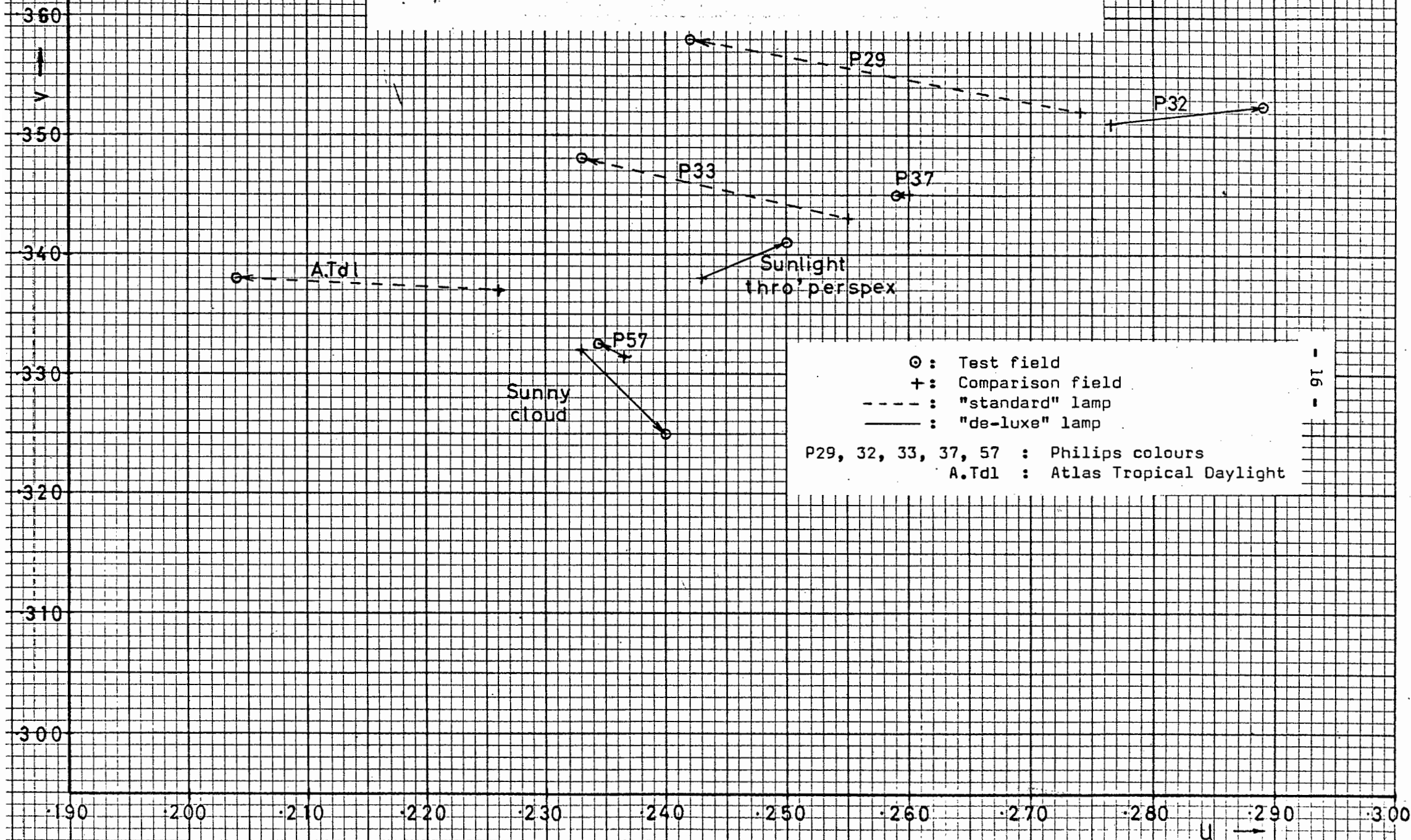


Fig. 9. (u,v) Shifts for N.P.L. Original filter device, showing observer differences

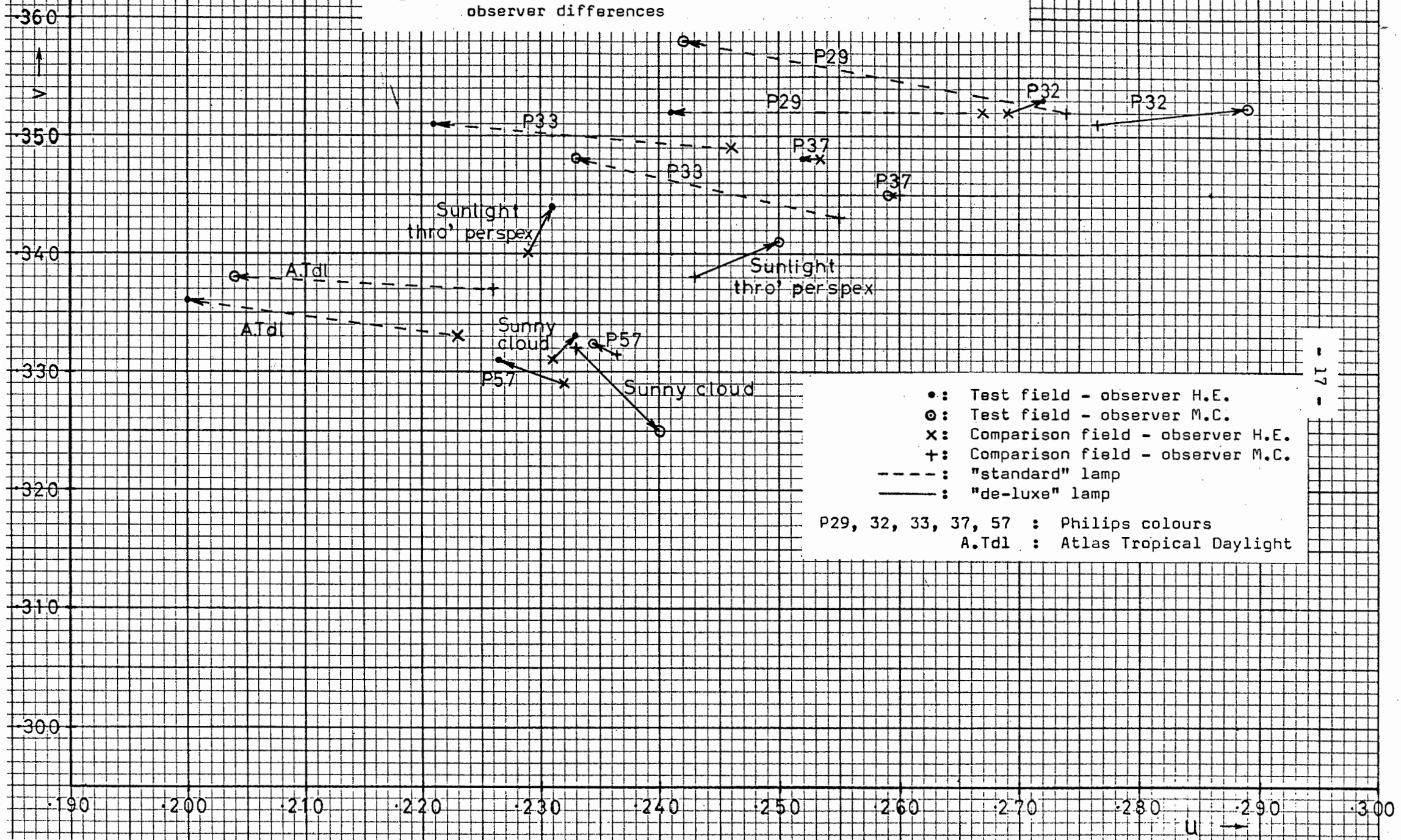
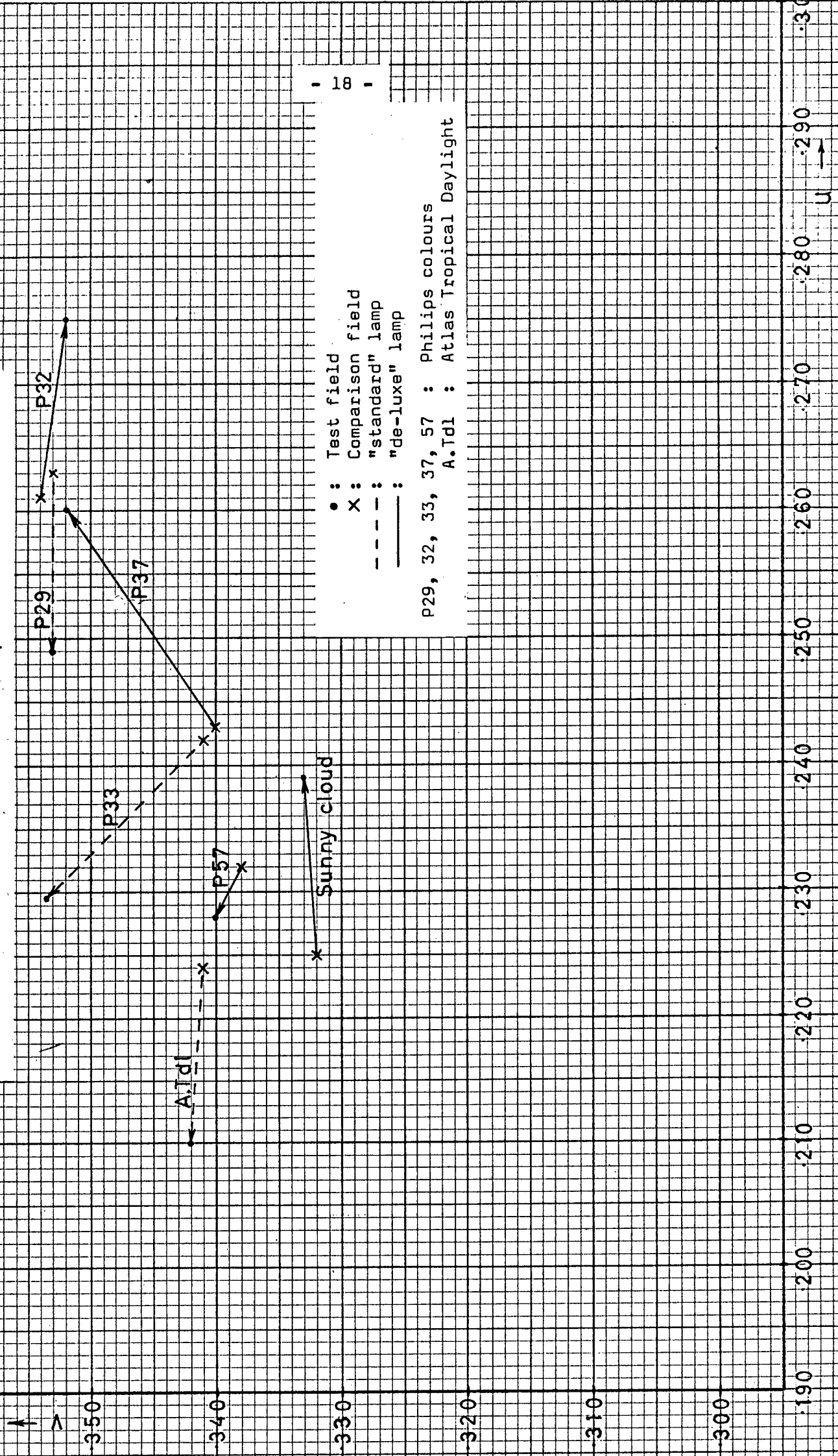


Fig. 10. (u,v) Shifts for M.C. III filter device, observer H.F.



- : Test field
- X : Comparison field
- - - : "standard" lamp
- : "de-luxe" lamp

P29, 32, 33, 37, 57 : Philips colours
 A.Td1 : Atlas Tropical Daylight

Fig. 11. (u,v) Shifts for M.C. III filter device, observer M.C.

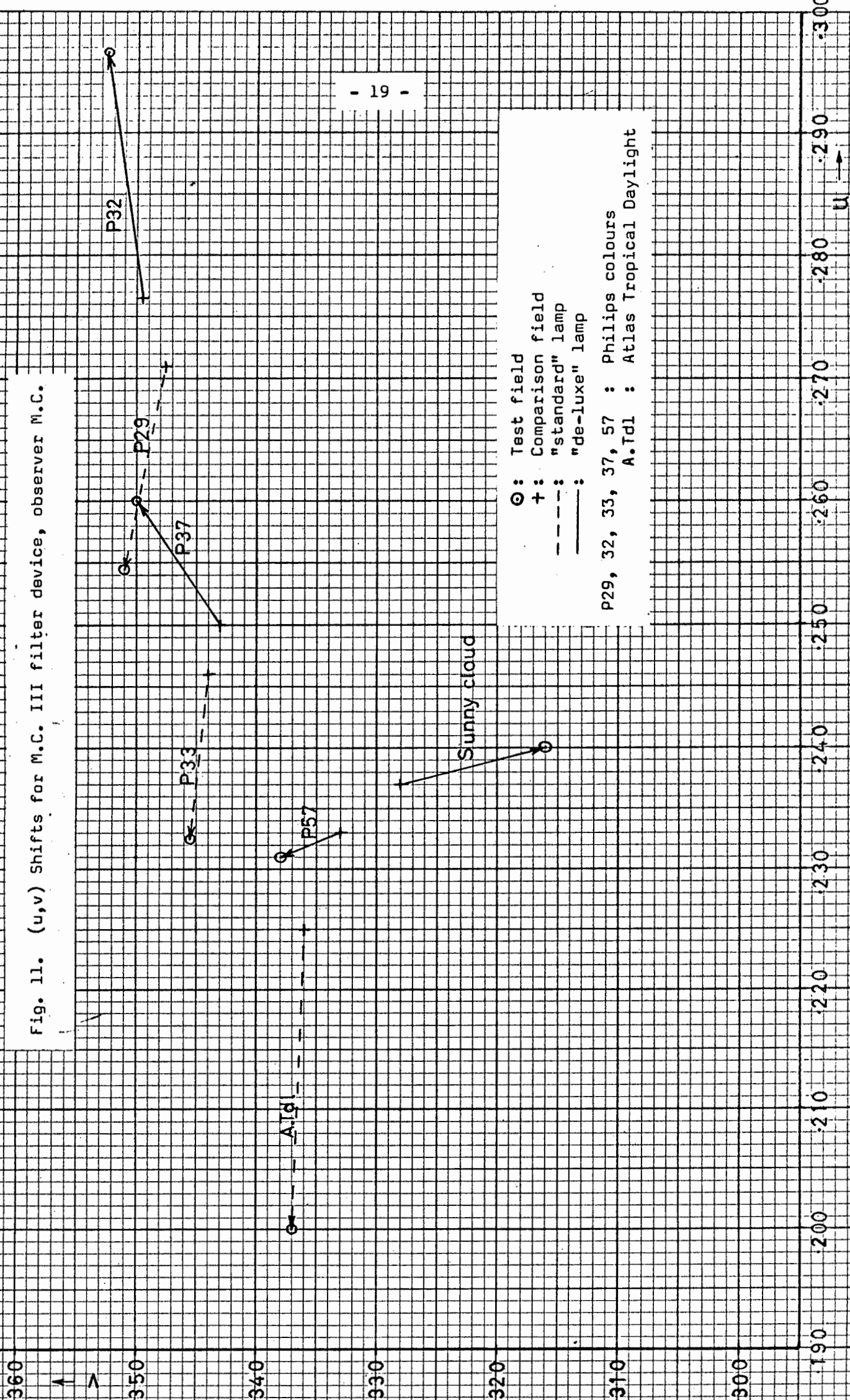
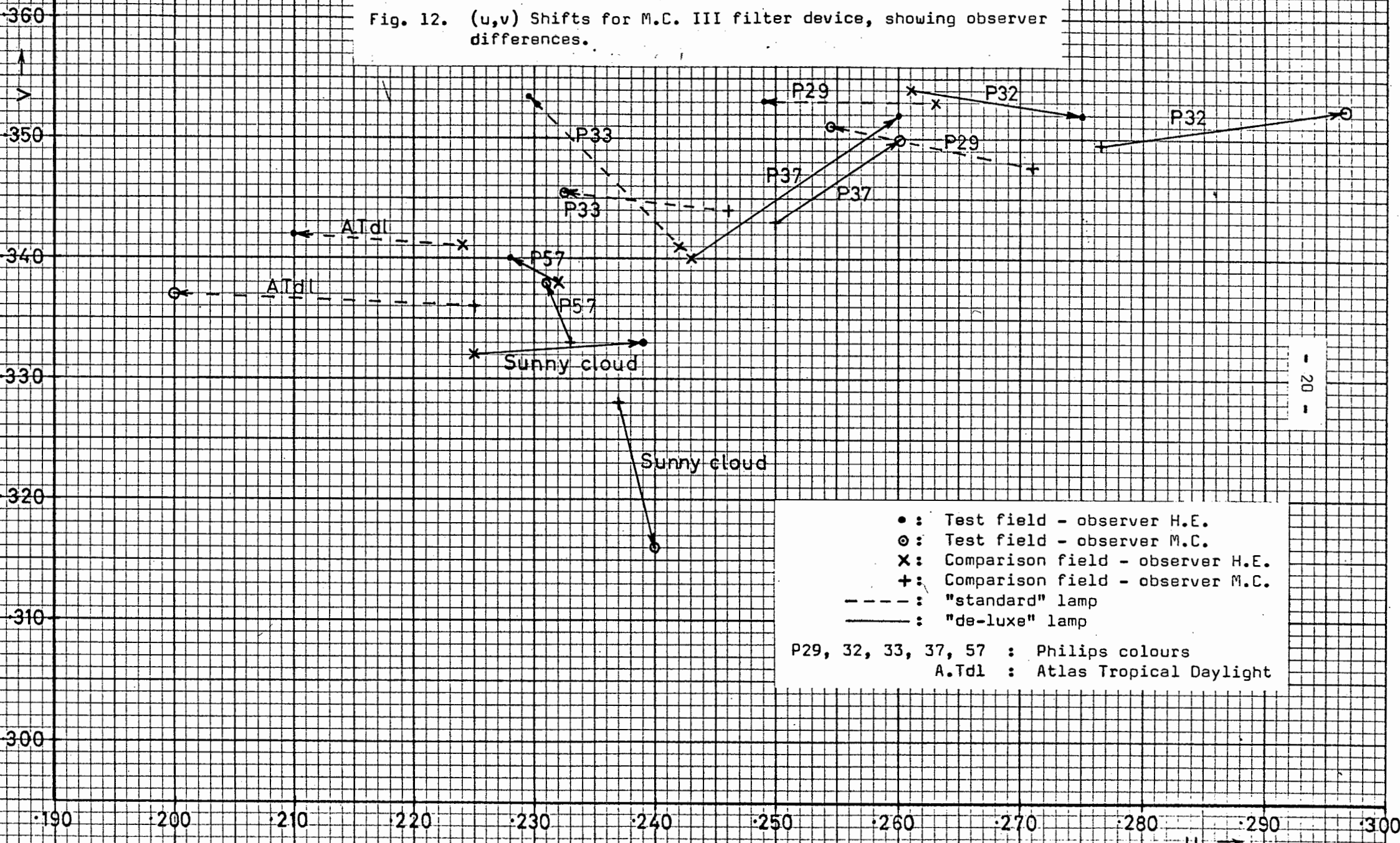


Fig. 12. (u,v) Shifts for M.C. III filter device, showing observer differences.



• : Test field - observer H.E.
 ○ : Test field - observer M.C.
 X : Comparison field - observer H.E.
 + : Comparison field - observer M.C.
 - - - : "standard" lamp
 ——— : "de-luxe" lamp
 P29, 32, 33, 37, 57 : Philips colours
 A.Tdl : Atlas Tropical Daylight

20

Fig. 13. (u,v) Shifts for M.C. II filter device, observer M.C.

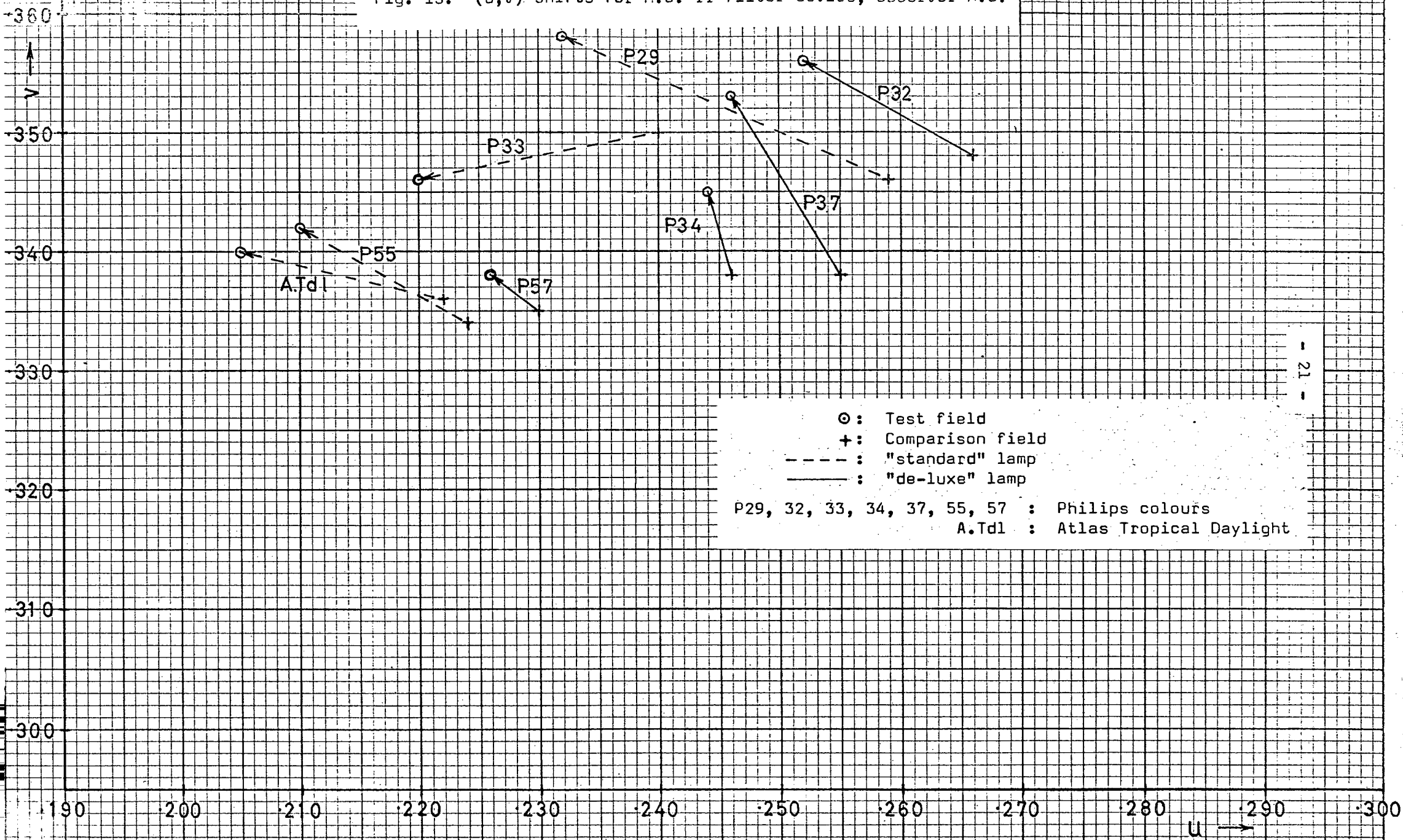


Fig. 14 (u,v) Shifts for Large Demonstration filter device, observer M.C.

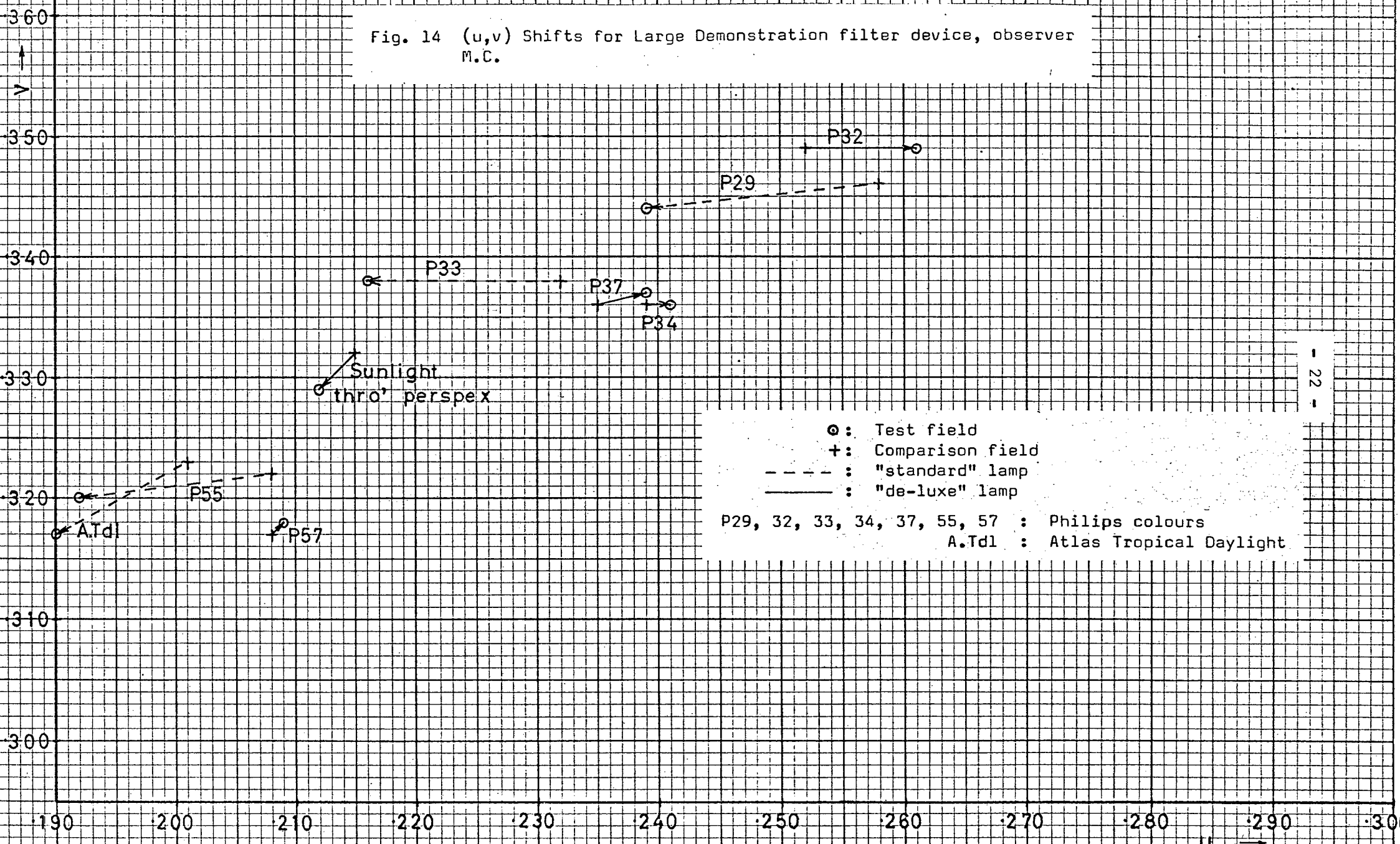
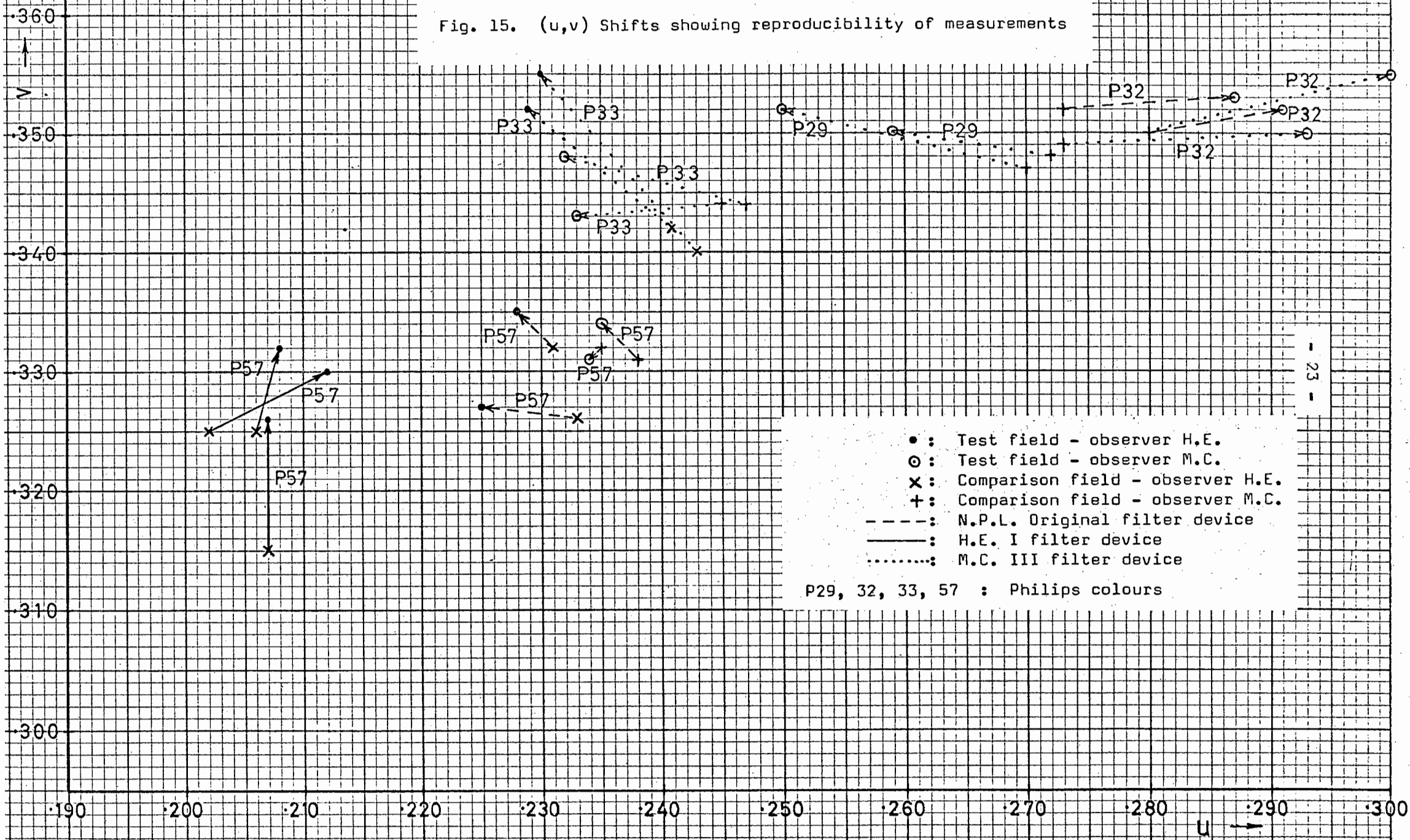


Fig. 15. (u,v) Shifts showing reproducibility of measurements



Note that the didymium glass in this filter instrument was of a different make from that used in the other filter devices.

The shifts plotted in Figs. 10 and 11 show that with device M.C. III both observers see, in relation to the comparison field, the test field pinkish on the P32, and the test field yellowish on the P37. An approximate match is obtained on a P57. Fig. 12 shows that observer M.C. again sees the test field of device M.C. III as purplish when looking at a sunny cloud. As the shifts on de-luxe and standard lamps are in opposite directions, one may identify lamps with this instrument according to the direction of shift.

In Fig. 13 it is seen that all lamps viewed through device M.C. II appear greenish to observer M.C. Note that this filter device was designed to be metameric on a sunny cloud (section 2.1). Its composition was such that it did not prove to be highly successful for lamp identification purposes.

The shifts of Fig. 14 show that the Large Demonstration device works effectively for observer M.C. for identification of lamps, near metamerism being obtained for de-luxe lamps and larger shifts seen for standard lamps.

Thus, some of these initial single-comparison filter instruments had the inherent disadvantage that their chromaticities on a source having ideal colour rendering properties, such as sunlight, appeared different for various normal observers. This visual problem had to be overcome before a filter device could be built which would work equally well for any observer.

3. "UNIVERSAL" SINGLE-COMPARISON FILTER DEVICES

3.1 Design

It was found that, after placing a yellow filter in front of the field containing the didymium glass (Part II), the two groups of observers were able to reach agreement as to what they saw when observing a sunlight spectrum. "Universal" (i.e. works for any observer) filter instruments were then built with a pale yellow filter across both the test and comparison fields. The Kodak No. 2E and No. 2A pale yellow filters were found to be suitable, as very strong colour filters such as the "Cinemoid" No. 1 Yellow changed the chromaticity of the instrument too drastically. The 2A has a cut-off at about 420 nm, while the 2E (slightly stronger) has a cut-off at about 430 nm. Pale blue colour filters were also placed in front of the test field to change the chromaticity of the didymium glass from a pink to a neutral grey when looking at a cloudy sky. The composition of these filter instruments was as follows:

UNIV. I:

Test Field : 1 x 5 mm thick Didymium glass (Schott BG 36)

1 x "Cinemoid" No. 17 Steel Blue stage colour filter

1 x Kodak No. 2A pale yellow filter

1 x Kodak No. 2E pale yellow filter

Comparison

Field: : 1 x "Cinemoid" No. 55 Chocolate Tint stage colour filter

1 x "Cinemoid" No. 3 Straw stage colour filter

1 x Kodak No. 96 0.2 neutral density filter

1 x Kodak No. 2E pale yellow filter

UNIV. II:

Test Field: 1 x 5 mm thick Didymium glass (Schott BG 36)
1 x "Cinabex" No. 17 Steel Blue stage colour filter
1 x Kodak No. 2E pale yellow filter

Comparison
Field: 1 x "Cinemoid" No. 55 Chocolate Tint stage colour filter
1 x "Cinemoid" No. 3 Straw stage colour filter
1 x Kodak No. 96 0.1 neutral density filter
1 x Kodak No. 2E pale yellow filter

A marked difference between some colour samples of the same number was observed, e.g. "Cinemoid" No. 17 Steel Blue looked slightly paler than "Cinabex" No. 17 Steel Blue. For this reason the trade names of the colour filters were recorded. These filter devices were constructed in holders as in Fig. 3.

The UNIV. I appeared almost metameric to observer H.E. on sunlight (see Records, section R5.2), but to observer M.C. the test field appeared slightly pinkish (Fig. 16). The UNIV. II was made to be metameric for observer M.C. on a grey sky, but the test field then appeared slightly greenish to observer H.E. (Fig. 17). It was not found possible, even by trying other combinations, to obtain a perfect match for both observers on a particular filter instrument. Note that the above observations represent shifts in the opposite direction (as may be seen by comparing Figs. 16 and 17) and thus a chromaticity correction for one observer leads to a larger shift for the other observer. A combination of filters could, however, be found which lead to a compromise between

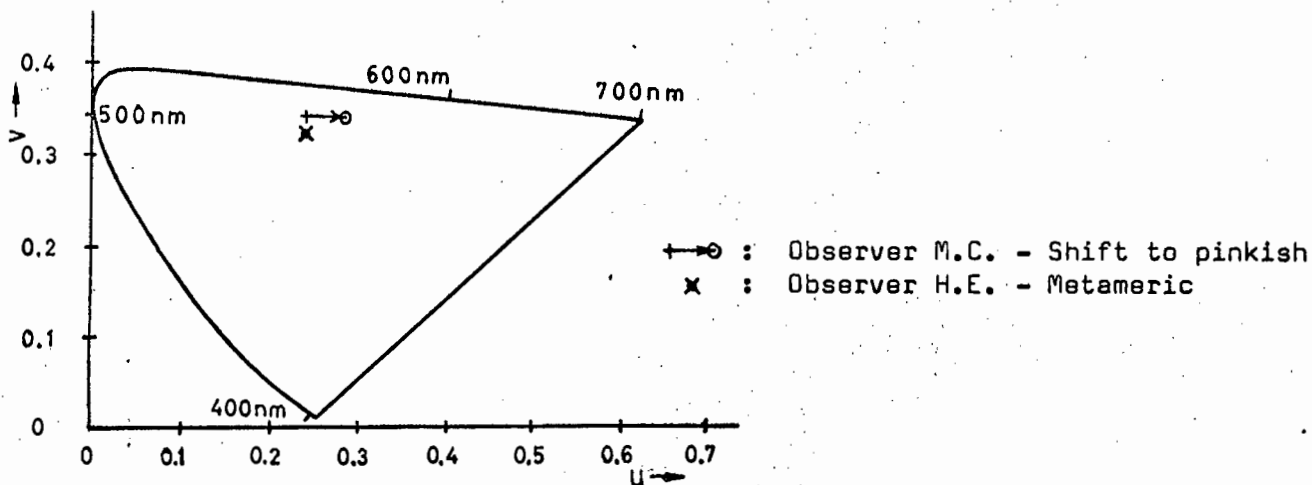


Fig. 16. Chromaticity shifts for UNIV. I device (designed for H.E.) on sunlight

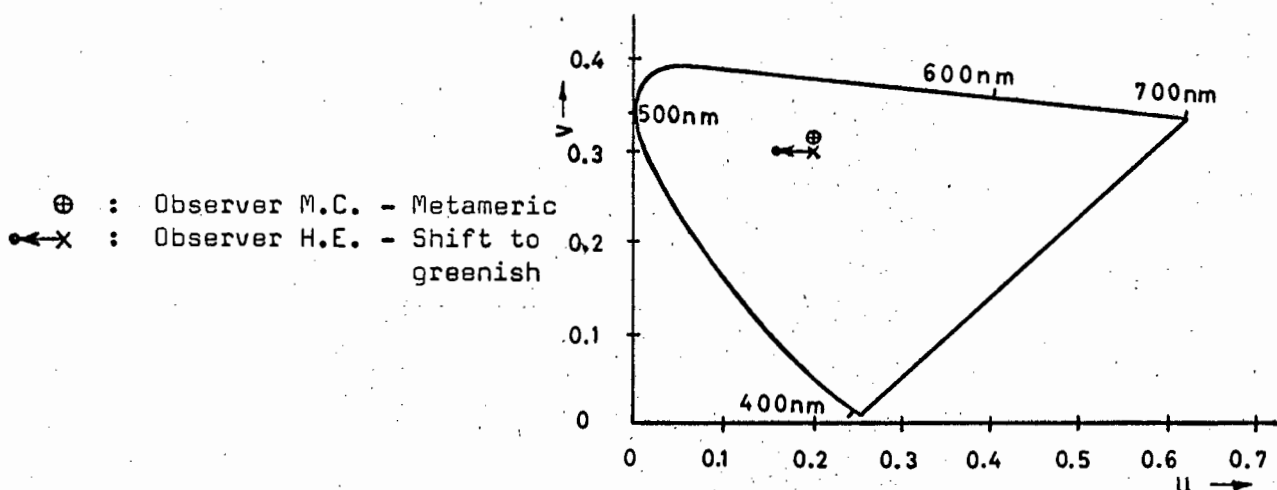


Fig. 17. Chromaticity shifts for UNIV. II device (designed for M.C.) on a grey sky

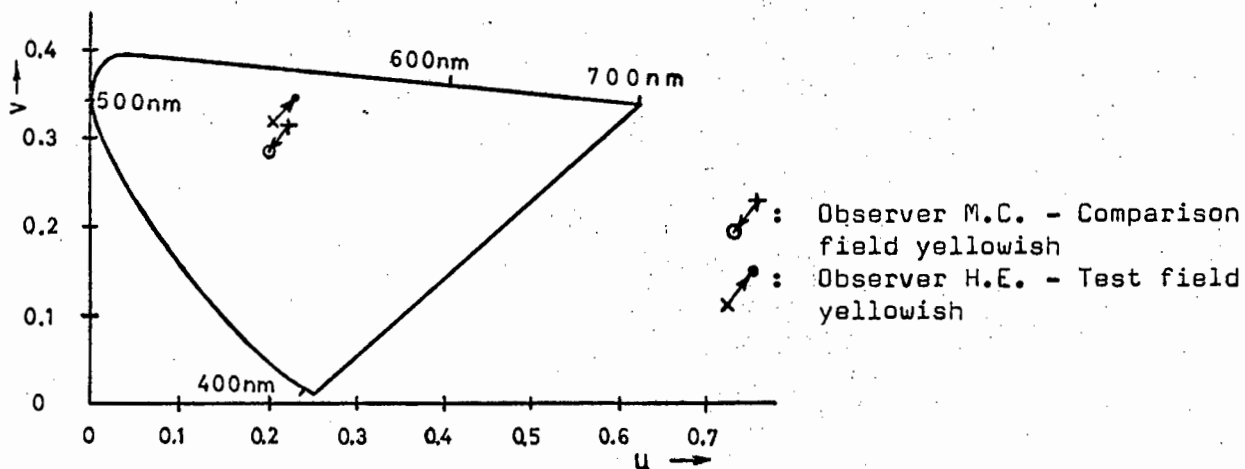


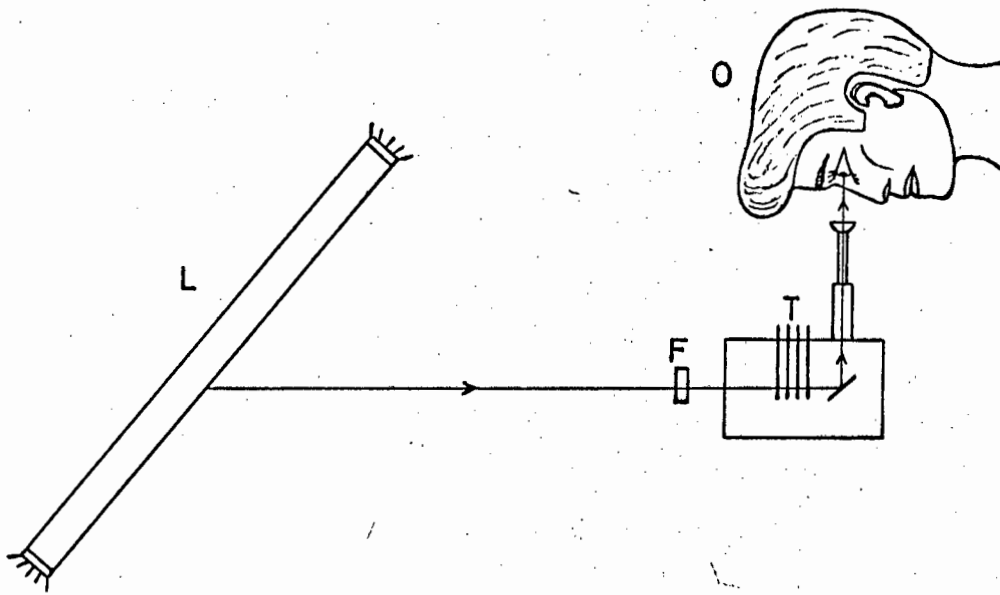
Fig. 18. Chromaticity shifts for a "compromise" device on a grey sky

the observers (combination (b), Records section R5.2). On a grey sky observer M.C. saw the comparison field yellowish, while observer H.E. saw the test field yellowish (Fig. 18). For example, from Fig. 16 it can be seen that metamerism would be obtained for observer M.C. only by a further greenish chromaticity shift of the test field. This would then lead to observer H.E. seeing the test field as greenish, as in Fig. 17. However, these "universal" filter devices did serve to bring the observations made by the two observer groups very much closer together.

3.2 Search for better colour filters

In order to obtain the comparison steps for a multi-comparison filter device (as in section 4), it was necessary to acquire a suitable gradation of colour filters which, in combination, would match the test field when observing the range of fluorescent lamps normally used in practice.

The first method employed was to view the lamps through a series of Tintometer filters (Fig. 19). The plastic box containing the Lovibond glass colour slides (as referred to in Appendix 4) and vertical viewing tube was taken out of its compartment and the C.I.E. Davis-Gibson light filter removed. The test field of the filter instrument (e.g. UNIV. II) was placed in the sample field, and its chromaticity when viewing a particular lamp matched against a combination of Tintometer glasses in the other field of view. The numbers of the glass colour slides were recorded for various filter instruments and different lamps (see Records, section R4.1). The range of lamps used included a warm white "standard"



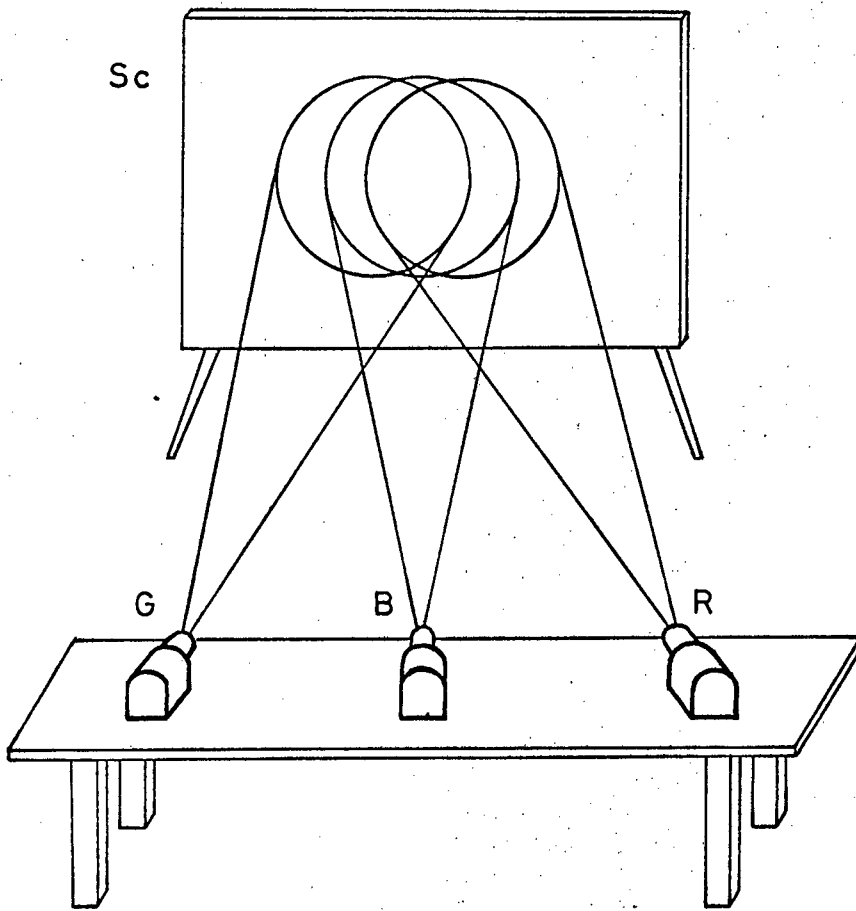
- L : Test lamp
- T : Tintometer colour filters
- F : Filter device in sample field
- O : Observer

Fig. 19. Modified use of Tintometer for obtaining suitable slides for filter device.

and "de-luxe" (P29 and P32), a cool white "standard" and "de-luxe" (P33 and P37), and a 6500K (daylight) "standard" and "de-luxe" (Atlas Tropical Daylight and P57).

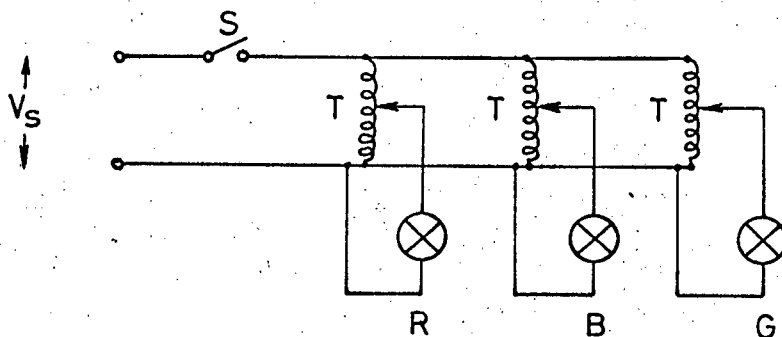
From these results a suitable range of red, yellow and blue Tintometer colour filters which would be required to build a multi-comparison filter device was determined. However, on obtaining a quotation for these glasses from the Tintometer Ltd., Salisbury, England, it was decided that it would be too costly to build a practical filter instrument with such glasses.

The second method employed was to photograph a mixture of coloured light from projector lamps in front of which red, green and blue colour filters had been placed. These three lamps, adjusted by means of variacs, were focussed onto a board with white paper pinned to it (Figs. 20 and 21). A number of hues of varying saturation and lightness were photographed. The individual components of red, green and blue on the centre and ends of the board were recorded by means of a portable illumination meter. This was necessary to be able to reproduce the particular colour at a later stage. This method was not entirely satisfactory as the colours were not reproduced very accurately on the colour film, probably because the daylight type colour reversal film had been used. Had film balanced for tungsten light been selected, the results obtained might have been better. The range of fluorescent lamps used in the first method were photographed both directly as well as through a piece of didymium glass. Again the results were not accurate reproductions of what one actually saw, but a few suitable colour slides were obtained. It was hoped to use these colour slides in the construction



- R : Red projector lamp
- G : Green projector lamp
- B : Blue projector lamp
- Sc : White screen

Fig. 20. Arrangement used in colour photographic method for obtaining suitable filters.



- V_S : 230V A.C. regulated supply
- T : Variacs
- S : switch
- R,G,B : red, green and blue projector lamps

Fig. 21. Circuit diagram used for adjustment of projector lamps

of filter instruments, but this method was abandoned.

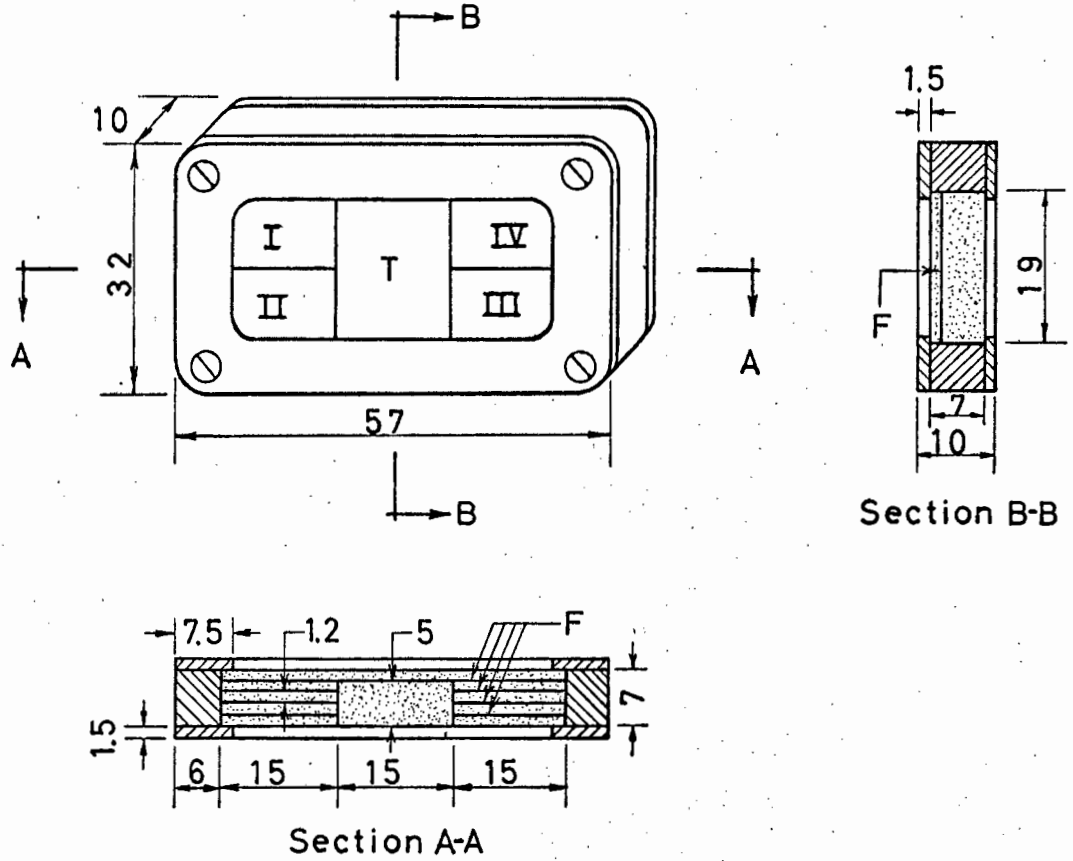
It was thus decided to use combinations of stage colour filters in the construction of a multi-comparison instrument. These stage colour filters were obtainable locally in large sheets at moderate cost. However, one is not able to get as small chromaticity changes as one could using the Tintometer glasses.

4. "UNIVERSAL" MULTI-COMPARISON FILTER DEVICES

4.1 Design

The multi-comparison filter instruments were constructed as in Fig. 22. Basically, these filter devices consisted of five filter combinations contained in a pocket-size holder. The device has a central section composed of didymium glass in combination with other stage colour filters (the test field), and four comparison filter combinations, two on either side of this central portion (the comparison fields). It was intended to construct these comparison fields so that one could classify a lamp in terms of its C.I.E. Colour Rendering Index, merely by judging nearest to which comparison field the test field appeared when viewing the lamp.

No. I comparison field was designed to match the test field when looking at a sunny cloud, and thus, it may be said, serves as the reference step. No. II comparison field was made to be metameric with the test field when observing a cool white lamp of high colour rendering index, such as the Philips Colour 37 (P37). Thus No. II field serves as a comparison step for "de-luxe" lamps. The No. III field was metameric with the test field on what may be called a "semi de-luxe" lamp such as the Westinghouse warm white or cool white de-luxe lamps, of poorer colour rendering properties than the lamps metameric on field No. II. No. IV comparison field was built to be metameric on a "standard" cool white or warm white lamp, with C.I.E. Colour Rendering Index of approximately 50.



- T : Test field
- I : Comparison field I
- II : Comparison field II
- III : Comparison field III
- IV : Comparison field IV
- : Glass
- F : Colour filters (placed between glasses)

All dimensions in millimetres

Fig. 22. Construction of "universal" multi-comparison filter device

The following approach was used in the design of the instrument. A series of fluorescent tubes was selected to include the warm white, cool white and 6500K ranges of lamps commonly used in practice. The lamps used were a Philips Colour 29 - warm white (P29), a Philips Colour 32 - warm white de-luxe (P32), a Westinghouse warm white de-luxe, a Philips Colour 33 - cool white (P33), a Philips Colour 37 - cool white de-luxe (P37), a Westinghouse cool white de-luxe, an Atlas Tropical Daylight (6500K) - abbreviated (A.Td1), and a Philips Colour 57 - daylight de-luxe (P57). In addition, an overcast sky and an incandescent lamp were used as reference sources in the daylight and 2800K regions respectively.

The principle of "universality" (see Part II) was applied by placing a pale yellow filter across the didymium glass. In addition a Steel Blue stage colour filter in combination with the didymium was used to change the pink hue of the didymium glass in the test field towards a neutral grey. The various comparison fields were obtained by matching the test field against a number of combinations of stage colour filters when observing a particular lamp. This involved many hours of trial and error during which a large number of different combinations of stage colour filters were tried for both observers M.C. and H.E. Eventually what was thought to be the optimum filter combinations for comparison fields I → IV were obtained.

4.2 Composition

The first "universal" multi-filter built, called UM. I, had the following composition:

UM. I

Test Field: 1 x 5 mm thick Didymium glass (Schott BG 36)
1 x "Cinabex" No. 17 Steel Blue stage colour filter
1 x Kodak No. 2E pale yellow filter
1 x 1.2 mm thick glass

Comparison
Field I: 1 x "Cinemoid" No. 3 Straw stage colour filter
1 x "Cinemoid" No. 55 Chocolate Tint stage colour filter
1 x Kodak No. 2A pale yellow filter
1 x Kodak No. 96 0.1 neutral density filter
4 x 1.2 mm thick glasses

Comparison
Field II: 1 x "Cinemoid" No. 38 Pale Green stage colour filter
1 x "Cinemoid" No. 53 Pale Salmon stage colour filter
1 x "Cinemoid" No. 55 Chocolate Tint stage colour filter
4 x 1.2 mm thick glasses

Comparison
Field III: 1 x "Cinemoid" No. 38 Pale Green stage colour filter
1 x "Cinabex" No. 52 Pale Gold stage colour filter
1 x "Cinemoid" No. 60 Pale Grey stage colour filter
4 x 1.2 mm thick glasses

Comparison
Field IV: 1 x "Cinemoid" No. 38 Pale Green stage colour filter
1 x "Cinemoid" No. 55 Chocolate Tint stage colour filter
1 x Kodak No. 96 0.1 neutral density filter
1 x Kodak No. 96 0.2 neutral density filter
4 x 1.2 mm thick glasses

A second and improved version of the above filter instrument was built using segments of large sheets of stage colour filters which were obtainable locally. This instrument was called UM. II and is the filter instrument at present in use. This has the following construction:

UM. II:

Test Field: 1 x 5 mm thick Didymium glass (Schott BG 36)
1 x "Cinemoid" No. 17 Steel Blue stage colour filter
1 x Kodak No. 2E pale yellow filter
1 x Kodak No. 96 0.1 neutral density filter
1 x 1.2 mm thick glass

Comparison
Field I: 2 x "Cinemoid" No. 3 Straw stage colour filters
1 x "Cinemoid" No. 60 Pale Grey stage colour filter
1 x Pink filter paper
5 x 1.2 mm thick glasses

Comparison
Field II: 1 x "Cinemoid" No. 38 Pale Green stage colour filter
1 x "Cinemoid" No. 52 Pale Gold stage colour filter
1 x "Cinemoid" No. 55 Chocolate Tint stage colour filter
1 x Kodak No. 2E pale yellow filter
2 x Pink filter papers
5 x 1.2 mm thick glasses

Comparison
Field III: 1 x "Cinemoid" No. 38 Pale Green stage colour filter
1 x "Cinemoid" No. 52 Pale Gold stage colour filter
1 x "Cinemoid" No. 60 Pale Grey stage colour filter
5 x 1.2 mm thick glasses

Comparison
Field IV: 1 x "Cinemoid" No. 38 Pale Green stage colour filter
1 x "Cinemoid" No. 55 Chocolate Tint stage colour filter
1 x Kodak No. 96 0.1 neutral density filter
1 x Kodak No. 96 0.2 neutral density filter
5 x 1.2 mm thick glasses

The results of observations on lamps by different observers are given in Records section R5.2. Good agreement was obtained between the results of observations by observers H.E. and M.C. The greatest discrepancy was as follows: with instrument UM. II, observer H.E. found the nearest match to the test field on sunlight to be between comparison fields Nos. I and II, but closer to I; observer M.C. obtained an identity with field No. I.

4.3 Determination of $\tau(\lambda)$ for test and comparison fields

In order to obtain the U.C.S. (u,v) co-ordinates for the fields on various lamps, and hence the vector shifts from the test field to the comparison fields, the transmission curves ($\tau(\lambda)$) for the fields were measured. The method is given in Appendix 3, and the results in Records section R2.1. $\tau(\lambda)$ was obtained not only for the particular field, but also for the individual colour filters comprising that field. This enabled checks to be made on the measurements of $\tau(\lambda)$ for the fields, which consisted of a number of colour filters, according to the relation

$$\tau(\lambda)_{1, 2, \dots, i} = \tau(\lambda)_1 \times \tau(\lambda)_2 \times \dots \times \tau(\lambda)_i \quad \dots\dots\dots (4.1)$$

where i is the number of filters in the field.

Measurement of $\tau(\lambda)$ for the fields was done at 10 nm intervals from 730 nm to 380 nm in all cases except that the didymium glass and the test field were measured at 5 nm intervals. This was done since $\tau(\lambda)$ for the didymium glass varies considerably over an interval of 10 nm in some regions of the spectrum.

In Figs. 23, 24, 25, 26 and 27 the values of $\tau(\lambda)$ as measured for the test and comparison fields have been plotted. From Fig. 23 may be seen how the pale yellow filter absorbs the peak in the transmission curve of the didymium glass below 425 nm, which is the essential requirement for "universal" operation of the device (described in detail in Part II). The resultant filter (test field) thus hardly transmits below 420 nm. The principal absorption region of the test field between 565 nm and 605 nm which removes the yellow boost in standard fluorescent lamps may also clearly be seen. Figs. 24, 25, 26 and 27 show that the transmission curves of the comparison fields are much smoother than that of the test field. Fig. 27 shows that the 0.1 and 0.2 neutral density filters were not perfectly neutral; they were however suitable for the purpose used. It may also be seen that the glass used in the device appeared slightly greenish, its transmission curve reaching a maximum at about 550 nm.

In order to convert the $\tau(\lambda)$ curve measured at 5 nm intervals for the test field to an equivalent weighted curve $\tau'(\lambda)$ at 10 nm spacing for computational purposes, the following formula was used:

$$\tau'(\lambda) = \frac{\tau(\lambda) + \frac{\tau(\lambda - 5) + \tau(\lambda + 5)}{2}}{2} \dots\dots\dots (4.2)$$

Fig. 23. "Universal" multi-comparison device II - test field.
Transmission curves of components and resultant.

- X·X·: "Cinemoid" No. 17 Steel Blue (Be)
- +·+·: Kodak No. 2E pale yellow (Yw)
- : Kodak No. 96 0.1 neutral density (0.1N)
- : 1 x 1.2 mm thick glass (Gs)
- : 1 x 5 mm thick Didymium glass - Schott BG 36 (Dm)
- : Resultant filter field (Rt)

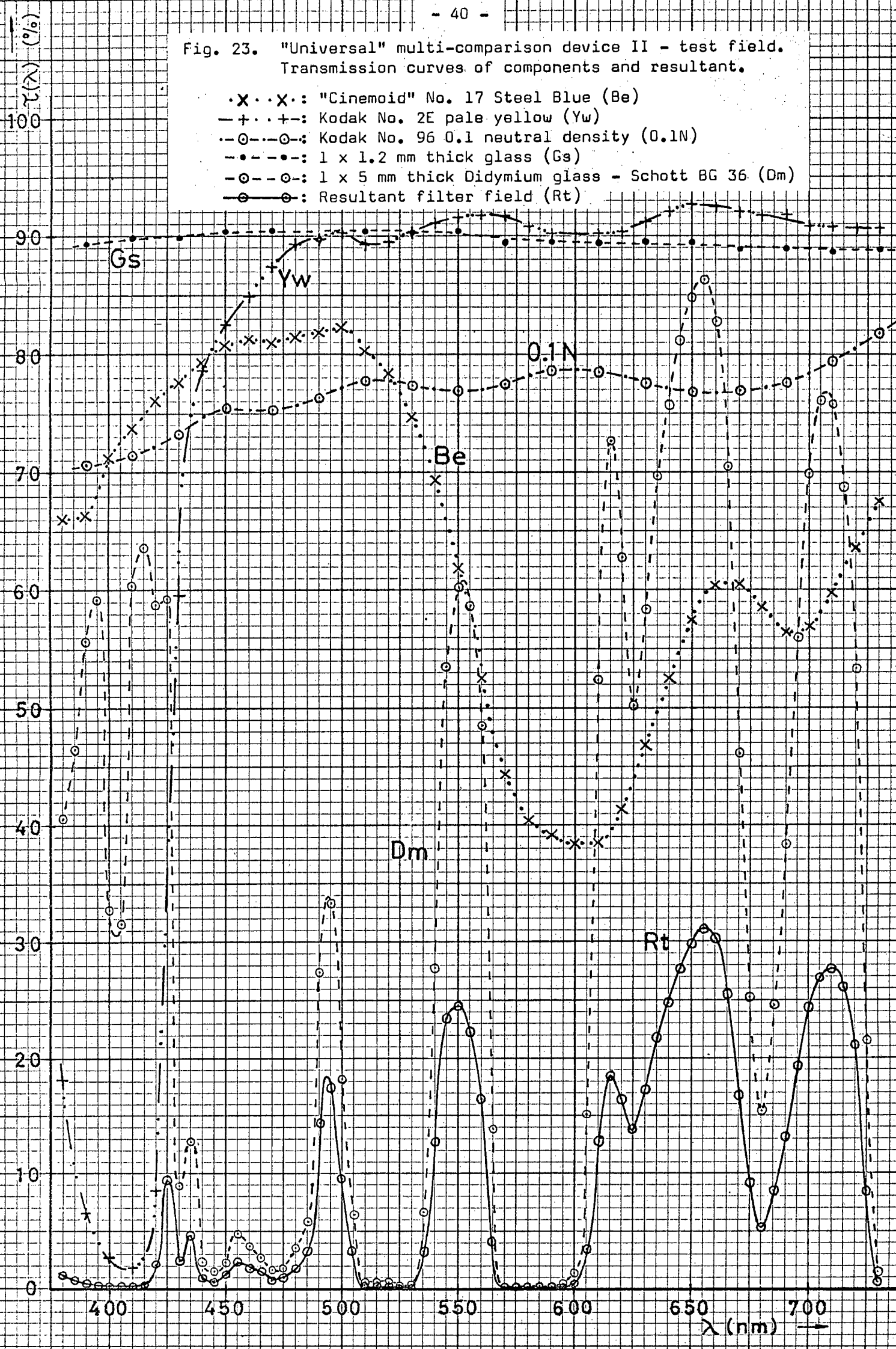


Fig. 24. "Universal" multi-comparison device II - comparison field I. Transmission curves of components and resultant.

- : "Cinemoid" No. 3 Straw - 2x in filter field (Sw)
- +•+•+•+: "Cinemoid" No. 60 Pale Grey (Gy)
- x-x-x-x-x: Pink filter paper (Pk)
- : 5 x 1.2 mm thick glasses (Gs)
- : Resultant filter field (Rt)

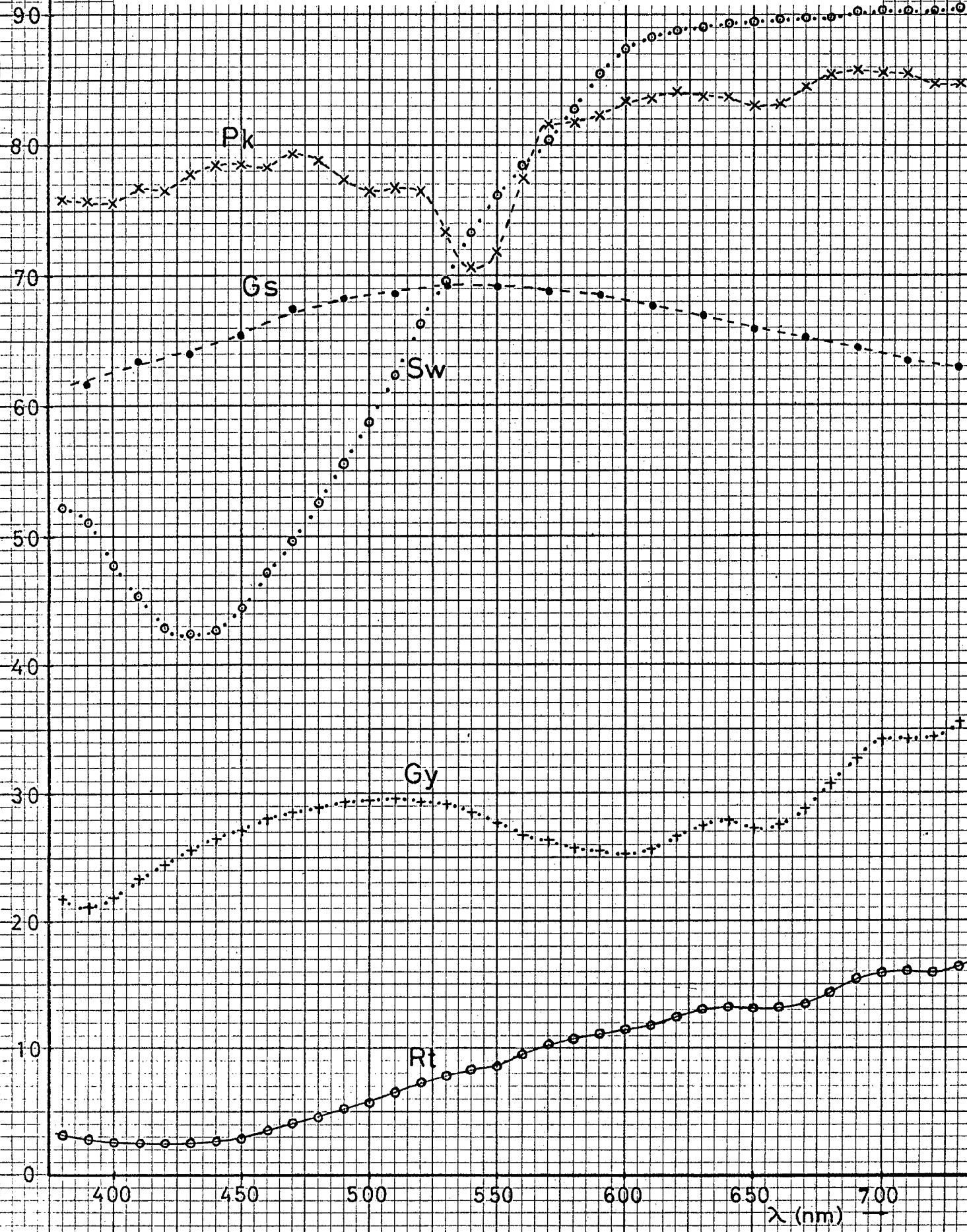


Fig. 25. "Universal" multi-comparison device II - comparison field II.
Transmission curves of components and resultant.

- +··+·: "Cinemoid" No. 38 Pale Green (Gn)
- ⊕··⊕·: "Cinemoid" No. 52 Pale Gold (Gd)
- ⊙--⊙-: "Cinemoid" No. 55 Chocolate Tint (Ch)
- +··+-: Kodak No. 2E pale yellow (Yw)
- x--x-: Pink filter paper - 2x in filter field (Pk)
- : 5 x 1.2 mm thick glasses (Gs)
- ⊙---⊙: Resultant filter field (Rt)

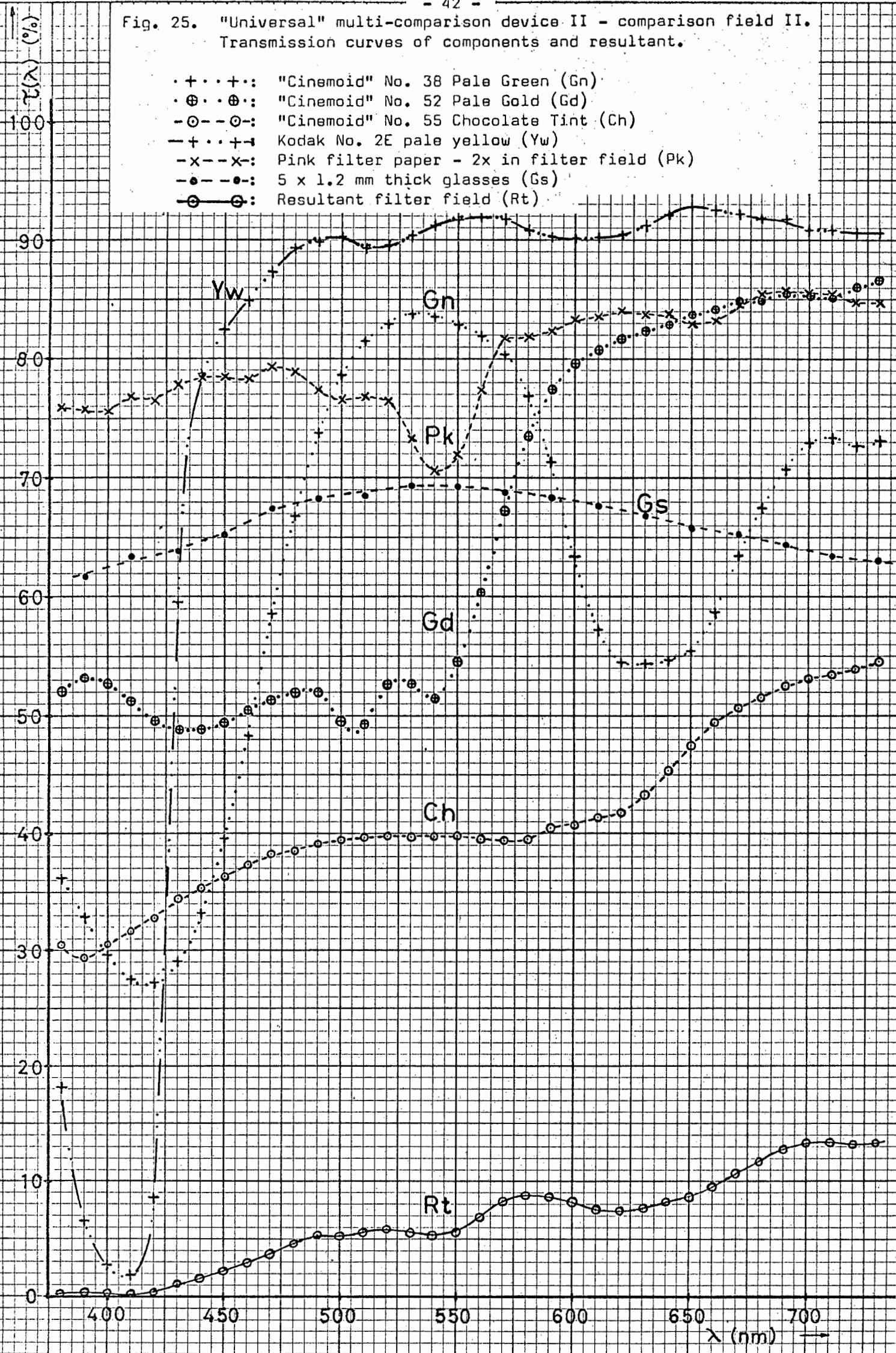


Fig. 26. "Universal" multi-comparison device II - comparison field III. Transmission curves of components and resultant.

- +··+·: "Cinemoid" No. 38 Pale Green (Gn)
- ⊕··⊕·: "Cinemoid" No. 52 Pale Gold (Gd)
- +---+ -: "Cinemoid" No. 60 Pale Grey (Gy)
- : 5 x 1.2 mm thick glasses (Gs)
- ⊖—⊖: Resultant filter field (Rt)

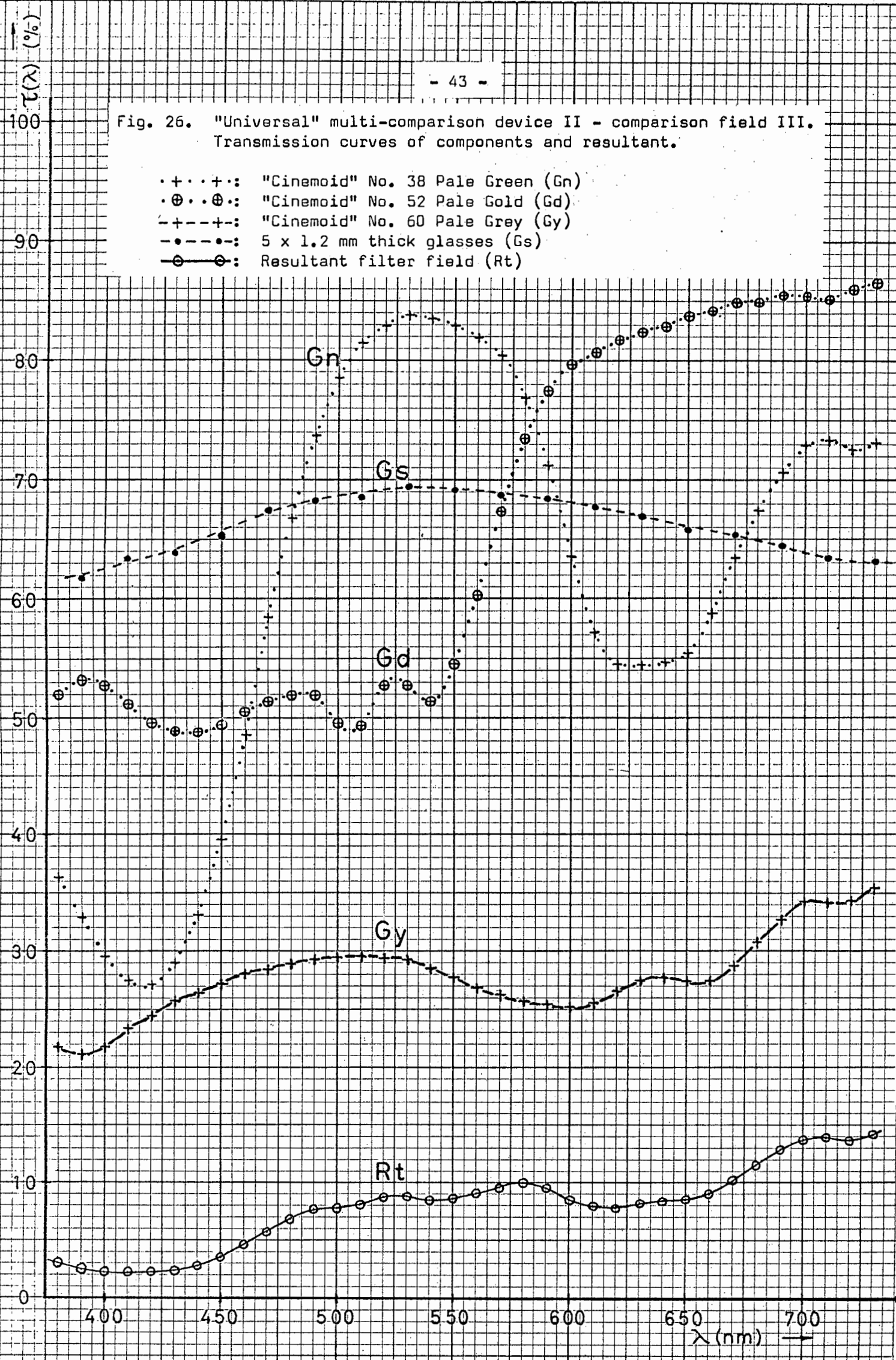
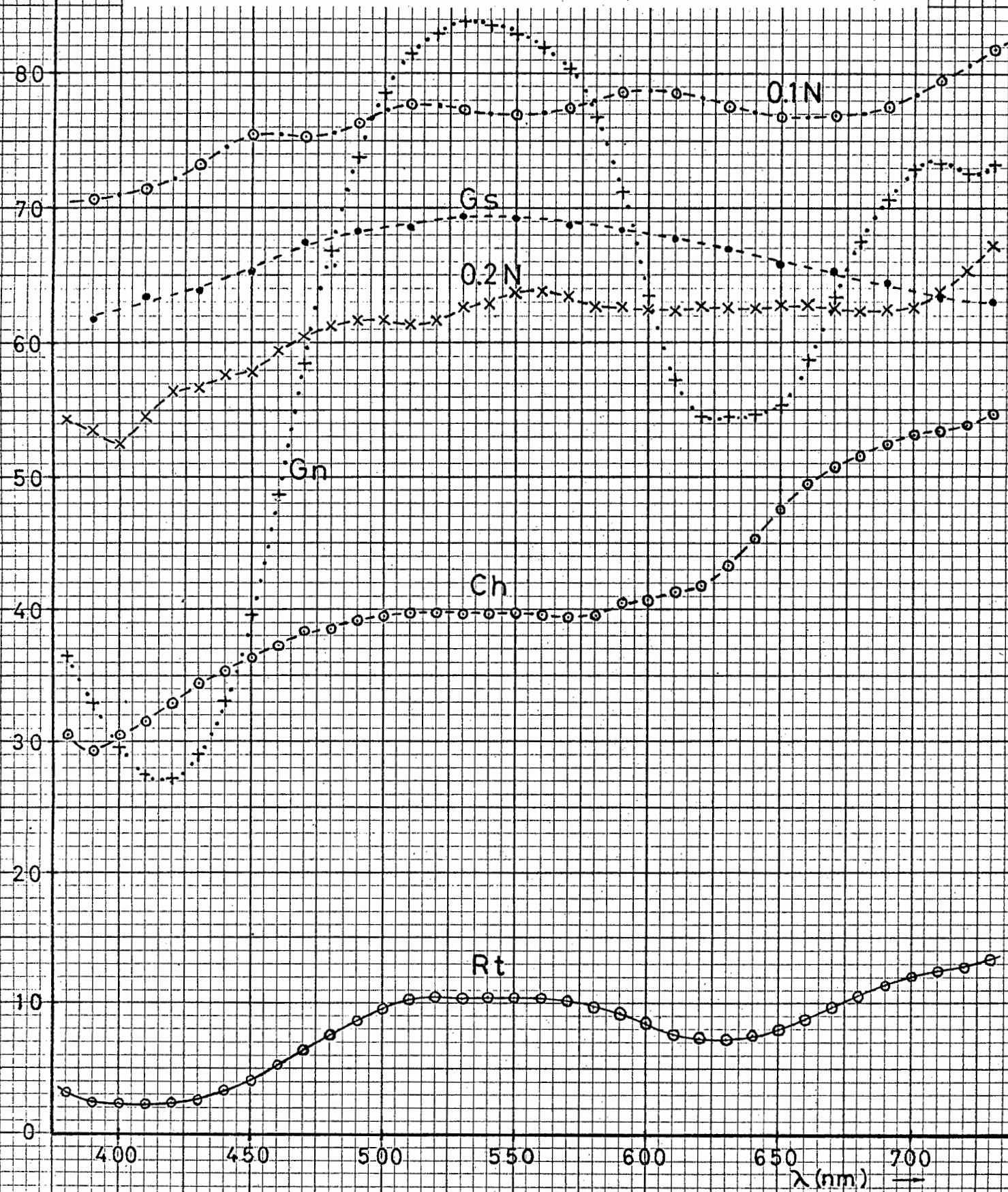


Fig. 27. "Universal" multi-comparison device II - comparison field IV. Transmission curves of components and resultant.

- +··+·: "Cinemoid" No. 38 Pale Green (Gn)
- : "Cinemoid" No. 55 Chocolate Tint (Ch)
- X-X-: Kodak No. 96 0.2 neutral density (0.2N)
- : Kodak No. 96 0.1 neutral density (0.1N)
- : 5 x 1.2 mm thick glasses (Gs)
- : Resultant filter field (Rt)



The calculation was made using an Olivetti Programma Desk Computer, substituting the measured values of $\tau(\lambda)$ at 5 nm intervals. To check the validity of this equivalent curve, the C.I.E. Chromaticity co-ordinates x , y and z were calculated for an equal-energy spectrum for both the 10 nm and 5 nm curves (see Records, section R6). The results were almost identical.

4.4 Determination of C.I.E. (u,v) U.C.S. co-ordinates for filter fields

While the C.I.E. (x,y) chromaticity diagram is useful for specifying colours, it has one serious disadvantage: it misrepresents colour differences, e.g. a certain distance in the blue region may mean a very appreciable colour difference, while the same distance in the green region may seem hardly noticeable. For this reason it was preferable to use the C.I.E. (u,v) U.C.S. ("Uniform Chromaticity Scale") diagram⁽⁷⁾ to represent the colour changes observed when viewing different lamps through the filter device.

The tristimulus values X , Y and Z were calculated for various test lamps (suffix K) and the five fields (index j) as:

$$\begin{aligned}
 X_{K,j} &= \int \bar{x}(\lambda) P_K(\lambda) \tau_j(\lambda) \\
 Y_{K,j} &= \int \bar{y}(\lambda) P_K(\lambda) \tau_j(\lambda) \dots\dots\dots (4.3) \\
 Z_{K,j} &= \int \bar{z}(\lambda) P_K(\lambda) \tau_j(\lambda)
 \end{aligned}$$

(All computations were made using the IBM 1130 digital computer, details of which are given in Appendix 2). The spectral tristimulus values $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ were obtained from published tables. The spectral power distributions of the test lamps $P_K(\lambda)$ were obtained from manufacturer's

data (or could have been measured), and the transmission factors of the fields $\tau_j(\lambda)$ were obtained by measurement as in Appendix 3.

The C.I.E. (u,v) co-ordinates for the fields on the test lamps were obtained by the transformation:

$$u_{K,j} = 4X_{K,j} / (X_{K,j} + 15Y_{K,j} + 3Z_{K,j}) \dots\dots\dots (4.4)$$

$$v_{K,j} = 6Y_{K,j} / (X_{K,j} + 15Y_{K,j} + 3Z_{K,j}) \dots\dots\dots (4.5)$$

and the (u,v) shifts from the test field to the various comparison fields (index i, where i = I, II, III and IV for excellent, good, fair and poor colour rendering) were calculated as:

$$\begin{aligned} |(u,v)_T - (u,v)_{C,i}| &= \{(u_T - u_{C,i})^2 + (v_T - v_{C,i})^2\}^{\frac{1}{2}} \dots\dots\dots (4.6) \\ &= \{(u_{K_{Didy}} - u_{K,j})^2 + (v_{K_{Didy}} - v_{K,j})^2\}^{\frac{1}{2}} \dots\dots\dots (A2.15) \end{aligned}$$

These calculations were repeated for observations on the reference illuminant (found in the Colour Rendering Index section of the programme) of approximately the same chromaticity as the test lamp. The printout of these computed values may be seen in the Records section R1.

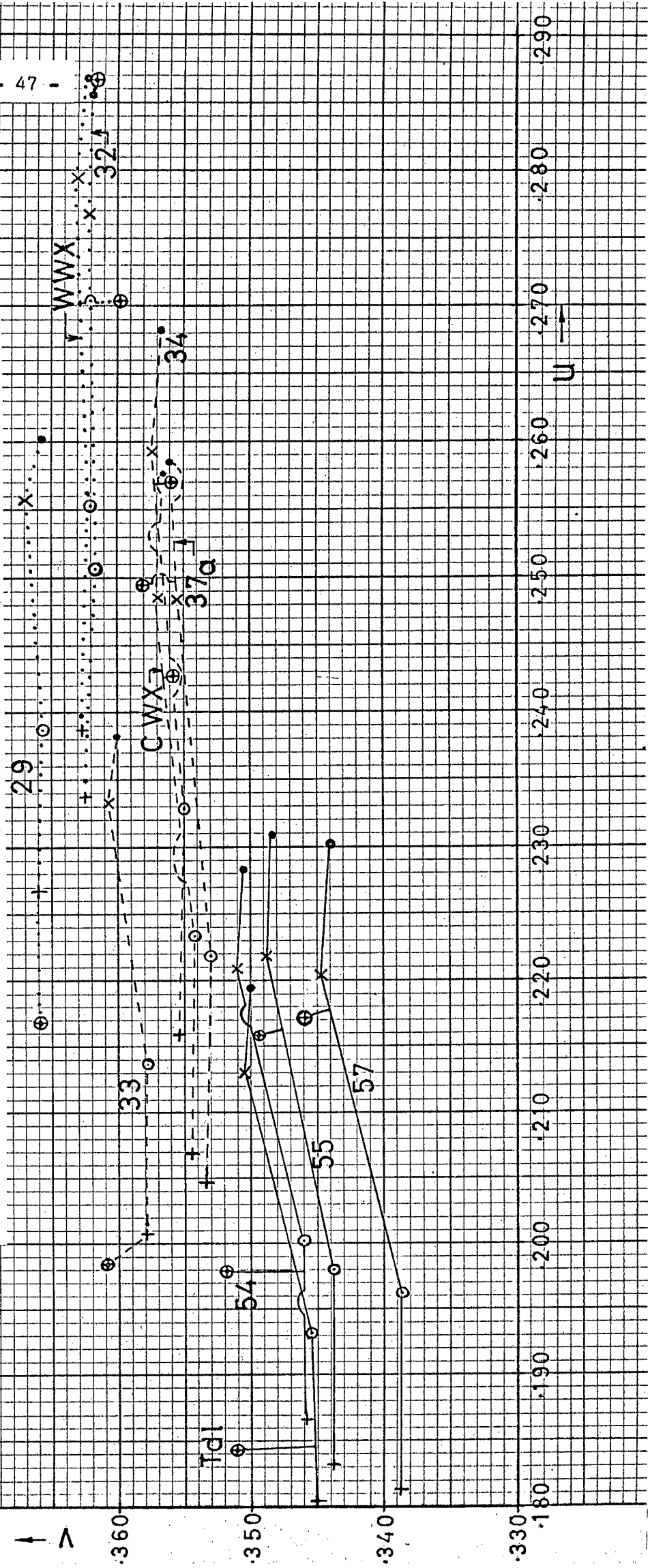
4.5 Correlation of chromaticities of test and comparison fields with the C.I.E. Colour Rendering Index

Using the computer programme as described in Appendix 2, the (u,v) co-ordinates of the test and comparison fields were obtained for observations on a number of warm white, cool white and daylight (6500K) lamps. In Fig. 28 the chromaticities of these filter fields have been plotted in a (u,v) diagram for some typical fluorescent lamps. This diagram shows that in general the shift in the v-direction from the test

Fig. 28. (u,v) Co-ordinates of test and comparison fields for "universal" multi-comparison device II on warm white, cool white and 6500K lamps.

- ⊕: Test field (didymium)
 - : Comparison field I
 - X: Comparison field II
 - ⊙: Comparison field III
 - +: Comparison field IV
 - : 6500K lamps
 - - -: Cool white lamps
 -: Warm white lamps
- 29, 32, 33, 34, 37, 54, 55, 57 : Philips colours
 WWX, CWX : General Electric warm white de-luxe and cool white de-luxe lamps
 Td1 : Atlas Tropical daylight

Comparison and test fields are linked together for a particular lamp.



field to the comparison fields is very small in comparison to the u-shift. Consequently, the shift in the u-direction alone was used in further evaluations, and the u-shifts were considered to give an adequate indication of the performance of the device. This simplification aided comprehension considerably.

Table II explains the appearances of the four comparison fields (F_i).

Table II. Comparison Fields

Comparison Field (F_i)		Match with test field indicates R_a of lamp to be:
i	Appearance	
I	Pink	Excellent
II	Pale Brown	Good
III	Grey	Fair
IV	Green	Poor

In Figs. 29, 30 and 31 the shifts in the u-direction from the test field to the various comparison fields ($u_T - u_{C,i}$) have been plotted against the C.I.E. General Colour Rendering Index. Figs. 29, 30 and 31 were plotted respectively for lamps of the warm white ($\pm 3000K$), cool white ($\pm 4200K$) and daylight ($\pm 6500K$) ranges. Note that above the zero line the test field looks pink compared with the comparison field, while below this line the test field looks green compared with the comparison field. Intersection with the zero line means a match between the test and comparison field. Fig. 29 clearly predicts that the instrument tends to

Fig. 29. u -Shifts (from test field to comparison fields) vs R_a for "universal" multi-comparison device II on warm white lamps.

- u_T : u co-ordinate of test field (didymium)
- $u_{C,i}$: u co-ordinate of comparison field ($i = I, II, III, IV$ for excellent, good, fair and poor colour rendering)
- : F_I : Comparison field I
- x-x- : F_{II} : Comparison field II
- : F_{III} : Comparison field III
- +·+· : F_{IV} : Comparison field IV
- 29, 32 : Philips colours
- WW, WWX : General Electric warm white and warm white de-luxe lamps
- K : Planckian Radiator (3050K)
- PK : Test field pink compared with comparison field
- GN : Test field green compared with comparison field

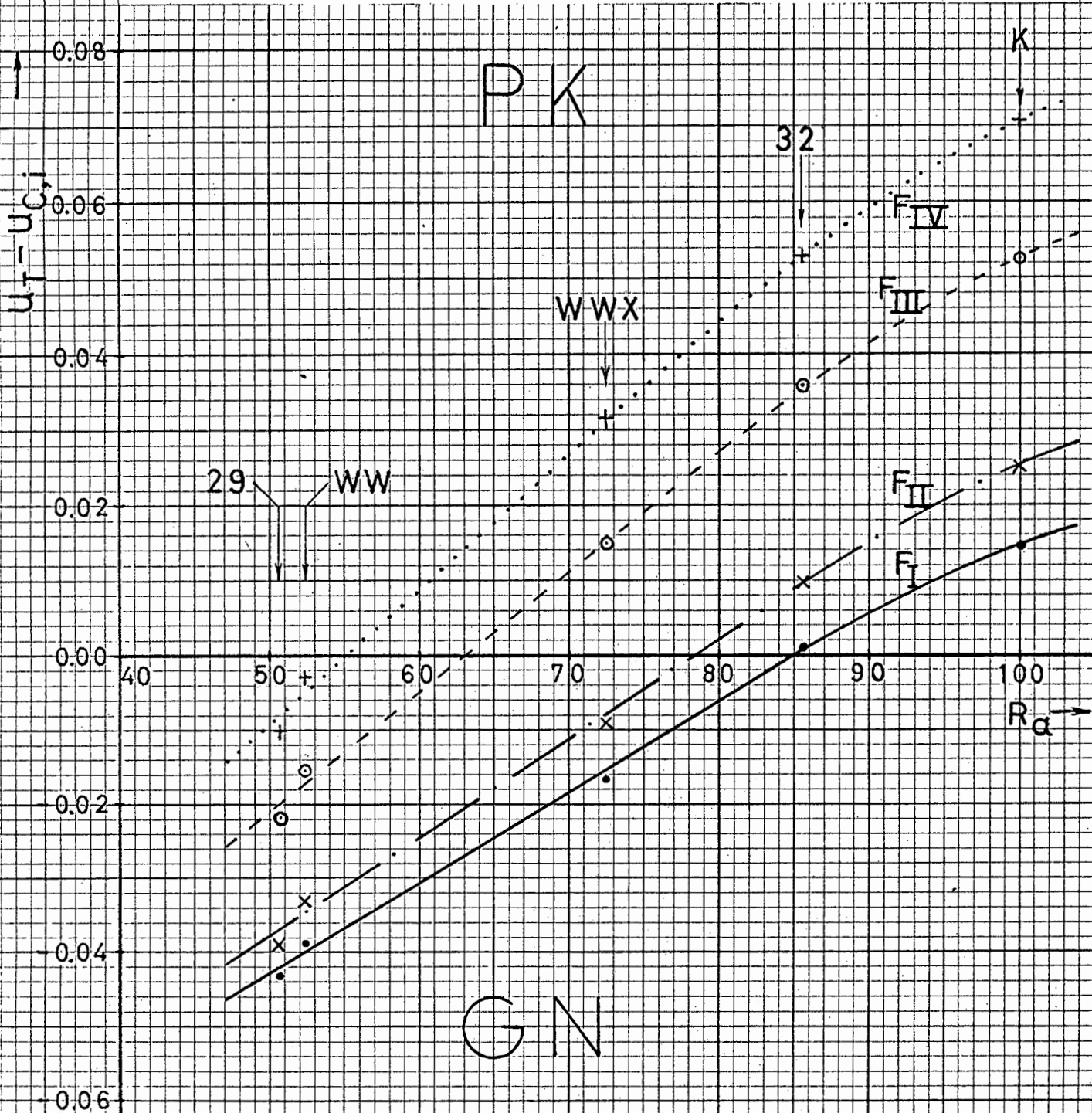


Fig. 30. u -Shifts (from test field to comparison fields) vs R_a for "universal" multi-comparison device II on cool white lamps.

- u_T : u co-ordinate of test field (didymium)
- $u_{C,i}$: u co-ordinate of comparison field ($i = I, II, III, IV$ for excellent, good, fair and poor colour rendering)
- $\text{---}\circ\text{---}$ F_I : Comparison field I
- $\text{---}\times\text{---}$ F_{II} : Comparison field II
- $\text{---}\circ\text{---}$ F_{III} : Comparison field III
- $\text{---}\cdot\text{---}$ F_{IV} : Comparison field IV
- 33, 34, 37 : Philips colours
- CW, CWX : General Electric cool white and cool white de-luxe lamps
- K : Planckian Radiator (4200K)
- PK : Test field pink compared with comparison field
- GN : Test field green compared with comparison field

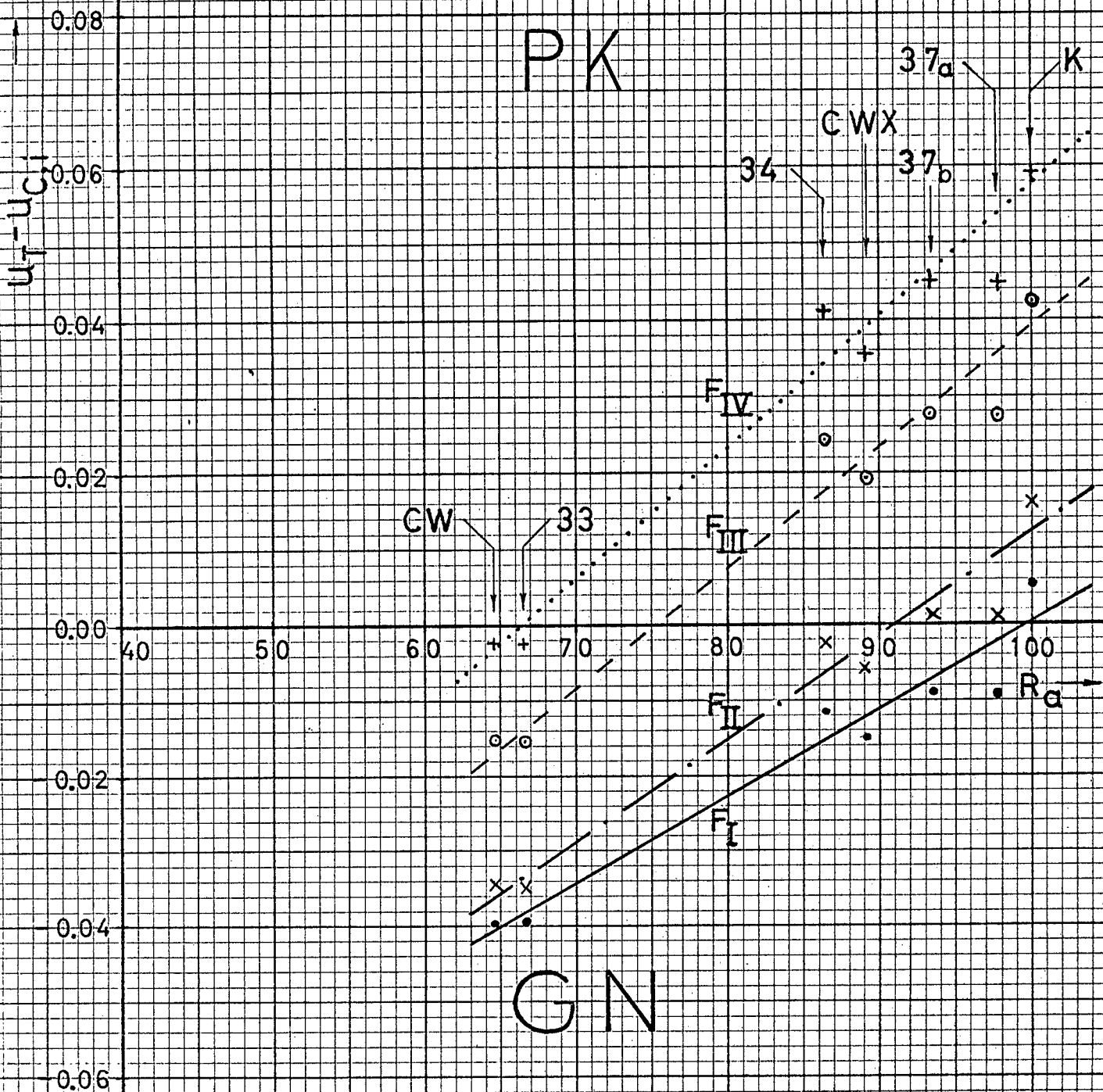
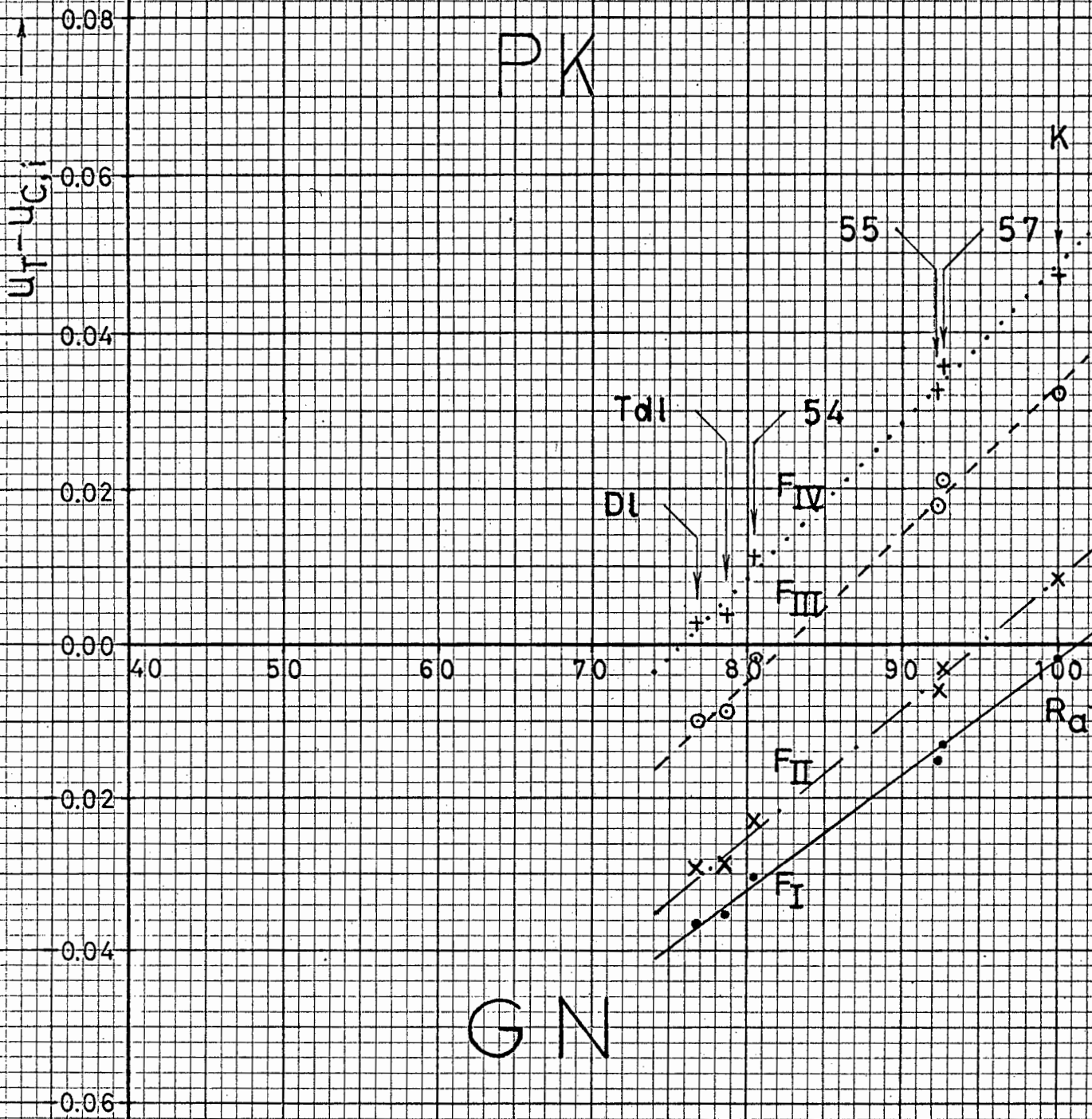


Fig. 31. u -Shifts (from test field to comparison fields) vs R_a for "universal" multi-comparison device II on 6500K lamps.

- u_T : u co-ordinate of test field (didymium)
- $u_{C,i}$: u co-ordinate of comparison field ($i = I, II, III, IV$ for excellent, good, fair and poor colour rendering)
- F_I : Comparison field I
- ×··× F_{II} : Comparison field II
- F_{III} : Comparison field III
- +···+· F_{IV} : Comparison field IV
- 54, 55, 57 : Philips colours
- Tdl : Atlas Tropical Daylight
- Dl : Thorington Daylight
- K : Planckian Radiator (6750K)
- PK : Test field pink compared with comparison field
- GN : Test field green compared with comparison field



assess warm white lamps leniently e.g. a de-luxe lamp such as the Philips Colour 32 is metameric ($u_T - u_{C,i} = 0.0$) on F_I and not F_{II} , whereas Figs. 30 and 31 show that cool white de-luxe and daylight de-luxe lamps are assessed more strictly being metameric on F_{II} . This dependency of the assessment on colour temperature of the lamps was observed during the initial stages of building these filter devices, and appears to be inherent in the properties of didymium glass. From Figs. 29, 30 and 31 metamerism ($u_T - u_{C,i} = 0.0$) with F_{IV} is predicted for a warm white lamp with $R_a \approx 55$, for a cool white lamp with $R_a \approx 65$ and for a 6500K lamp with $R_a \approx 75$ i.e. standard lamps designed for high efficacy. Similarly, approximate matches with the other comparison fields are predicted according to Table III.

Table III. R_a Calibration of UM. II filter device

Matching Field	Lamp Colour Temperature		
	2900K W.W.	4200K C.W.	6500K D.L.
F_I	85	100	100
F_{II}	75	90	95
F_{III}	65	75	85
F_{IV}	55	65	75

Thus F_I serves as a reference ($R_a = 100$) comparison field for all except the warm-white range where a match represents a de-luxe lamp, F_{II} represents the de-luxe comparison field, F_{III} the "semi" de-luxe comparison

field and F_{IV} the standard lamp comparison field.

The chromaticity change between each comparison field indicates as a rule a change of approximately 10 units of Colour Rendering Index.

Table III predicts an increase of about 10 units of index for a match on the same comparison field on a cool white compared with a warm white lamp. A varying increase exists between a 6500K lamp compared with a cool white lamp as shown in Table III.

The absolute values of the total (u,v) shifts from the test field to the comparison fields, $\left| (u,v)_T - (u,v)_{C,i} \right|$ (see equation 4.6), were plotted against R_a for warm white, cool white and 6500K lamps in Figs. 32, 33 and 34 respectively. These curves showed minima (i.e. test field looks closest to comparison field) at approximately the same values of R_a as tabulated in Table III.

From Figs. 30 and 33 it may be seen that the Philips Colour 34 lamp did not appear to lie precisely on the curves for any of the filter fields $F_I \rightarrow F_{IV}$, but slightly above them. This may be explained by the fact that the Colour 34 is of a lower colour temperature (3800K) compared with the other cool white lamps (\pm 4200K). The General Electric cool white de-luxe lamp appeared to have a higher R_a (89) than the Westinghouse cool white de-luxe lamp used for tests during the construction of the filter instrument. The G.E. cool white de-luxe matched on F_{II} , while the Westinghouse cool white de-luxe matched very well on F_{III} (Table III would thus predict the Westinghouse lamp to have an $R_a \approx 75$).

The u co-ordinates of the test and comparison fields were plotted against R_a in Figs. 35, 36 and 37 for observations on different lamps. These three graphs clearly show how the device operates. From Fig. 35

Fig. 32. (u,v) Shifts (from test field to comparison fields) vs R for "universal" multi-comparison device II on warm white lamps.

$(u,v)_T$: (u,v) co-ordinates of test field (didymium)

$(u,v)_{C,i}$: (u,v) co-ordinates of comparison field ($i = I, II, III, IV$ for excellent, good, fair and poor colour rendering)

$$\left| (u,v)_T - (u,v)_{C,i} \right| = \left[(u_T - u_{C,i})^2 + (v_T - v_{C,i})^2 \right]^{\frac{1}{2}}$$

..... equation (4.6)

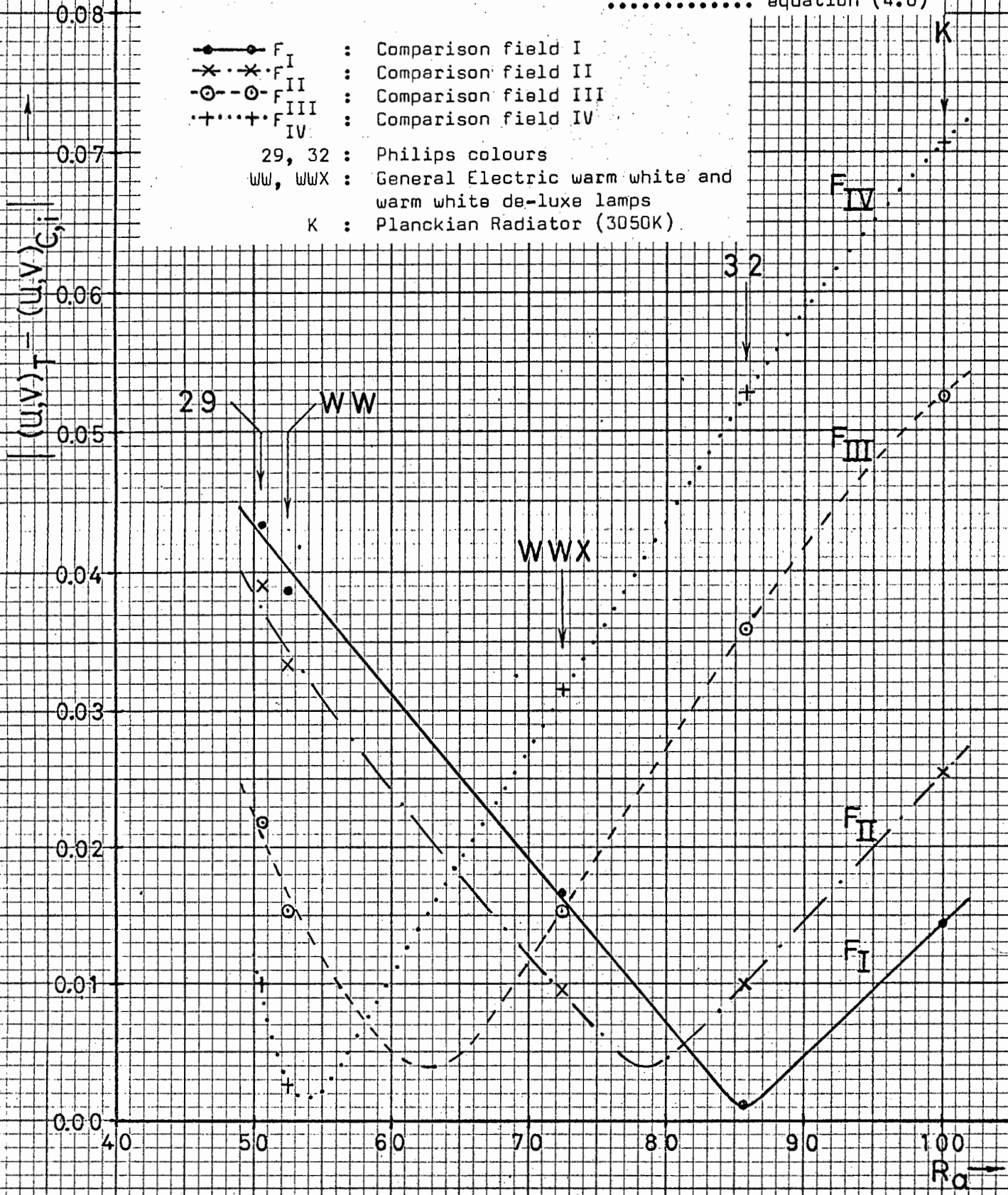


Fig. 33. (u,v) Shifts (from test field to comparison fields) vs R_a for "universal" multi-comparison device II on cool white^a lamps.

(u,v)_T : (u,v) co-ordinates of test field (didymium)
 (u,v)_{C,i} : (u,v) co-ordinates of comparison field (i = I, II, III, IV for excellent, good, fair and poor colour rendering)

$$\left| (u,v)_T - (u,v)_{C,i} \right| = \left[(u_T - u_{C,i})^2 + (v_T - v_{C,i})^2 \right]^{\frac{1}{2}}$$

..... equation (4.6)

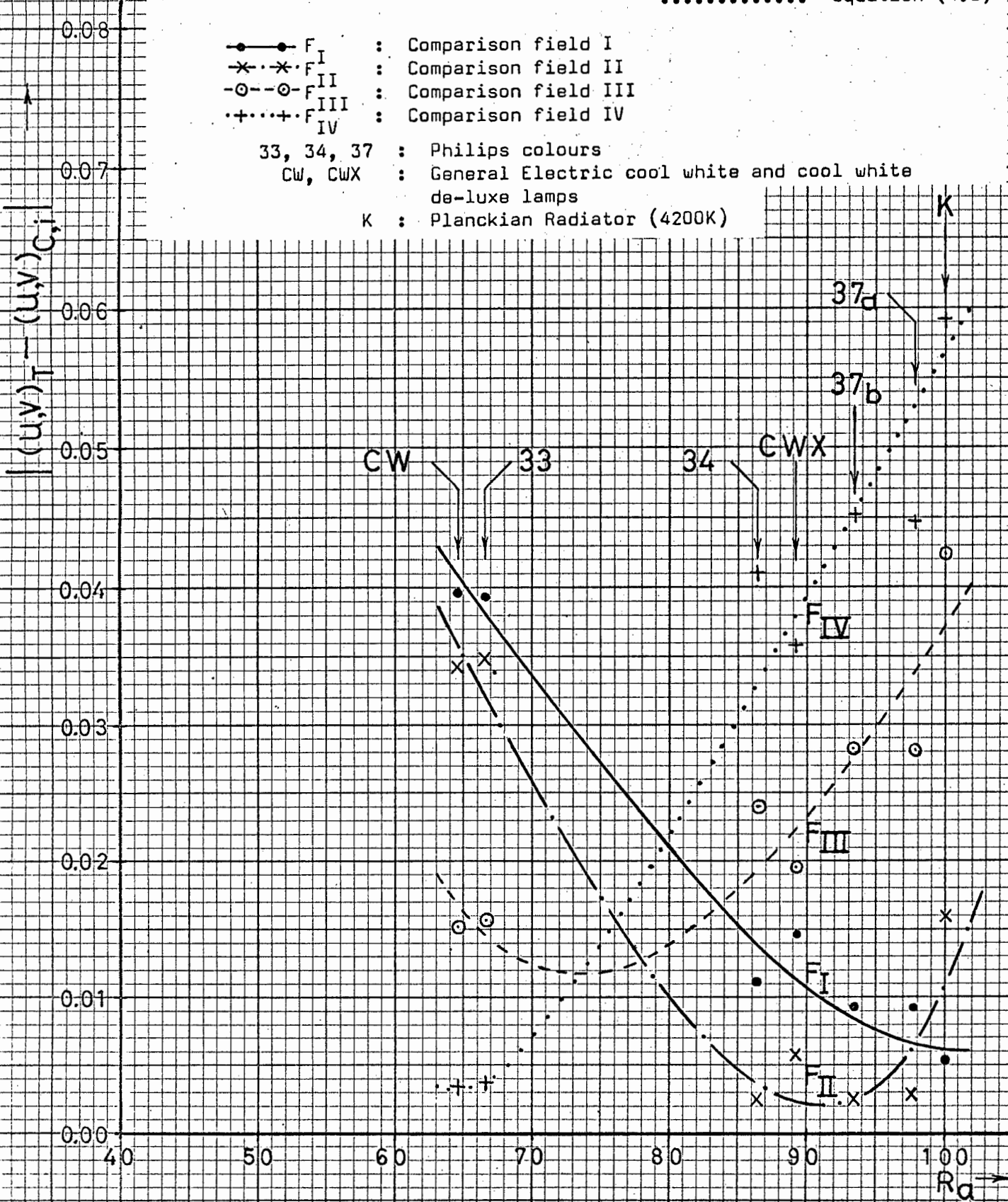


Fig. 34. (u,v) Shifts (from test field to comparison fields) vs R_a for "universal" multi-comparison device II on 6500K lamps.

$(u,v)_T$: (u,v) co-ordinates of test field (didymium)
 $(u,v)_{C,i}$: (u,v) co-ordinates of comparison field ($i =$ I, II, III, IV for excellent, good, fair and poor colour rendering)

$$\left| (u,v)_T - (u,v)_{C,i} \right| = \left[(u_T - u_{C,i})^2 + (v_T - v_{C,i})^2 \right]^{\frac{1}{2}}$$

..... equation (4.6)

- F I : Comparison field I
 - ×·×· F II : Comparison field II
 - F III : Comparison field III
 - +····+ F IV : Comparison field IV
- 54, 55, 57 : Philips colours
 Tdl : Atlas Tropical Daylight
 D1 : Therington Daylight
 K : Planckian radiator (6750K)

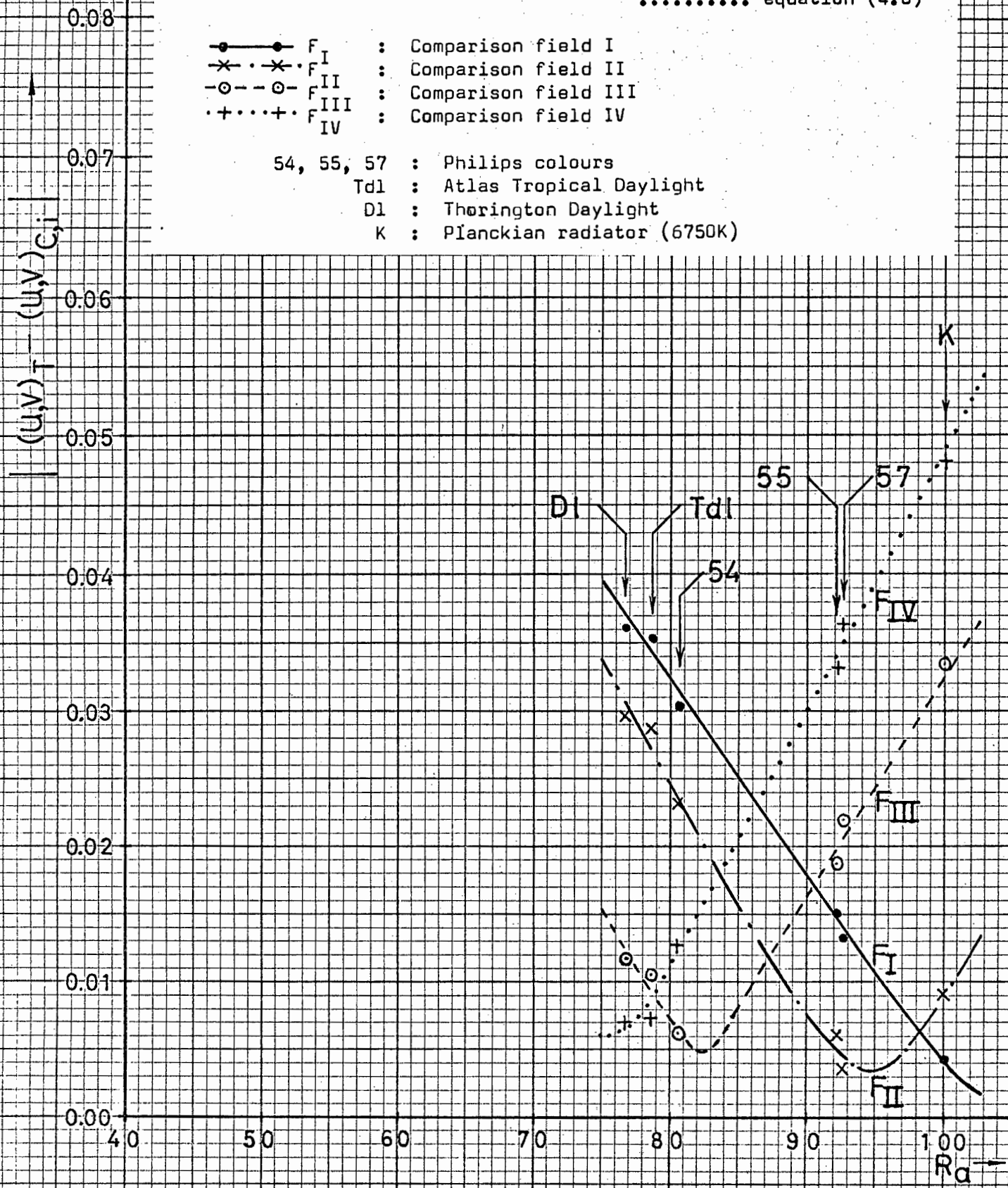


Fig. 35. u Co-ordinates of test and comparison fields vs R_a for "universal" multi-comparison device II on warm white lamps.

- u_T : u co-ordinates of test field (didymium)
- $u_{C,i}$: u co-ordinates of comparison field ($i = I, II, III, IV$ for excellent, good, fair and poor colour rendering)
- $-\oplus-\oplus-$ F_T : Test field
- $-\bullet-\bullet-$ F_I : Comparison field I
- $-\times-\times-$ F_{II} : Comparison field II
- $-\circ-\circ-$ F_{III} : Comparison field III
- $-\cdot-\cdot-$ F_{IV} : Comparison field IV
- 29, 32 : Philips colours
- WW, WWX : General Electric warm white and warm white de-luxe lamps
- K : Planckian Radiator (3050K)

Nearest correlated colour temperature of lamp recorded in brackets in K.

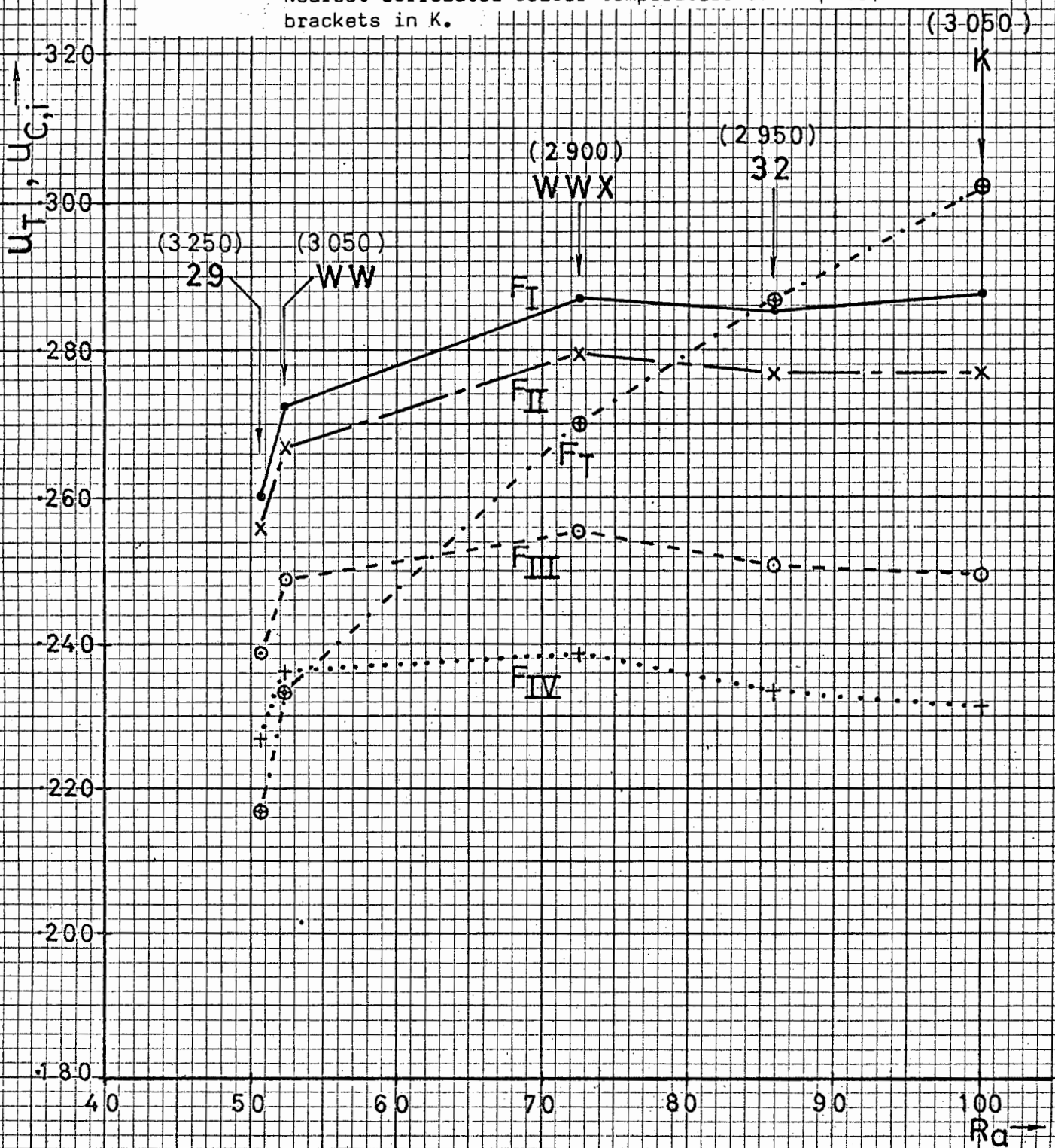


Fig. 36. u Co-ordinates of test and comparison fields vs R_a for "universal" multi-comparison device II on cool white lamps.

- u_T : u co-ordinate of test field (didymium)
- $u_{C,i}$: u co-ordinate of comparison field ($i = I, II, III, IV$ for excellent, good, fair and poor colour rendering)
- $\text{---}\oplus\text{---}\oplus\text{---}$ F_T : Test field
- $\text{---}\bullet\text{---}\bullet\text{---}$ F_I : Comparison field I
- $\text{---}\times\text{---}\times\text{---}$ F_{II} : Comparison field II
- $\text{---}\circ\text{---}\circ\text{---}$ F_{III} : Comparison field III
- $\text{---}\cdot\text{---}\cdot\text{---}$ F_{IV} : Comparison field IV
- 33, 34, 37 : Philips colours
- CW, CWX : General Electric cool white and cool white de-luxe lamps.
- K : Planckian Radiator (4200K)

Nearest correlated colour temperature of lamp recorded in brackets in K.

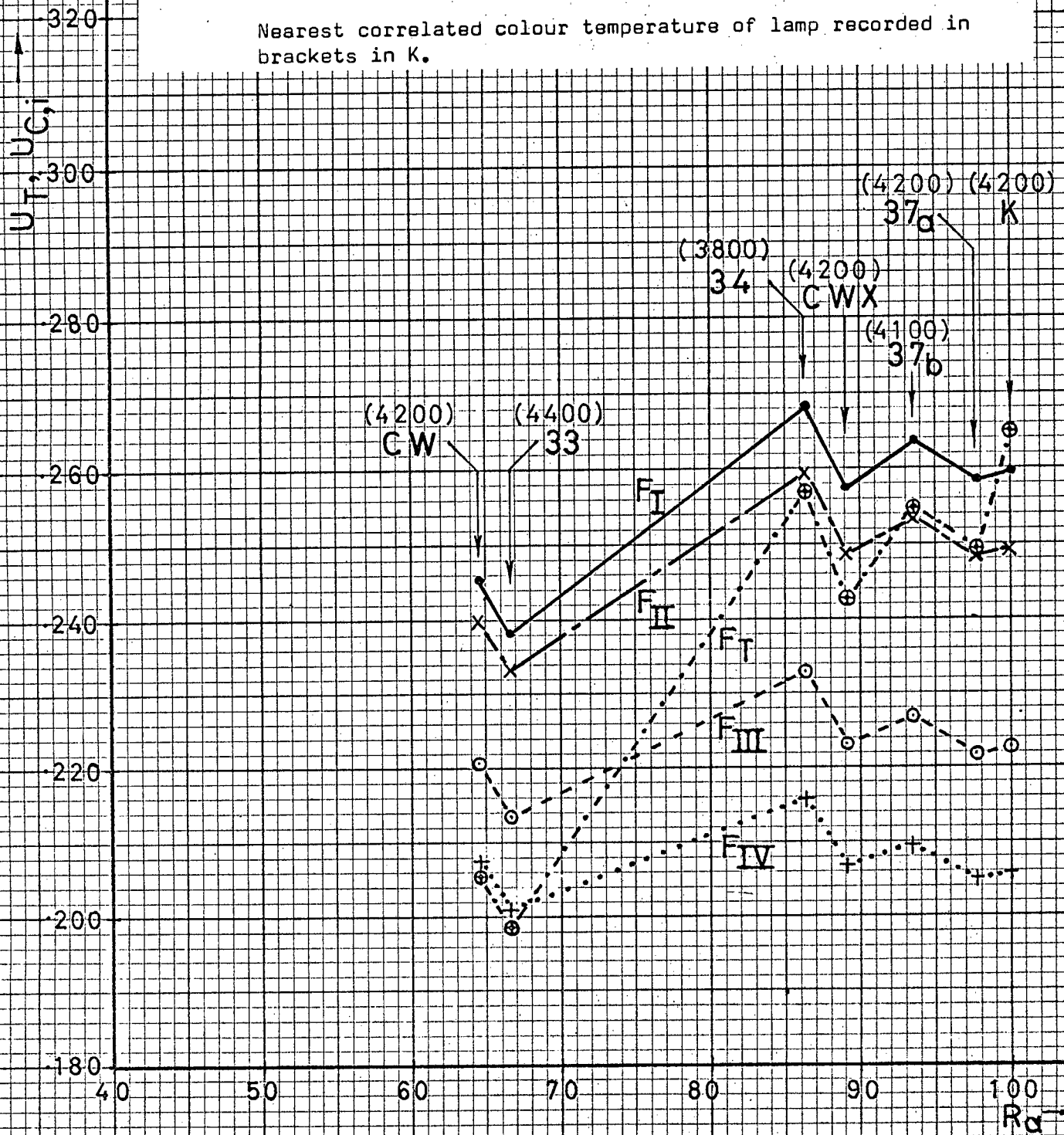
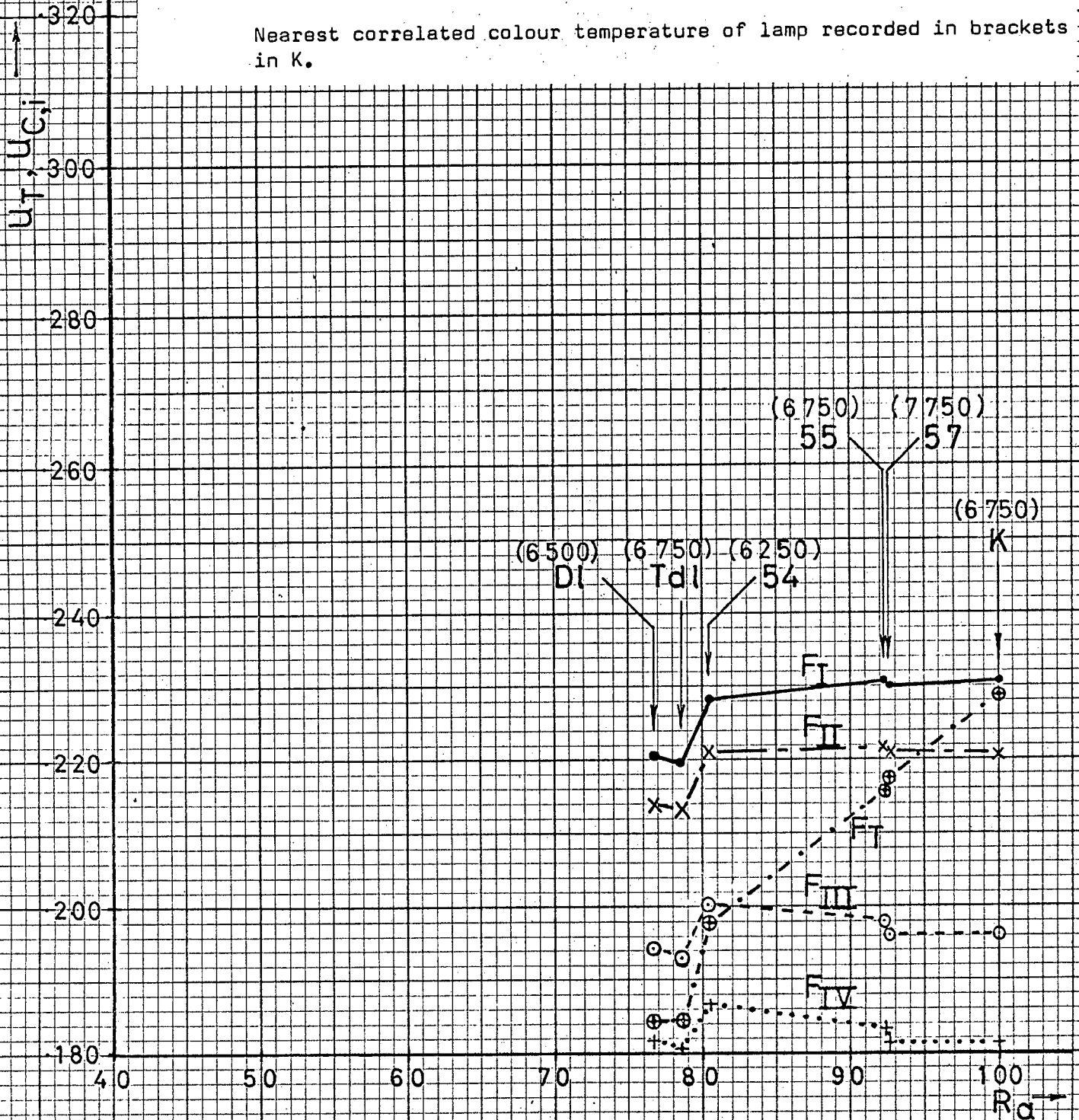


Fig. 37. u Co-ordinates of test and comparison fields vs R_a for "universal" multi-comparison device II on 6500K lamps.

- u_T : u co-ordinates of test field (didymium)
- $u_{C,i}$: u co-ordinates of comparison field ($i = I, II, III, IV$ for excellent, good, fair and poor colour rendering)
- $\text{---}\oplus\text{---}\oplus\text{---}$ F_T : Test field
- $\text{---}\bullet\text{---}\bullet\text{---}$ F_I : Comparison field I
- $\text{---}\times\text{---}\times\text{---}$ F_{II} : Comparison field II
- $\text{---}\circ\text{---}\circ\text{---}$ F_{III} : Comparison field III
- $\text{---}\oplus\text{---}\oplus\text{---}$ F_{IV} : Comparison field IV
- 54, 55, 57 : Philips colours
- D1 : Thorington Daylight
- Td1 : Atlas Tropical Daylight
- K : Planckian Radiator (6750K)

Nearest correlated colour temperature of lamp recorded in brackets in K.



can be seen that on the standard General Electric warm white (with a computed $R_a = 52.3$) the test field matches F_{IV} . Table III would predict $R_a \approx 55$. Similarly the same figure shows that the General Electric warm white de-luxe (which has $R_a = 72.5$) matches between F_{II} and F_{III} . Interpolation in Table III would give $R_a \approx 70$. Fig. 35 also shows that when the Philips Colour 32 (with $R_a = 85.9$) is observed through the device, the test field matches F_I . Table III indicates that the lamp should have an $R_a \approx 85$. The test field thus moves through the full range of comparison fields, matching on F_{IV} for standard warm white lamps and F_I for warm white de-luxe lamps. The device should therefore be able to predict values of R_a to within less than 5 units of index if Table III is used as a guide.

For metameric lamps, one would have expected nearly horizontal lines in Figs. 35, 36 and 37 for the comparison fields (F_I , F_{II} , F_{III} and F_{IV}) since their transmission curves are quite smooth (see Figs. 24, 25, 26 and 27). Variations in their u co-ordinates are due to differences in colour temperature of the lamps. In general, lower u co-ordinates are expected for lamps of higher colour temperature and vice versa. For example, in Fig. 35 the u-values of the comparison fields for the Philips Colour 29 (3250K) are lower than those for the General Electric warm white (3050K). The large variation of the test field with colour rendering index, however, is essential for the operation of the device.

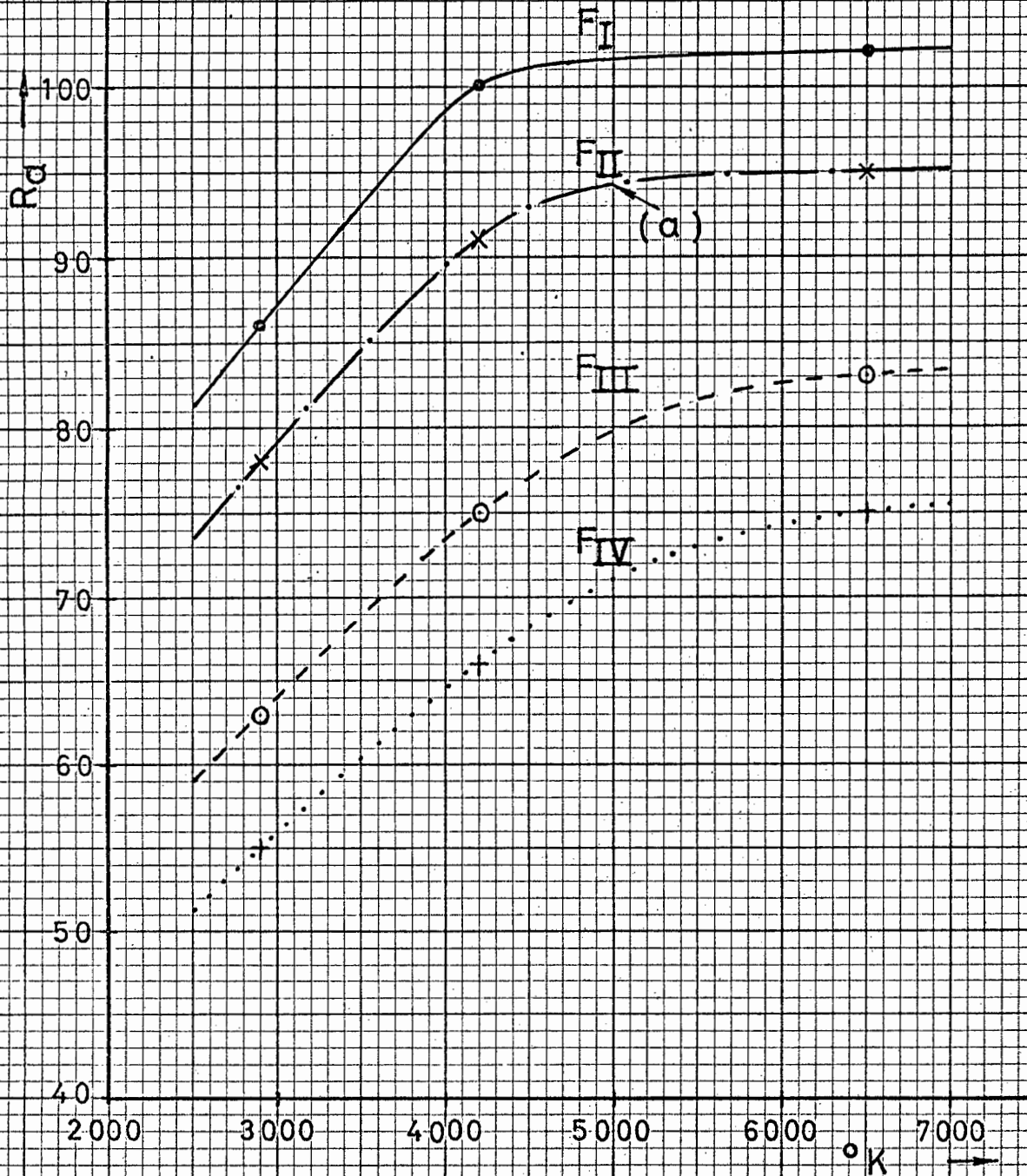
Figs. 36 and 37 show that for cool white de-luxe and 6500K de-luxe lamps, a match is obtained with F_{II} and not F_I as was the case for the warm white lamps which the instrument tends to assess more leniently. In both these diagrams the test field is again seen to move across the

range of u co-ordinates covered by the comparison fields, metamerism being obtained on F_{IV} for standard cool white or daylight lamps and on F_{II} for de-luxe lamps. F_{III} serves as a useful step between F_{II} and F_{IV} as may be seen, for example, in Fig. 37 where the Colour 54 ($R_a = 80.5$) matches almost on F_{III} , but slightly towards F_{IV} . An estimated value of R_a from Table III for a 6500K lamp matching almost on F_{III} would be just less than 85, which is again within less than 5 units of the calculated value of the index.

Ideally, an instrument would be desired where metamerism with a particular comparison field corresponds to a certain value of R_a irrespective of the colour temperature of the lamp tested. However, this ideal condition could not be realized with this simple filter device. In Fig. 38 the values of R_a for a match between the test field and a particular comparison field have been plotted against colour temperature for lamps of 2900K, 4200K and 6500K. These values of R_a were obtained from the points of intersection of the F_I , F_{II} , F_{III} and F_{IV} curves with the zero axis (u -shift = 0.0) in Figs. 29, 30 and 31. The R_a values thus obtained were in close agreement with those acquired from Figs. 32, 33 and 34 using the minima of the F_I , F_{II} , F_{III} and F_{IV} curves (least (u,v) shift). The curves of Fig. 38 enable an assessment of R_a to be made for lamps which have a colour temperature between or beyond the warm white, cool white and 6500K ranges. For example, the computer printout (Records section R1) for the Philips Colour 47 (5000K) shows that on this lamp the test field would match F_{II} to within 0.0028 (u,v) units. From Fig. 38, a lamp of 5000K matching F_{II} (point (a) in the diagram) has a Colour Rendering Index of 94. The calculated value from computer results was 96.1, which is very

Fig. 38. Calibration curve for "universal" multi-comparison device II : Colour rendering index (R_a) indication for a match between the test field and a particular comparison field vs colour temperature of lamp tested.

- F^I : Comparison field I
- x·-x· F^{II} : Comparison field II
- F^{III} : Comparison field III
- +····+· F^{IV} : Comparison field IV

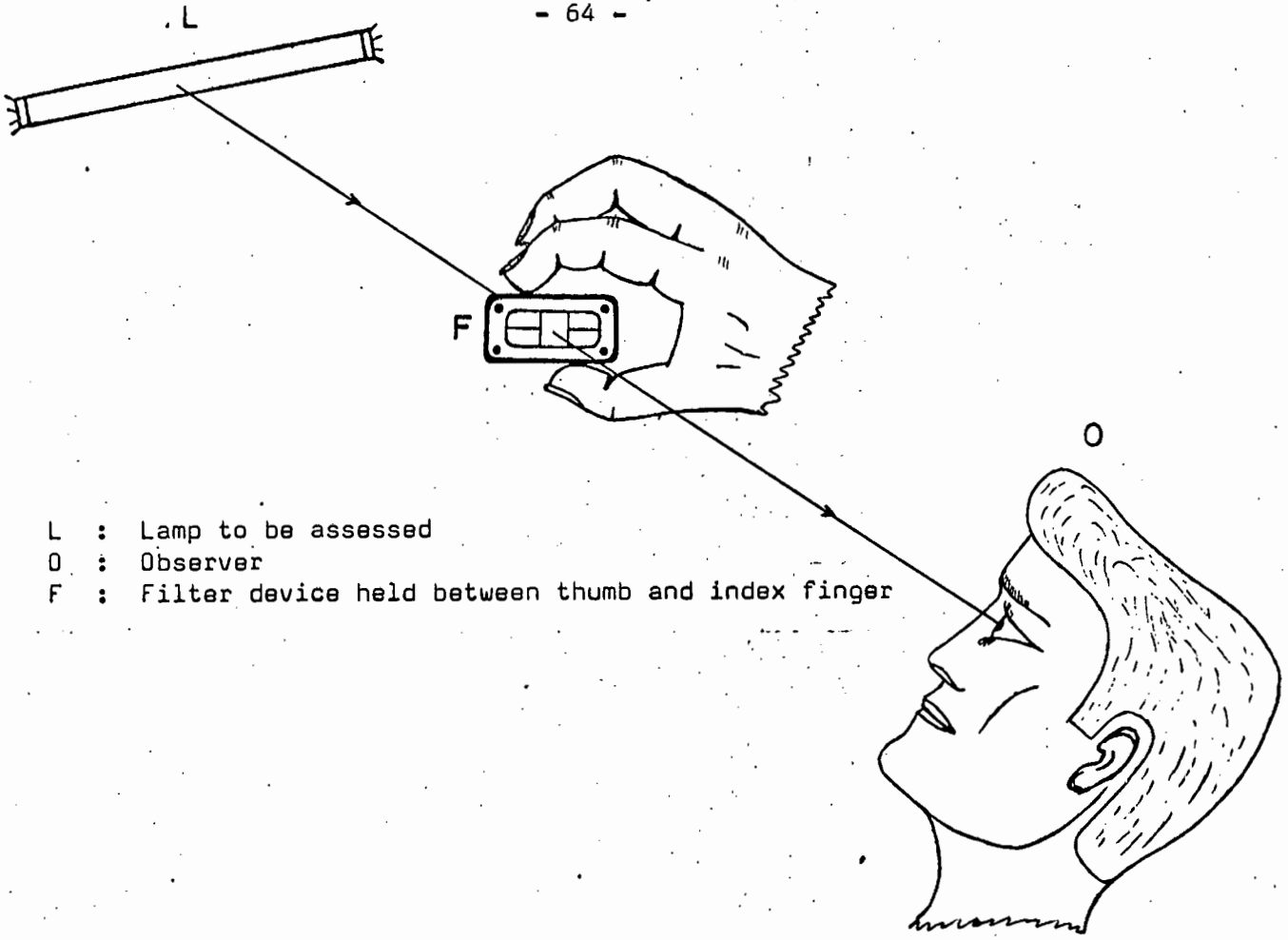


close to the assessment that could be made using the filter device. Table III represents rounded off values obtained from Fig. 38.

4.6 Method of use of multi-comparison filter instrument

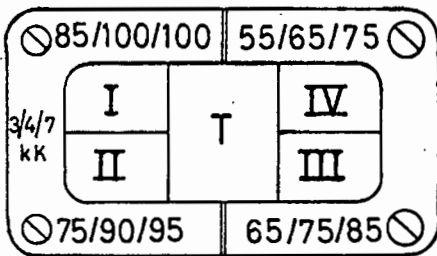
In order to determine the colour rendering properties of a particular lighting installation, one views the lamp(s) through the filter instrument as in Fig. 39, and assesses nearest to which comparison field the central (didymium) field of the instrument appears. Now the values of R_a recorded in Table III have been marked on the instrument next to the appropriate fields F_I to F_{IV} as in Fig. 40. By observing first whether the lamp falls in the warm white, cool white or 6500K range one is able to determine which of the three values of R_a marked next to this particular comparison field applies to lamp under observation. One may also judge a lamp to be metameric with the central field between any two of the comparison fields. In this case, taking R_a to lie between the two specified values would be justified. It is suggested that an observer could determine the colour rendering index of a lamp possibly to within 5 or 10 units of index (definitely to within <10 units). Moreover, an experienced observer need have no use of the tabulated values next to the comparison fields, but would simply underrate warm white lamps bearing in mind the approximate values suggested in Table III.

The adequacy of determining R_a to within 5 or 10 units is supported by recent research by Halstead, Palmer, Morley and Stainsby⁽⁸⁾ who found that one cannot detect less than 5 units in the colour rendering index easily. Thus both practical experience and the meaning of the index scale (viz. 4.6 units in the index, whether general or special, correspond



L : Lamp to be assessed
 O : Observer
 F : Filter device held between thumb and index finger

Fig. 39. Technique of observation for assessment of Colour Rendering Index of a lamp.



T : Test field
 I : Comparison field I
 II : Comparison field II
 III : Comparison field III
 IV : Comparison field IV

3/(or first number) : Colour temperature 2900 - 3200K
 4/(or second number) : Colour temperature 3900 - 4400K
 7 (or third number) : Colour temperature 6500 - 8000K

Numbers refer to values of R_a for warm white (3000K)/cool white (4200K)/6500K lamps respectively when the test field is meta-meric with the particular comparison field.

Fig. 40. Calibration of "universal" multi-comparison device II against R_a for warm white, cool white and 6500K lamps.

to 1 N.B.S. or C.I.E. unit of colour difference) indicate that differences in R_i of about five units will correspond to visually perceptible colour differences. A C.I.E. publication⁽⁹⁾ states that: "No such simple rule can be given for R_a . It is obtained as the average of eight R_i values, and even when two light sources have exactly the same R_a , differences of more than 5 units in one or more of the R_i 's may still be possible, so that their colour rendering properties will be different for the object colours in question".

This simple filter device was designed for assessing fluorescent lamps commonly used, and, for this limited but important application, it should be useful in practice. Further research, beyond the scope of this thesis, would be required for extension of its application to other discharge lamps.

4.7 Summary and recommendations

A portable visual pocket device has been developed for an approximate determination of the C.I.E. Colour Rendering Index for the range of fluorescent lamps commonly used in practice. No claim is made for high accuracy or for application to other discharge lamps which have not been investigated.

Further research work might show whether extension of the application of the filter device to other sources apart from fluorescent lamps would be warranted.

An improvement on this device would be one designed to assess all lamps equally, irrespective of their colour temperature. Whether this refinement could be made with the existing filter device is somewhat doubtful.

PART II

VISION INVESTIGATION

5. DIFFERENCES AMONGST OBSERVERS WITH NORMAL COLOUR VISION

5.1 Two groups of normal observers

From observations made during the construction of the initial single-comparison filter devices (section 2.2), there appeared to be two distinct groups of observers having normal colour vision - those who saw as observer M.C. (called Group I) and those who saw as observer H.E. (called Group II). In order to determine into which group a particular observer could be classified, the following quick and elementary test was applied: the single-comparison filter devices M.C. I and H.E. I (for composition see Appendix 5) were held side by side with a sunny cloud as a background and the observer was asked which of the four fields appeared different. If the observer stated that he saw the comparison field of H.E. I to be the odd one, this looking greenish-grey while all the others looked violet, he would belong to Group I. If the observer saw the comparison field of M.C. I to be the odd one, this appearing a violet colour while all the others looked greenish grey, he would then belong to Group II. These observations are summarized in Table IV.

Table IV. Classification of observers

Device	Test field		Comparison field	
	H.E. I	M.C. I	H.E. I	M.C. I
GROUP I observer (e.g. M.C.)	Violet	Violet	Grey	Violet
GROUP II observer (e.g. H.E.)	Grey	Grey	Grey	Violet

Tests (see Records, section R7) made using this simple method of classification showed that the ratio of Group I observers to Group II observers was approximately in the ratio 2 : 1.

5.2 Yellow filter test

This difference in vision amongst normal observers was an obstacle which had to be overcome before a filter device could be built which would work equally well for either group of observers.

It was found that by placing a yellow filter such as the "Cinabex" No. 1 Yellow with a $\tau(\lambda)$ cut-off at about 474 nm (found approximately by means of a visual test with a spectroscope) in front of filter instruments H.E. I or II, observers H.E. and M.C. then saw these filter instruments metameric on sunlight (see Records, section R7). This discovery formed the basis of the design of future "universal" (i.e. works for both "groups" of normal observers) filter instruments.

Analysis of the $\tau(\lambda)$ curve for the didymium glass (Fig. 1), used e.g. in the filter instruments H.E. I and II, shows a peak in the region 405 nm to 430 nm and a trough from 435 nm to 480 nm. This yellow filter thus removed the peak in the short-wavelength region. This led to the theory that both groups of observers were not equally sensitive to radiation in the violet region.

5.3 Violet sensitivity tests

Some corroboration of the results of the yellow filter test was necessary.

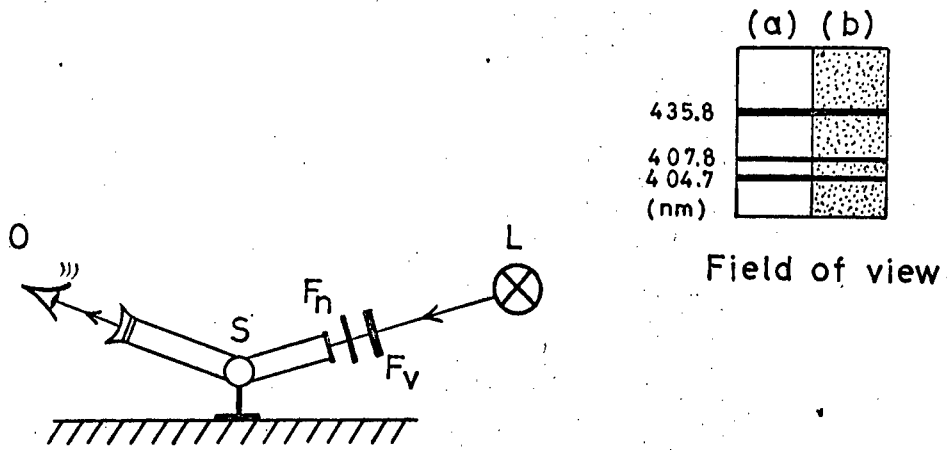
Test I: A quick and simple comparison test between the violet sensitivity

of the two groups of observers was carried out as follows. The slit of a prism spectroscope was illuminated with the light from a mercury discharge lamp as in Fig. 41. Several lines of different colours could then be seen in the eyepiece. The different wavelengths were deviated through different angles by the prism; hence the line images were separated. The mercury 404.7, 407.8 and 435.8 nm lines were isolated from the other spectral lines by placing an interference filter $(\tau(\lambda)_{\max} : 406 \text{ nm}; \text{ half-width} = 24 \text{ nm})$ in front of the collimator slit. This filter still transmitted the 435.8 nm line, but with reduced intensity.

Statements were recorded as regards the luminances of the violet (404.7 nm) and blue (435.8 nm) lines as seen by the observers (see Records, section R7). Appropriate neutral density filters were placed over half the entrance of the collimator slit until a brightness balance was obtained between these two lines, one in the left hand and the other in the right hand field of view of the spectroscope. An interesting result was obtained, namely that the luminance ratio of 404.7/435.8 nm lines was approximately five times greater for an observer from Group I than for an observer from Group II.

This interesting result indicated that further and more accurate tests in the short-wavelength region would be warranted.

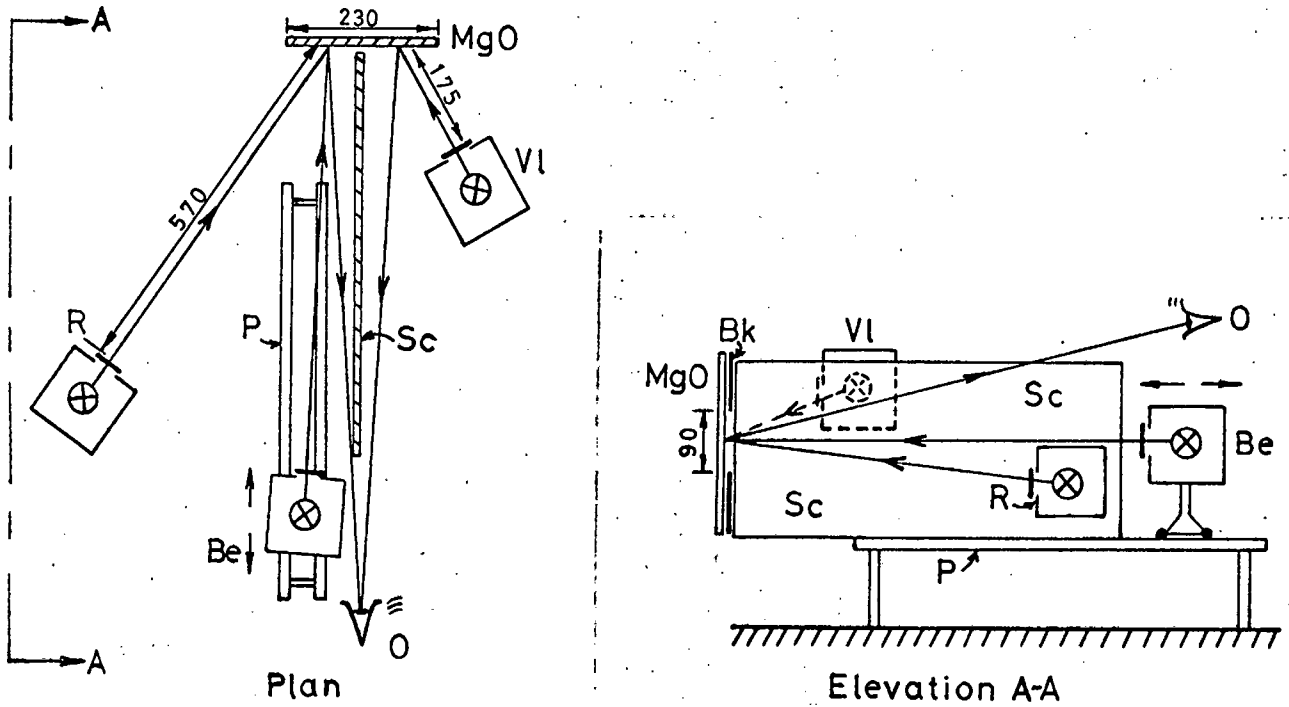
Test II: The apparatus was set up as in Fig. 42 to compare the intensity of blue light with that of violet light. Radiation from a 400W mercury vapour lamp was passed through a violet interference filter $(\tau(\lambda)_{\max} : 406 \text{ nm}; \text{ half-width} = 24 \text{ nm})$ and illuminated one half of a magnesium oxide surface, the field luminance being safely in the photopic region. The other half of the magnesium oxide surface was illuminated with the light



- (a) : Section of field excluding neutral density filter
- (b) : Section of field including neutral density filter

- O : Observer
- S : Prism spectroscope
- L : 125W Mercury discharge lamp
- F_n : Kodak neutral density filter
- F_v : Schott interference filter ($\tau(\lambda)_{\max} : 406 \text{ nm}$)

Fig. 41. Arrangement using a spectroscope for violet sensitivity test I.



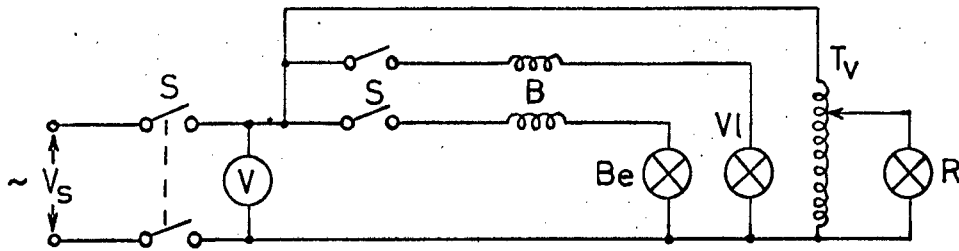
- MgO : Magnesium oxide surface
- Sc : Screen (dividing fields)
- P : Photometer bench
- Bk : Black velvet paper
- O : Observer
- R : Incandescent lamp (controlled by variac)
+ Ilford 204 tricolour red filter
- Vl : 400W Hg lamp + Schott violet interference filter
($\tau(\lambda)_{\max} = 46\%$ at 406 nm, half-width = 24 nm)
- Be : 125W Hg lamp + Schott blue interference filter
($\tau(\lambda)_{\max} = 53\%$ at 431 nm, half-width = 22 nm)

NOTE : All dimensions in millimetres

Fig. 42. Arrangement on photometer bench used for violet sensitivity test II.

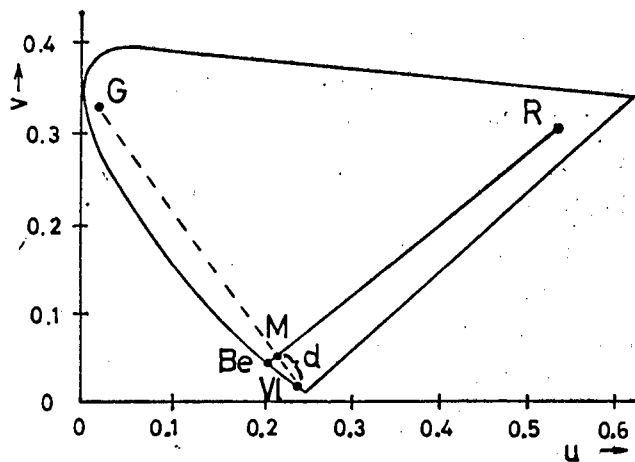
from a 125W mercury vapour lamp in front of which a blue interference filter ($\tau(\lambda)_{\max} : 431 \text{ nm}$; half-width = 22 nm) had been placed, together with the light from an incandescent lamp passed through a red colour filter (circuit diagram Fig. 43). The red lamp was used for colorimetric compensation⁽¹⁰⁾ only, and its luminance contribution was relatively small. Adjustment was obtained on the red lamp by using a variac, and adjustment of the illumination from the blue light was made by moving the lamp along a photometer bench, since the mercury discharge lamp cannot be dimmed by reducing the voltage across it. The illumination from the violet lamp on the magnesium oxide surface was kept constant. All three lamps were contained in suitably shielded compartments. The two halves of the magnesium oxide surface were separated by a non-reflecting screen. The area of each half of the white surface illuminated was limited to approximately 100 mm x 100 mm in order to obtain uniform illumination, the remaining section of the white surface being screened off with non-reflecting black velvet paper.

Observers were first tested for normal colour vision using the Ishihara charts. They were then asked to match (see Fig. 44) the violet light in hue, value and chroma using the controls of the blue and red lamps. Theoretically an identity is not possible as a small amount of green light, for example, added to the violet light is required to obtain a perfect match. This would be at the intersection of the straight lines joining the blue-red and violet-green points on the C.I.E. diagram (mixture M in Fig. 44). As this green light was not added, the observers merely obtained their closest match (distance (d) in Fig. 44), the violet light always appearing slightly more saturated. However, an exact colour balance is



- B : Ballasts
 T_v : Variac
 V_s : 230V A.C. regulated supply
 Be : Hg lamp + blue interference filter
 Vl : Hg lamp + violet interference filter
 R : Incandescent lamp + red filter
 S : Switches
 V : Voltmeter

Fig. 43. Circuit diagram used in violet sensitivity test II



- R : Red lamp
 Be : Blue lamp
 Vl : Violet lamp
 G : Green lamp that could be used to obtain mixture M
 d : Closest match between (red + blue) and violet lamps

Fig. 44. Comparison of blue and violet lamps with colour compensation by a red lamp.

not necessary, provided the remaining colour difference does not impair the brightness or contrast observation.

Observers from Group I obtained their match with the blue lamp relatively close to the white surface, whereas those from Group II positioned the blue lamp much further away, showing reduced sensitivity to the violet light. The individual components of red, blue and violet on the screen for each match by observers was recorded using an uncorrected photocell and operational amplifier (see Records, section R7).

Comparison of the blue/violet ratios for both groups of observers (see Records, section R7) showed that in some cases observers from Group I were twice as sensitive to the violet light as those from Group II. Some from Group I were only $1\frac{1}{2}$ times as sensitive as those from Group II.

The above test was repeated using another violet interference filter ($\tau(\lambda)_{\max} : 403 \text{ nm}$; half-width = 18 nm). This filter thus transmitted a narrower band of radiation (viz. 404.7 and 407.8 nm lines only) than in the previous test. Note that the 406 nm filter used in the previous test also transmitted a certain amount of the 435.8 nm line. The results showed that observers from Group I were from 4 to 20 times more sensitive to this light than those from Group II.

However, research in this field is far from complete, and to obtain more conclusive results mass observation tests should be conducted. The results do, however, clearly show the marked reduction of sensitivity of some normal observers to short-wavelength radiation, and the shorter the wavelength the greater the reduction in sensitivity.

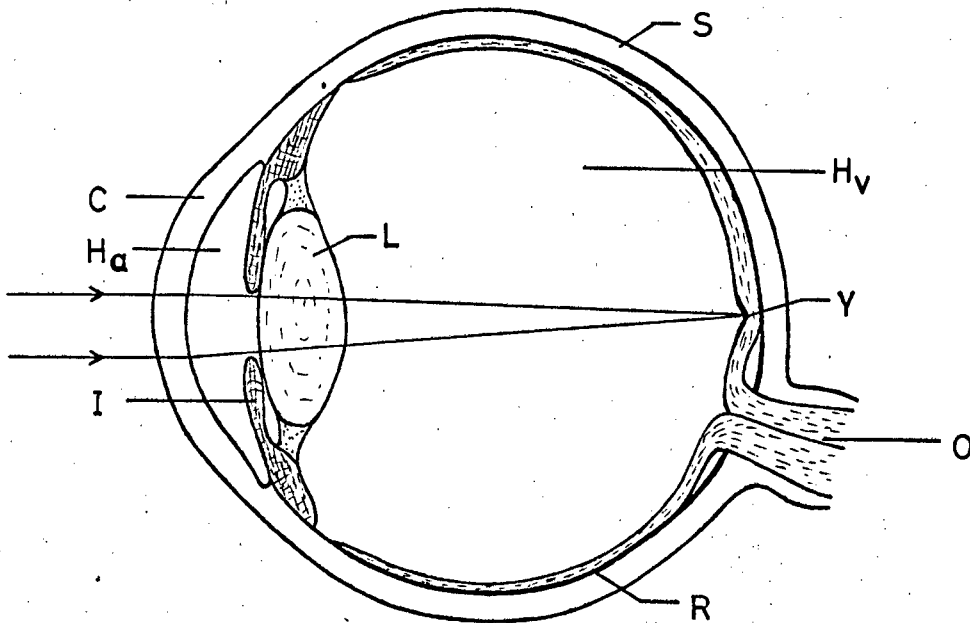
5.4 Discussion

The following explanation of the above observations is suggested. The basic relation which describes the response of the eye to radiation is its sensitivity to the various wavelengths of the spectrum. The response function expresses fundamental properties of the retinal receptors, and of the ocular structures which light must penetrate to reach them. The human retina contains two groups of receptors: rods, which function in dim light, and cones, the organs of vision in bright light and colour vision. The intrinsic sensitivities of rods and cones are modified by the presence of coloured intraocular structures. One of these is the lens, which in man is yellowish in colour. The cornea and other ocular humours also absorb some light in the violet and ultra-violet. The retina itself contains a yellow pigment, concentrated in a diffuse central zone about the fovea, the macula lutea or yellow spot. Its concentration varies from one individual to another and is correlated with the coloration of the hair, the skin and the iris and would explain in part the variation of normal subjects as regards their factors of relative luminous efficacy. Fig. 45 shows how transmission through the eye may be represented as:

$$\tau(\lambda)_{\text{ocular media}} \times \tau(\lambda)_{\text{macular pigment}}$$

Wald⁽¹¹⁾ extracted a small number of human maculas. The yellow pigment was identified as a lutein, the xanthophyll in the leaves of trees, and he obtained the values of $\tau(\lambda)$ for the macular pigment (τ_m in Fig. 46).

Ludvigh and MacCarthy⁽¹²⁾ studied the transparency of the eye for four subjects over the age of 60 years. The authors made allowance for the known yellowing of the lens with age and obtained values of $\tau(\lambda)$



- C : Cornea
- L : Lens
- H_a : Aqueous humour
- H_v : Vitreous humour
- Y : Yellow spot in foveal region containing macular pigmentation
- I : Iris
- O : Optic nerve
- R : Retina
- S : Sclera

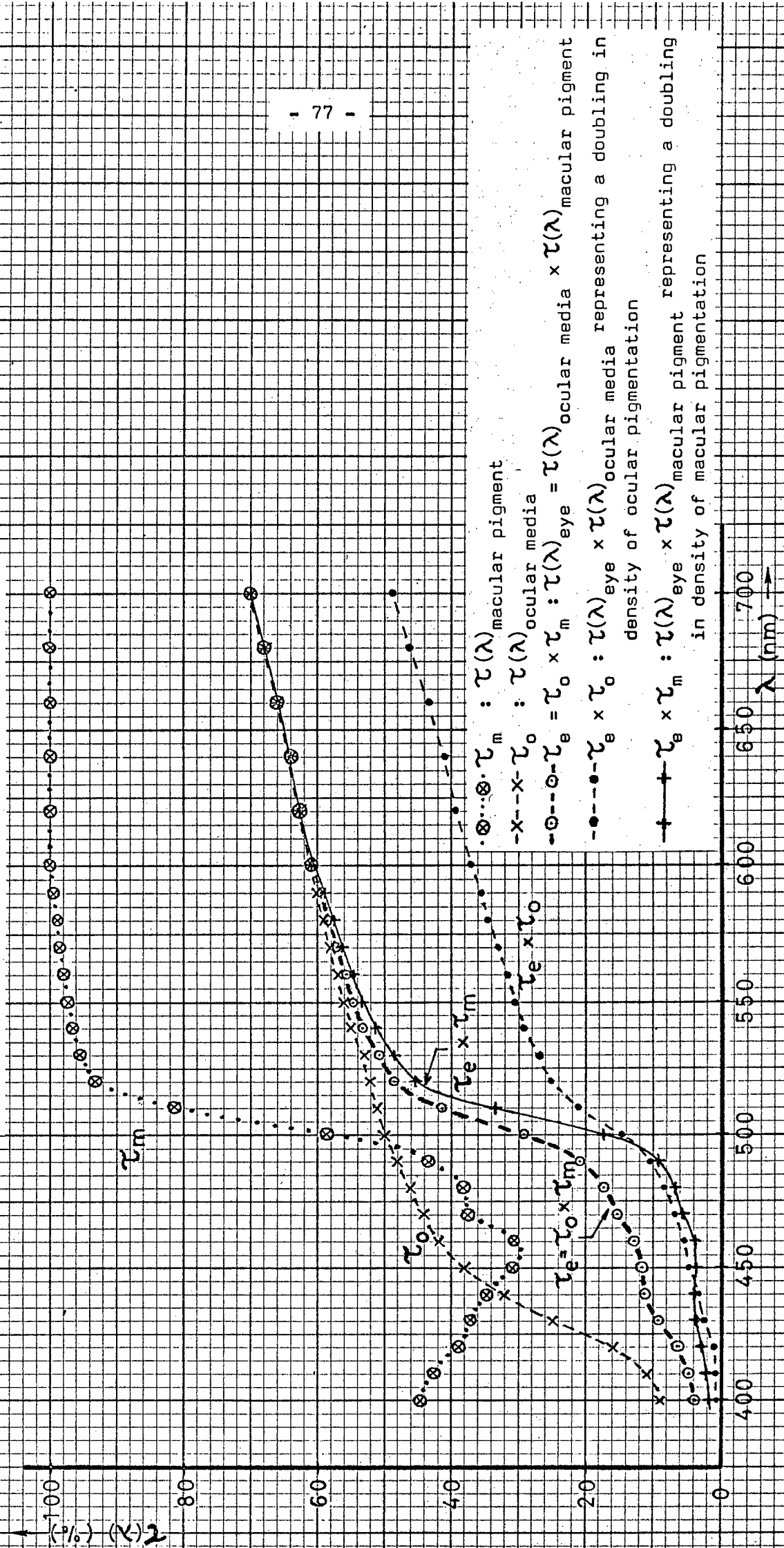
} $\tau(\lambda)_{\text{ocular media}}$

} $\tau(\lambda)_{\text{macular pigment}}$

$$\tau(\lambda)_{\text{eye}} = \tau(\lambda)_{\text{ocular media}} \times \tau(\lambda)_{\text{macular pigment}}$$

Fig. 45. Schematic section of the human eye showing the components of $\tau(\lambda)_{\text{eye}}$

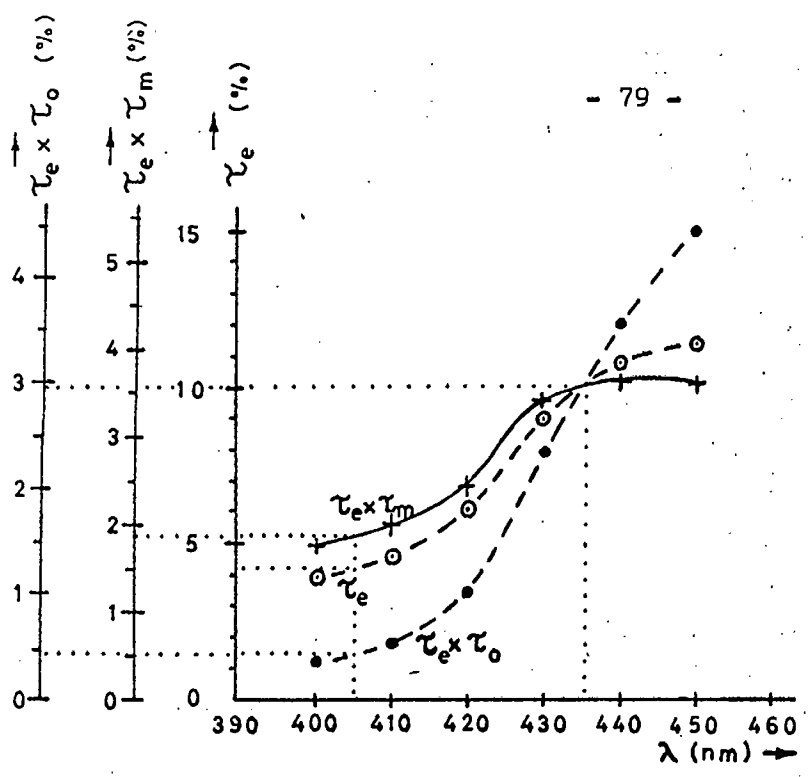
Fig. 46. Transmission curves for the human eye



of the ocular media⁽¹³⁾ representative of subjects of 21 years of age (τ_o in Fig. 46). The product of these two curves (τ_e in Fig. 46) represents the effect of both macular and ocular pigmentation. Curve ($\tau_e \times \tau_o$) was obtained by forming the product of curves (τ_e) and (τ_o), representing subjects with an assumed doubling in density of ocular pigmentation. This would reduce the sensitivity ratio 405/436 nm (possibly Group II observers) relative to a reference condition (say curve τ_e , possibly Group I observers). Curve ($\tau_e \times \tau_m$) was obtained by multiplying curve (τ_e) by curve (τ_m), representing subjects with an assumed doubling in density of macular pigmentation. This would have the effect of increasing the 405/436 nm sensitivity ratio. These results showing variations in the 405/436 nm sensitivity ratio have been depicted in Fig. 47, where a portion of some curves in Fig. 46 have been redrawn and scaled to intersect at $\tau_e \approx 10\%$ at 436 nm.

It is suggested that the variations in vision found amongst our observers could be due to various densities in ocular and macular pigmentation.

Variations in the macular pigmentation have been recorded by Wald⁽¹¹⁾, who states that: "The depth of pigmentation, however, varies greatly in our observers. In one of them no pigmentation was perceptible; in another the pigment absorbed more than 90 per cent of light incident at 436 μ . These wide variations probably account for marked disagreements in the anatomical literature regarding the occurrence and depth of pigmentation in the fovea⁽¹⁴⁾. It is clear from our data that some foveas are virtually unpigmented, while others are intensely colored. In the latter instance, the pigment must affect profoundly the contributions of blue and violet light to the color sensations of the fovea". Note that both the density



- τ_e : Reference condition
- +--+ $\tau_e \times \tau_m$: Density of macular pigmentation doubled
- $\tau_e \times \tau_o$: Density of ocular pigmentation doubled

Relative to reference condition (τ_e), 405/436 nm ratio increases for heavier macular pigmentation ($\tau_e \times \tau_m$) and decreases for heavier ocular pigmentation ($\tau_e \times \tau_o$).

Note: All curves scaled to intersect at $\tau_e(\lambda) \approx 10\%$ at 436 nm.

Fig. 47. Variations in violet/blue sensitivity ratio caused by increased macular and ocular pigmentation.

of the ocular media and the macular pigmentation are known to increase with age (density, $\delta(\lambda) = -\log_{10} \tau(\lambda)$).

While this explanation may be satisfactory in accounting for the results of the short-wavelength sensitivity tests, it does not entirely account for the observations of the visual tests of section 5.1, where there appeared to be two distinct groups of normal observers.

5.5 Summary and recommendations

A problem arising from the difference in vision amongst observers with normal colour vision has been overcome.

A more detailed investigation into the visual problem where large differences in the violet sensitivities of normal observers were found, may yield interesting results.

APPENDICES

APPENDIX 1

(x,y) → (u,v) Nomogram (15)

A1.1 Transformation

The relation between the C.I.E. (x,y) co-ordinates and the C.I.E. (u,v) U.C.S. co-ordinates is given by the formulae:

$$x = \frac{1.5u}{u - 4v + 2} \dots\dots\dots (A1.1)$$

and
$$y = \frac{v}{u - 4v + 2} \dots\dots\dots (A1.2)$$

From (A1.1) we have

$$\frac{4x}{3 - 2x} = \frac{u}{1 - 2v}$$

i.e.
$$f_3(x) = \frac{f_1(u)}{f_2(v)} \dots\dots\dots (A1.3)$$

From (A1.2) we have

$$\frac{1 + 4y}{y} = \frac{u + 2}{v}$$

i.e.
$$f_6(y) = \frac{f_4(u)}{f_5(v)} \dots\dots\dots (A1.4)$$

Both equations (A1.3) and (A1.4) are in the form

$$f(u) = f(v).f(w)$$

from which it is possible to draw an alignment chart - a Z chart.

The method used was to obtain a Z chart for the u, v and x scales (Fig. 48), and superimpose a Z chart for the u, v and y scales (Fig. 49), keeping a common scale for u and v.

Fig. 50 shows the proposed diagram. While the intersections with the parallel scales by the x scale at $(u = 0, v = 0.5)$ and by the y scale at $(u = -2, v = 0)$ are determined by the abovementioned transformation formulae, the distance between the parallel scales as well as the unit length of the u and v axes are arbitrary. The scales selected in Fig. 50 were chosen to give optimum angles of intersection when using the nomogram for $(x,y) \rightarrow (u,v)$ transformations (and vice versa) in widely used regions of the diagram.

A1.2 Graduation of scales

Graduation of u, v and x scales

Let the parallel scales (Fig. 48) be graduated in accordance with the scale equations

$$D_1(u) = m_u f_1(u) \quad \dots\dots\dots (A1.5)$$

$$\text{and } D_1(v') = m_v f_2(v') \quad \dots\dots\dots (A1.6)$$

where $v' = -v$

The diagonal scale for $f_3(x)$ joins $f_1(u_0)$ and $f_2(v'_0)$, the zero values of $f_1(u)$ and $f_2(v')$.

Let the straight line joining points u_1 and v'_1 cut the diagonal scale at x_1 . From similar triangles $u_0 u_1 x_1$ and $v'_0 v'_1 x_1$:

$$\frac{D_1(u)}{D_1(v')} = \frac{D(x)}{K_1 - D(x)} \quad \text{or} \quad D_1(u) = D_1(v') \frac{D(x)}{K_1 - D(x)}$$

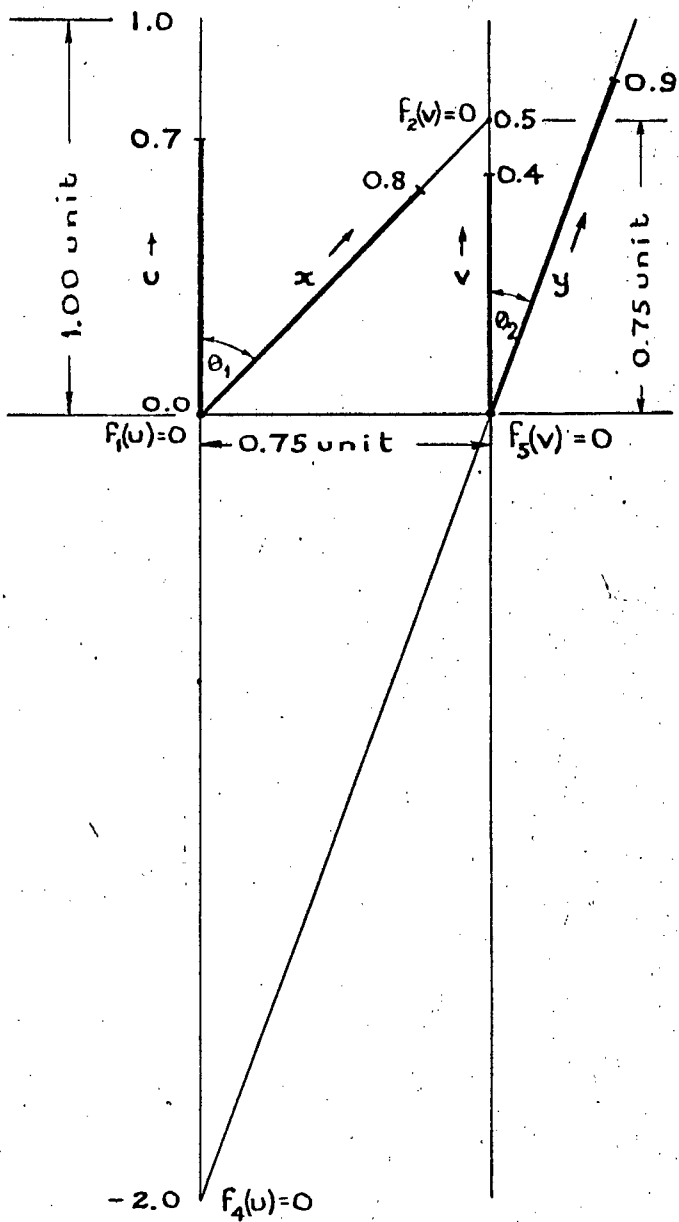


Fig. 50. Graduation of (u, v) and (x, y) scales

Thus, from (A1.5) and (A1.6)

$$m_u f_1(u) = m_v f_2(v') \frac{D(x)}{K_1 - D(x)}$$

When $f_1(u) = f_2(v') \cdot f_3(x)$ (see equation (A1.3))

$$\text{then } \frac{D(x)}{K_1 - D(x)} = \frac{m_u}{m_v} f_3(x)$$

$$\text{from which } D(x) = \frac{K_1 m_u f_3(x)}{m_u f_3(x) + m_v} \text{ (A1.7)}$$

Graduate the u-scale as:

$$D_1(u) = m_u f_1(u) \text{ where } f_1(u) = u$$

u varies from 0 → 1.0. Scale selected = 1 unit (Fig. 50)

$$\therefore m_u = \frac{1}{(1 - 0)} = 1$$

$$\text{i.e. } D_1(u) = u \text{ (in units) (A1.8)}$$

Graduate the v'-scale as:

$$D_1(v') = m_v f_2(v')$$

Since this scale must be graduated from the top down, put $v' = -v$ and use the negative part of the v' scale as a positive scale for v .

$$\text{Now } f_2(v) = 1 - 2v \quad \therefore f_2(v') = 1 + 2v'$$

v' varies from -0.5 → 0. Scale length = 0.75 units

$$\therefore m_v = \frac{0.75}{(1 - 0)} = 0.75$$

$$\text{i.e. } D_1(v') = 0.75(1 + 2v') \text{ (in units) (A1.9)}$$

where $v' = -v$

Also $\tan \theta_1 = \frac{0.75}{0.75} = 1 \therefore \theta_1 = 45^\circ$

$K_1 = 0.75 \sec 45^\circ = 1.06065$

then, substituting in (A1.7)

$$D(x) = \frac{1.06065 \frac{4x}{3 - 2x}}{\frac{4x}{3 - 2x} + 0.75}$$

$\therefore D(x) = \frac{1.06065x}{0.625x + 0.5625}$ units (A1.10)

The u,v and x scales may be drawn by substituting values in equations (A1.8), (A1.9) and (A1.10) respectively.

Graduation of u,v and y scales

Since the negative part of the v' scale is used for v, a different formula from D(x) must be used for D(y).

Let the parallel scales (Fig. 49) be graduated in accordance with the scale equations

$D_2(u) = n_u f_4(u)$ (A1.11)

and $D_2(v) = n_v f_5(v)$ (A1.12)

The diagonal scale for $f_6(y)$ joins $f_4(u_0)$ and $f_5(v_0)$, the zero values of $f_4(u)$ and $f_5(v)$.

Let the straight line joining points u_1 and v_1 cut the diagonal scale at y_1 .

From similar triangles $u_0 u_1 y_1$ and $v_0 v_1 y_1$

$$\frac{D_2(u)}{D_2(v)} = \frac{K_2 + D(y)}{D(y)} \quad \text{or} \quad D_2(u) = D_2(v) \frac{K_2 + D(y)}{D(y)}$$

Thus, from (A1.11) and (A1.12)

$$n_u f_4(u) = n_v f_5(v) \frac{K_2 + D(y)}{D(y)}$$

When $f_4(u) = f_5(v) \cdot f_6(y)$ (see equation (A1.4))

$$\text{then } \frac{K_2 + D(y)}{D(y)} = \frac{n_u}{n_v} f_6(y)$$

$$\text{from which } D(y) = \frac{K_2}{\frac{n_u}{n_v} f_6(y) - 1} \quad \text{..... (A1.13)}$$

Graduate the u-scale as:

$$D_2(u) = n_u f_4(u) \text{ where } f_4(u) = u + 2$$

u varies from -2 → 1. Scale selected = 3 units (Fig. 50)

$$\therefore n_u = \frac{3}{(3 - 0)} = 1$$

$$\text{i.e. } D_2(u) = u + 2 \text{ (in units)} \quad \text{..... (A1.14)}$$

Graduate the v scale as:

$$D_2(v) = n_v f_5(v) \text{ where } f_5(v) = v$$

v varies from 0 → 0.5. Scale selected = 0.75 unit

$$\therefore n_v = \frac{0.75}{(0.5 - 0)} = 1.5$$

i.e. $D_2(v) = 1.5v$ (in units) (A1.15)

Equations (A1.14) and (A1.15) are consistent with equations (A1.8) and (A1.9) respectively, and the u and v scales may alternatively be drawn by using equations (A1.14) and (A1.15), but with different zero positions.

Now $\tan \theta_2 = \frac{0.75}{2} = 0.375 \therefore \theta_2 = 20^\circ 33'$

$K_2 = 2 \sec 20^\circ 33' = 2.1358$

then, substituting in (A1.13)

$D(y) = \frac{2.1358}{\frac{1 + 4y}{1.5y} - 1} = \frac{3.2037y}{1 + 2.5y}$ units (A1.16)

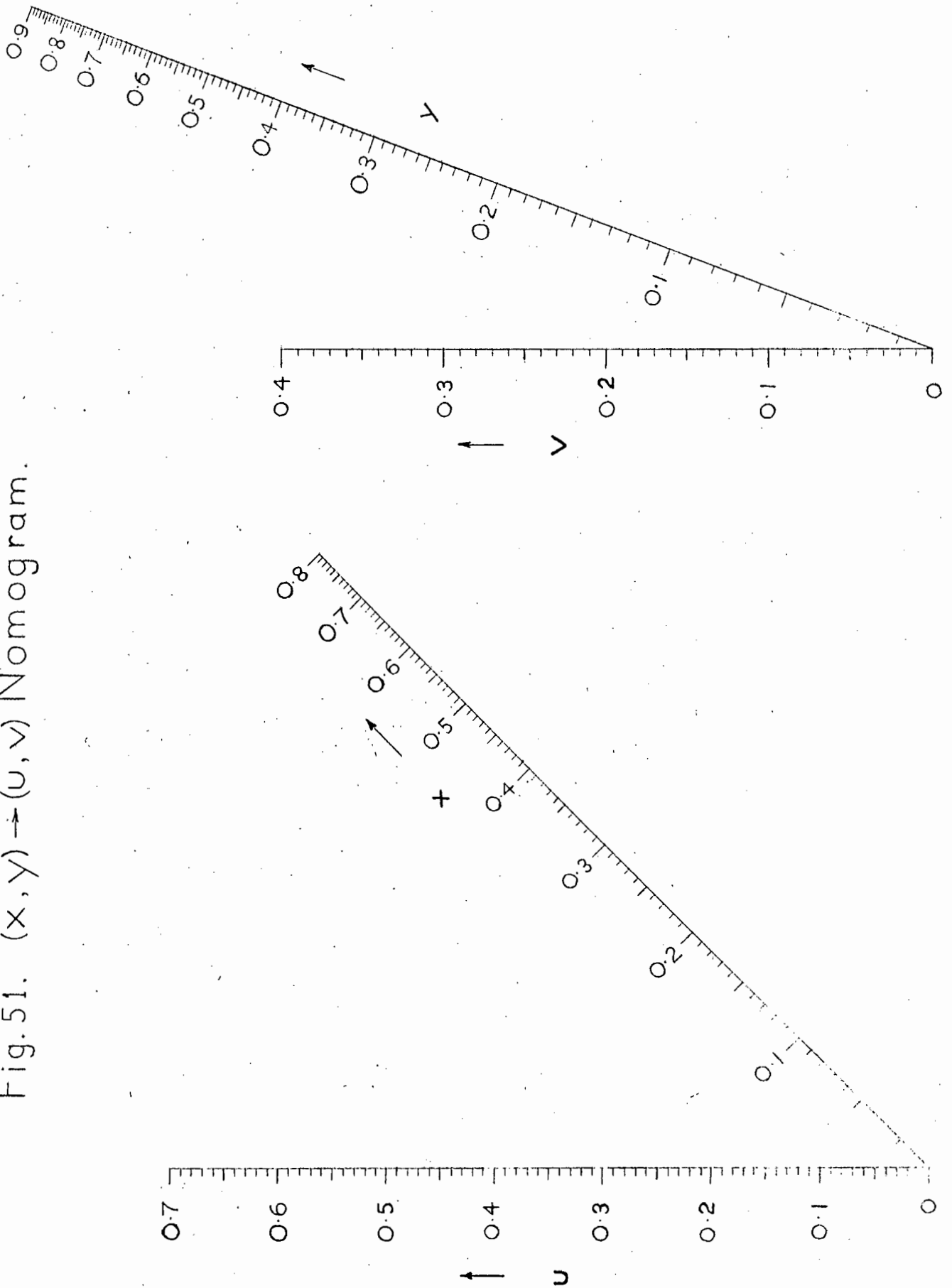
Equation (A1.16) enables the y scale to be calibrated.

A1.3 Method of use

Fig. 51 shows the nomogram drawn to a scale of 1 unit = 200 mm. The u scale was calibrated from 0 to 0.7, the v scale from 0 to 0.4, the x scale from 0 to 0.8 and the y scale from 0 to 0.9. The nomogram was drawn maintaining linear scales for u and v. As u and v are U.C.S. co-ordinates, equal steps on the u and v scales represent equal colour differences.

In order to use the nomogram for (x,y) → (u,v) transformations (or vice versa), a straight line is merely drawn through the known (x,y) points and the points of intersection on the (u,v) axes are read off. The scales selected were found to be improved compared with those used by other authors (16), (17).

Fig. 51. $(x, \gamma) \rightarrow (u, v)$ Nomogram.



APPENDIX 2

Computer Programme

(This section should be read in conjunction with the flow diagram (section A2.6) and the listing of the source programme (Records, section R1)).

A FORTRAN programme was written to use the IBM 1130 computer for the calculation of:

- (i) The C.I.E. General Colour Rendering Index of light sources^{(18), (19)}.
- (ii) The C.I.E. Special Colour Rendering Index for specified samples.
- (iii) The C.I.E.-U.C.S. co-ordinates u , v , W^* for specified samples and filters.
- (iv) Filter chromaticities and vector shifts from the test field to the other filter fields.

Some programme details will be explained in the sequence of occurrence in the source programme.

A2.1 Data input

Storage allocations for all one-dimensional or two-dimensional arrays used in the programme are assigned by the DIMENSION statement⁽²⁰⁾. Although the logical unit numbers for the printer and card reader are 5 and 8 respectively, these numbers have been assigned the symbols IW and IR, and in all READ and WRITE statements the integer that specifies the logical unit number to be used for input or output is referred to as IR or IW. Should later on the re-configuring of the system take place and the FORTRAN input/output logical unit numbers be changed, only two cards need be repunched and not all the READ and WRITE statements.

The first information READ into storage is the number of lamp spectra to be processed (LRUNS). This is followed by the spectral tristimulus values $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ for wavelengths at 10 nm intervals from 380 nm to 720 nm, then the four mercury lines at 405 nm, 436 nm, 546 nm, 578 nm and the sodium line at 589 nm.

The spectral reflection factors $\beta_i(\lambda)$ of the eight test-colour samples⁽¹⁹⁾, ⁽²¹⁾ used for calculating the General Colour Rendering Index are then READ in ($i = 1 \rightarrow 8$). They are selected to cover the hue circuit, are moderate in saturation, and approximately the same in lightness (Munsell value 6/ for daylight). These are followed by the special purpose test-colour samples used for calculating the Special Colour Rendering Index ($i = 9 \rightarrow 14$). Using the Munsell notation, these samples are:

- | | |
|--------------|---------------|
| (1) 7.5R 6/4 | (8) 10P 6/8 |
| (2) 5Y 6/4 | (9) 4.5R 4/13 |
| (3) 5GY 6/8 | (10) 5Y 8/10 |
| (4) 2.5G 6/6 | (11) 4.5G 5/8 |
| (5) 10BG 6/4 | (12) 3PB 3/11 |
| (6) 5PB 6/8 | (13) 5YR 8/4 |
| (7) 2.5P 6/8 | (14) 5GY 4/4 |

Samples 15 to 17 are then READ in. Sample 15 represents the complexion of the average "female Caucasian"⁽²²⁾. Sample 16 is the reflectance of the average woman with cosmetics⁽²²⁾. Sample 17 is the lamp itself ($\beta(\lambda) = 1.0$).

The last 5 "samples" ($i = 18 \rightarrow 22$) are actually transmission factors of the fields of UM. II which the computer processes in the same

way as the reflection factors. Sample 18 is the test field of UM. II, sample 19 is field I (excellent), sample 20 is field II (good), sample 21 is field III (fair) and sample 22 is field IV (poor).

The statement READ(IR,3)((BETA(L,I), L = 1, 40), I = 1, 22) requires that the data $\beta_i(\lambda)$ be punched in columnwise, i.e. for sample 1 (I = 1) from I \rightarrow 40 λ values (L = 1, 40), then sample 2 (I = 2) from 1 \rightarrow 40 λ values (L = 1, 40) etc. I is equivalent to an outermost DO statement and L to an innermost DO. If the data should be punched row-wise, the values will be READ into the wrong cells of the array. The data must appear on the card in the order in which the list specifies and that order is under control of the indices L and I.

The factors $S_0(\lambda)$, $S_1(\lambda)$, $S_2(\lambda)$, $M_1(\theta)$ and $M_2(\theta)$ are READ in. These are required for the calculation of the reconstituted daylight reference illuminants. Note that the arrays $M_1(\theta)$ and $M_2(\theta)$ begin at the value 42 i.e. EMI(42) and range to 74 i.e. EMI(74). The reason for this will be explained later. Colour temperatures from 2300K \rightarrow 25000K⁽²³⁾ are then READ in, followed by their respective (u,v) co-ordinates. These are required for the selection of the reference illuminant of the nearest correlated colour temperature.

The last information to be READ in is $P_k(\lambda)$, the relative spectral power of the test lamp(s). It has been placed in this position as all the abovementioned data is READ in only once, but $P_k(\lambda)$ may be READ in a number of times, depending on the number of lamps to be processed. The entire calculation and printout for each lamp is recycled from this point by means of a DO statement.

A2.2 Calculation

The spectral power of the test lamp, $P_K(\lambda)$, is normalized (= 100) at 560 nm.

C.I.E. tristimulus values for all the test samples and filter fields (index i) under the test lamp (suffix K) are determined by the summation:

$$\begin{aligned}
X_{K,i} &= X_{K,i} + \bar{x}(\lambda)P_K(\lambda)\beta_i(\lambda) \\
Y_{K,i} &= Y_{K,i} + \bar{y}(\lambda)P_K(\lambda)\beta_i(\lambda) \quad \dots\dots\dots (A2.1) \\
Z_{K,i} &= Z_{K,i} + \bar{z}(\lambda)P_K(\lambda)\beta_i(\lambda)
\end{aligned}$$

$X_{K,i}$, $Y_{K,i}$ and $Z_{K,i}$ are zeroed initially, and λ ranges over the 40 wavelength values to complete the summation. The cycle is then repeated using a DO loop for the 22 samples and filter fields ($i = 1, 22$).

C.I.E. chromaticity co-ordinates (x,y) are calculated for the test lamp only as:

$$\begin{aligned}
x_K &= X_K / (X_K + Y_K + Z_K) \\
y_K &= Y_K / (X_K + Y_K + Z_K) \quad \dots\dots\dots (A2.2)
\end{aligned}$$

The percentage line energy contained in the test lamp is calculated by summing $\bar{y}(\lambda)P_K(\lambda)$ over the 405 nm, 436 nm, 546 nm, 578 nm and 589 nm lines and dividing by Y_K for the test lamp.

Transformation of the (x,y) co-ordinates to the (u,v) co-ordinates of the 1960 C.I.E.-Uniform Chromaticity Scale diagram was made using the formulae:

$$\begin{aligned}
u_{K,i} &= 4X_{K,i} / (X_{K,i} + 15Y_{K,i} + 3Z_{K,i}) \\
v_{K,i} &= 6Y_{K,i} / (X_{K,i} + 15Y_{K,i} + 3Z_{K,i}) \quad \dots\dots (A2.3)
\end{aligned}$$

For calculation of the Special Index it was also necessary to transform the Y-data to the lightness index W^* recommended in 1961. This was calculated as:

$$W_{K,i}^* = 25(100Y_{K,i}/Y_K)^{1/3} - 17 \quad \dots\dots\dots (A2.4)$$

The reference illuminant for light sources with correlated colour temperature 5000K or below is a Planckian radiator at the nearest colour temperature to the test lamp, and above 5000K a series of daylight spectral power distributions. The selection of the nearest correlated colour temperature is performed using the following method. The (u,v) co-ordinates of selected colour temperatures from 2300K to 25000K are READ in initially (74 values of $u_o(\theta)$ and $v_o(\theta)$) and the (u,v) co-ordinates of the test lamp are calculated as above (u_K, v_K). The distance from each of these co-ordinates to the test lamp is calculated in (u,v) units (starting at 2300K) as:

$$\left| (u,v)_\theta \right| = \left\{ (u_K - u_o(\theta))^2 + (v_K - v_o(\theta))^2 \right\}^{1/2} \quad \dots\dots (A2.5)$$

The computer selects the shortest of these distances as follows:

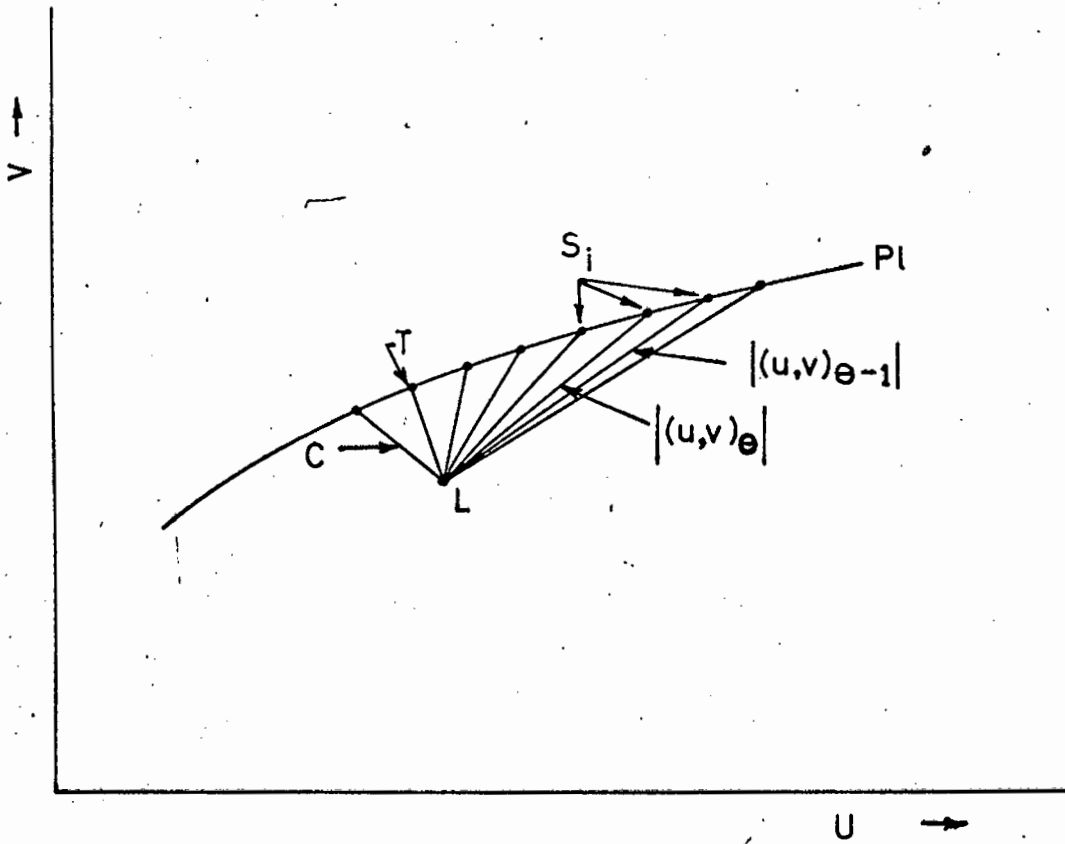
the use of an IF statement finds out when the value of the function

$\left\{ \left| (u,v)_\theta \right| - \left| (u,v)_{\theta-1} \right| \right\}$ changes sign. When this happens, the nearest colour temperature is at the previous value (see Fig. 52).

Should the abovementioned function not change sign (i.e. reference illuminant > 25000K) the DO loop is completed after the 74th value. By use of the statement $\theta = 74$, 25000K is then selected and the statement $\theta = \theta - 1$ is

by-passed using the GO TO statement.

The reference illuminant is intended to be of the same or nearly the same chromaticity as the test lamp, and a tolerance of 15 mireds⁽²⁴⁾ is suggested as a practical limit of difference (approximately 0.0060



- P1 : Planckian locus
- T : Nearest correlated colour temperature of test lamp
- L : Test lamp
- S_i : Selected colour temperatures READ into storage
- C : $|(u,v)_{\theta}| - |(u,v)_{\theta-1}|$ changes sign here

Fig. 52. Selection of nearest correlated colour temperature of test lamp.

$\Delta(u,v)$ units). Therefore the displacement from the test lamp to reference illuminant was calculated as:

$$\begin{aligned} \Delta u &= u_K - u_o(\theta) \\ \Delta v &= v_K - v_o(\theta) \end{aligned} \quad \dots\dots\dots (A2.6)$$

The use of an IF statement determines whether the reference illuminant is above or below 5000K. If it is equal to or below 5000K the spectral power distribution of the reference illuminant is determined as:

$$P_o(\lambda) = \frac{1}{\lambda^5 (e^{c_2/\lambda\theta} - 1)} \quad c_2 = 1.4388 \times 10^{-2} \text{ m K} \dots\dots (A2.7)$$

Wavelengths (λ) from 380 to 720 nm are regenerated using the formula $LAMDA(L) = 10.(L) + 370.$, where L varies from 1 to 35. The last 5 values of $P_o(\lambda)$ are set equal to zero (in the case of $P_K(\lambda)$ these values represented the lines). If the reference illuminant is above 5000K, the spectral power distribution is calculated as:

$$P_o(\lambda) = S_o(\lambda) + S_1(\lambda)M_1(\theta) + S_2(\lambda)M_2(\theta) \dots\dots (A2.8)$$

the values of which were READ in initially. Now for values of $\theta > 5000K$, the subscripts for the array θ_N must be such that $42 \leq N \leq 74$, e.g. for $\theta_N = 5200K$, $N = 43$. These values of the subscripts are identical to those used in the arrays $EM1(N)$ and $EM2(N)$, explaining why these are READ in initially starting from $N = 42$. $P_o(\lambda)$ is subsequently normalised to 100 at 560 nm.

Tristimulus values are then computed for the test samples and filter fields under the reference illuminant, suffix o, (in a similar manner as for the test lamp) as follows:

$$\begin{aligned} X_{o,i} &= X_{o,i} + \bar{x}(\lambda) P_o(\lambda) \beta_i(\lambda) \\ Y_{o,i} &= Y_{o,i} + \bar{y}(\lambda) P_o(\lambda) \beta_i(\lambda) \dots\dots\dots (A2.9) \\ Z_{o,i} &= Z_{o,i} + \bar{z}(\lambda) P_o(\lambda) \beta_i(\lambda) \end{aligned}$$

Transformation to the (u,v) U.C.S. co-ordinates and calculation of the lightness index W^* is done in the same way as for the test lamp.

The General Colour Rendering Index which represents an average for test samples 1 \rightarrow 8 is derived from the equation:

$$R_a = 100 - 460 \sum_{i=1}^8 \Delta E_{a,i} \dots\dots\dots (A2.10)$$

where

$$\Delta E_{a,i} = \left\{ \left[(u_{K,i} - u_{o,i}) - (u_K - u_o) \right]^2 + \left[(v_{K,i} - v_{o,i}) - (v_K - v_o) \right]^2 \right\}^{\frac{1}{2}} \dots\dots\dots (A2.11)$$

Chromaticity differences for individual or special test-colour samples provide useful information in addition to the General Index, and therefore the Special Colour Rendering Index R_I was calculated. This takes into account any lightness difference that may occur. $R_{I,i}$ is determined as:

$$R_{I,i} = 100 - 4.6 \Delta E_{I,i} \dots\dots\dots (A2.12)$$

where

$$\begin{aligned} \Delta E_{I,i} &= \left\{ \left[w_{K,i} - w_{o,i} \right]^2 + 13^2 \left[w_{K,i} (u_{K,i} - u_K) - w_{o,i} (u_{o,i} - u_o) \right]^2 \right. \\ &\quad \left. + 13^2 \left[w_{K,i} (v_{K,i} - v_K) - w_{o,i} (v_{o,i} - v_o) \right]^2 \right\}^{\frac{1}{2}} \dots\dots (A2.13) \end{aligned}$$

The colour shifts from the test field (didymium) to each of the four comparison filter fields under the reference lamp were calculated as:

$$\Delta(u,v)(Didy \rightarrow Filt_i)_o = \left\{ (u_{o_{Didy}} - u_{o,i})^2 + (v_{o_{Didy}} - v_{o,i})^2 \right\}^{\frac{1}{2}} \dots\dots (A2.14)$$

and similarly for the test lamp:

$$\Delta(u,v)(\text{Didy} \rightarrow \text{Filt}_i)_K = \left\{ (u_{K_{\text{Didy}}} - u_{K,i})^2 + (v_{K_{\text{Didy}}} - v_{K,i})^2 \right\}^{\frac{1}{2}} \dots \quad (\text{A2.15})$$

The colour shift from reference to test lamp as observed through the test field (didymium) is calculated as:

$$\Delta(u,v)(o \rightarrow K)_{\text{Didy}} = \left\{ (u_{o_{\text{Didy}}} - u_{K_{\text{Didy}}})^2 + (v_{o_{\text{Didy}}} - v_{K_{\text{Didy}}})^2 \right\}^{\frac{1}{2}} \dots \quad (\text{A2.16})$$

A2.3 Printout

Printout is begun on the third line of a new page by using the `FORMAT(1H1,///,1H1,)`; the carriage control `1H1` causes the jump to the first line of a new page, the `///` initiates the spacing of three lines and the `1H1` starts the printing in column 1 of the line.

The first values to be printed out are the wavelengths(λ), the spectral power distributions of both reference and test sources and a graph of the relative spectral irradiance of the test lamp. This is achieved as follows:

BLANK and X are made integer variables by means of the type statement `INTEGER` at the beginning of the programme, since only variable names starting with `I` to `N` are implicitly integer. `X` and `BLANK` are compiled into the object programme from the source programme at the time of compilation by the use of a `DATA` statement, such that the computer stores a blank space for the word `BLANK`. This obviates the need of a `READ` statement as well as its associated data card. It is essential here to insert the control card `ONE WORD INTEGERS` at the beginning of the programme to get the correct storage allocations for the particular `DATA` statement used. This control card causes integer variables to be allocated one word of core storage.

Alpha-numeric data (e.g. BLANK, X) is stored as two characters per word, i.e. two characters per integer variable, provided this control card is inserted.

A one-dimensional array LINE is set up, which may contain 86 alpha-numeric elements, each containing one character. A simple DO loop fills all 86 elements of LINE with BLANK spaces.

The integer J is set equal to $(1. + 0.25 \times P_K(\lambda))$. The 1 is necessary should $P_K(\lambda) = 0$ ($J(0)$ does not exist). The factor 0.25 is required to reduce the expression to < 86 , as this is approximately the number of spaces left available on the page. As J is an integer, the integer part of this expression is formed, any fractional part being truncated. This number is used to place the X in one of the 86 elements of LINE. After this the entire array LINE is printed, which now appears only as an X in a particular position, as all other positions are filled with blanks. The array is again blanked after the printing of the X at each particular wavelength.

The percentage line energy is subsequently printed out. This is followed by the sample number and the tristimulus values X, Y and Z for the test samples and filter fields under the test and reference sources. In the printout I 0 refers to the source itself, I 1 to sample 1, I 2 to sample 2 etc. The terms FILT 18, FILT 19 (the filter fields of UM. II) are identified in the following line of the printout.

The correlated colour temperature of the test lamp and the displacement from reference to test source are then printed.

This is followed by the printing of (u,v) and (x,y) values for the test lamp, the (u,v) values for the reference illuminant and the General

Colour Rendering Index, R_a . u , v and w^* are recorded for the test samples under both the test and reference sources. $\Delta E_{a,i}$ is printed for the first eight samples used in the calculation of R_a ; the values of $\Delta E_{I,i}$ and the Special Index $R_{I,i}$ are printed for all the samples.

The various shifts calculated from the test field to the other filter fields as observed under the test and reference sources are then printed out.

At the end of the programme, once the various test lamp spectra have been processed, the data READ in initially is printed. These are the values of $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$, $s_0(\lambda)$, $s_1(\lambda)$, $s_2(\lambda)$, θ , $u_0(\theta)$, $v_0(\theta)$, $M_1(\theta)$, $M_2(\theta)$ and $\beta_i(\lambda)$.

A2.4 Use of Programme

The values of the test lamp energies - $P_K(\lambda)$ - should be punched on the data cards according to the FORMAT(8F10.2), i.e. 8 values per card, the first value anywhere between columns 1 - 10, the second value anywhere between 11 - 20 etc. The values must be punched with a decimal point. Values of $P_K(\lambda)$ should be punched on the cards in the order $P_K(380)$, $P_K(390)$, $P_K(400)$, , $P_K(710)$, $P_K(720)$, $P_K(405)$, $P_K(436)$, $P_K(546)$, $P_K(578)$, $P_K(589)$. These data cards are then placed immediately behind the data cards on which the values of $u_0(\theta)$, $v_0(\theta)$ are recorded, i.e. at the end of the programme (all data cards are coloured yellow for easy identification). As many lamp spectra as required may be processed during the same run and should be placed one behind the other with the values of $P_K(\lambda)$ in the order described above. The very last card in the card deck which should be added after the values of $P_K(\lambda)$ is the card which reads // *
END OF DATA.

Another card which must be altered each time different numbers of lamps are processed is the card immediately after the card // XEQ. On this card should be punched the number of lamps to be processed, according to the FORMAT(I2). Thus if there are three lamp spectra, this card should have a blank space in column 1, and a 3 in column 2; if there are 11 lamps, place a 1 in column 1 and a 1 in column 2 etc. This card has been coloured differently for easy identification. All other FORTRAN statement cards are coloured blue.

A2.5 Abbreviations used in programme

- BETA(L,I) = $\beta_i(\lambda)$ - Spectral reflection (or transmission) factors
- BIGXK(I) = $X_{K,i}$ - C.I.E. tristimulus value for samples under test lamp
- BIGYK(I) = $Y_{K,i}$ - C.I.E. tristimulus value for samples under test lamp
- BIGZK(I) = $Z_{K,i}$ - C.I.E. tristimulus value for samples under test lamp
- BIGXO(I) = $X_{O,i}$ - C.I.E. tristimulus value for samples under reference illuminant
- BIGYO(I) = $Y_{O,i}$ - C.I.E. tristimulus value for samples under reference illuminant
- BIGZO(I) = $Z_{O,i}$ - C.I.E. tristimulus value for samples under reference illuminant
- DELTAU = Δu - Displacement from reference to test source - u direction
- DELTV = Δv - Displacement from reference to test source - v direction
- DENPK - Value of $P_K(560)$ read on data card
- DENMO - Value of $P_O(560)$ calculated before normalisation
- EABAR = $\sum_{i=1}^8 \Delta E_{a,i}$ - Sum of shifts of the 8 samples used in calculation of General Colour Rendering Index

EA(I) = $\Delta E_{a,i}$ - Shifts used in calculation of General Colour Rendering Index

EI(I) = $\Delta E_{I,i}$ - Shifts used in calculation of Special Colour Rendering Index

EM1(M) = $M_1(\theta)$ - Factor used in calculation of reconstituted daylight illuminant

EM2(M) = $M_2(\theta)$ - Factor used in calculation of reconstituted daylight illuminant

HG - % line energy

LAMDA = LAMBDA (λ) - Wavelength

LRUNS = Number of lamp runs - i.e. lamp spectra to be processed

POWRK(L) = $P_K(\lambda)$ - Test lamp spectral power

POWRO(L) = $P_O(\lambda)$ - Reference illuminant spectral power

RA = R_a - General Colour Rendering Index

RI(I) = $R_{I,i}$ - Special Colour Rendering Indices

REFTM - Nearest correlated colour temperature

SFDKO = $\Delta(u,v)(o \rightarrow K)$ - Shift from reference to test lamp as observed through the test field

SFTDK(I) = $\Delta(u,v)(D_{idy} \rightarrow Filt_i)_K$ - Shift from test field to adjacent comparison field (index i) under test lamp

SFTDO(I) = $\Delta(u,v)(D_{idy} \rightarrow Filt_i)_O$ - Shift from test field to adjacent comparison field (index i) under reference illuminant

SO(L) = $S_O(\lambda)$ - Factor used in calculation of reconstituted daylight illuminant

SI(L) = $S_I(\lambda)$ - Factor used in calculation of reconstituted daylight illuminant

$S_2(L) = S_2'(\lambda)$ - Factor used in calculation of reconstituted daylight illuminant

$SUMHG = \sum_{\text{lines}} \bar{y}(\lambda) P_K(\lambda)$ - Used in calculation of % line energy

$TEMP(K) = \theta$ - Colour temperatures

$UK(I) = u_{K,i}$ - U.C.S. co-ordinate of any test samples (index i) under test lamp (suffix K)

$VK(I) = v_{K,i}$ - U.C.S. co-ordinate of any test samples (index i) under test lamp (suffix K)

$UO(I) = u_{o,i}$ - U.C.S. co-ordinate of any test sample (index i) under reference illuminant (suffix o)

$VO(I) = v_{o,i}$ - U.C.S. co-ordinate of any test sample (index i) under reference illuminant (suffix o)

$UREF(K) = u_o(\theta)$ - U.C.S. co-ordinate of reference temperature

$VREF(K) = v_o(\theta)$ - U.C.S. co-ordinate of reference temperature

$UVABS = \left| (u,v)_\theta \right|$ - Distance in u,v diagram from test source to reference illuminant

$WAVLG = \text{Wavelength } (\lambda)$ - Includes decimal point

$WK(I) = w_{K,i}^*$ - Lightness index, samples under test lamp

$WO(I) = w_{o,i}^*$ - Lightness index, samples under reference illuminant

$XBAR(L) = \bar{x}(\lambda)$ - C.I.E. spectral tristimulus values

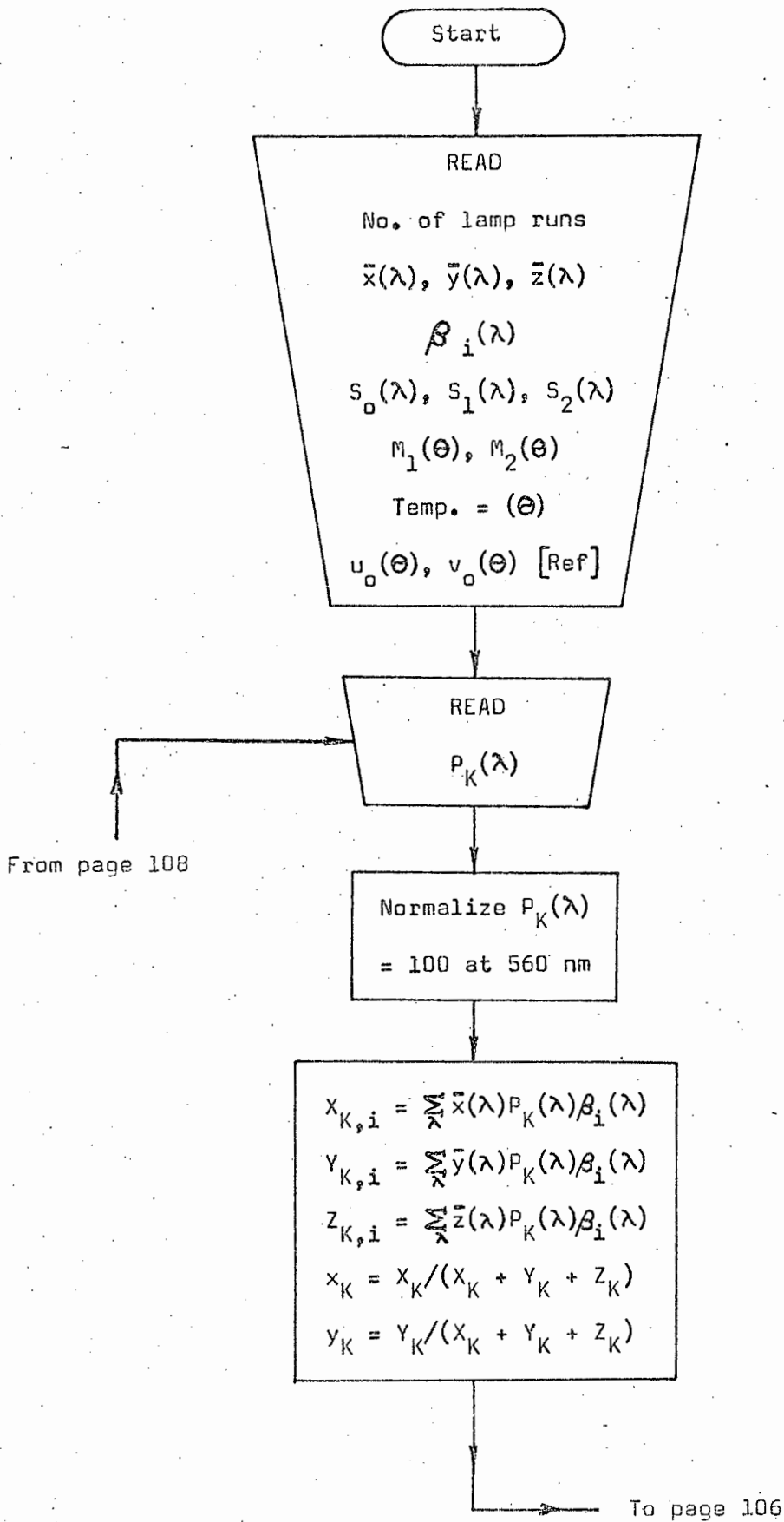
$XK = x_K$ - C.I.E. chromaticity co-ordinate of test lamp

$YBAR(L) = \bar{y}(\lambda)$ - C.I.E. spectral tristimulus values

$YK = y_K$ - C.I.E. chromaticity co-ordinate of test lamp

$ZBAR(L) = \bar{z}(\lambda)$ - C.I.E. spectral tristimulus values

FLOW DIAGRAM



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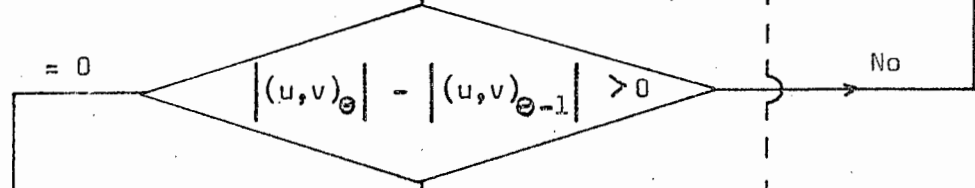
$$\% \text{ Line Energy} = 100 \times \sum_{\text{lines}} \bar{y}(\lambda) P_K(\lambda) / Y_K$$

$$u_{K,i} = 4X_{K,i} / (X_{K,i} + 15Y_{K,i} + 3Z_{K,i})$$

$$v_{K,i} = 6Y_{K,i} / (X_{K,i} + 15Y_{K,i} + 3Z_{K,i})$$

$$w_{K,i}^* = 25(100Y_{K,i} / Y_K)^{1/3} - 17$$

$$|(u,v)_\theta| = [(u_K - u_o(\theta))^2 + (v_K - v_o(\theta))^2]^{1/2}$$



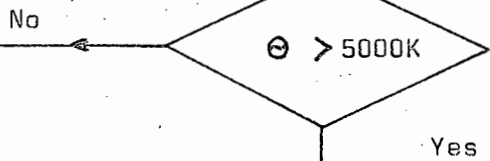
$$\theta = \theta - 1$$

Displacement

$$\Delta u = u_K - u_o(\theta)$$

$$\Delta v = v_K - v_o(\theta)$$

$\theta \geq 2500K$



Regenerate λ

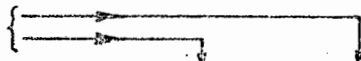
$$P_o(\lambda) = \frac{1}{\lambda(e^{14.388/\lambda} - 1)}$$

Regenerate λ (printout only)

$$P_o(\lambda) = S_o(\lambda) + S_1(\lambda)M_1(\theta) + S_2(\lambda)M_2(\theta)$$

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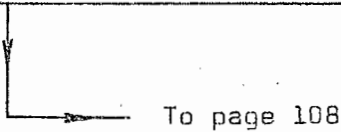


Normalize $P_o(\lambda)$
 = 100 at 560 nm

$$\begin{aligned} X_{o,i} &= \sum \bar{x}(\lambda) P_o(\lambda) \beta_i(\lambda) \\ Y_{o,i} &= \sum \bar{y}(\lambda) P_o(\lambda) \beta_i(\lambda) \\ Z_{o,i} &= \sum \bar{z}(\lambda) P_o(\lambda) \beta_i(\lambda) \\ u_{o,i} &= 4X_{o,i} / (X_{o,i} + 15Y_{o,i} + 3Z_{o,i}) \\ v_{o,i} &= 6Y_{o,i} / (X_{o,i} + 15Y_{o,i} + 3Z_{o,i}) \\ w_{o,i}^* &= 25(100Y_{o,i} / Y_o)^{1/3} - 17 \end{aligned}$$

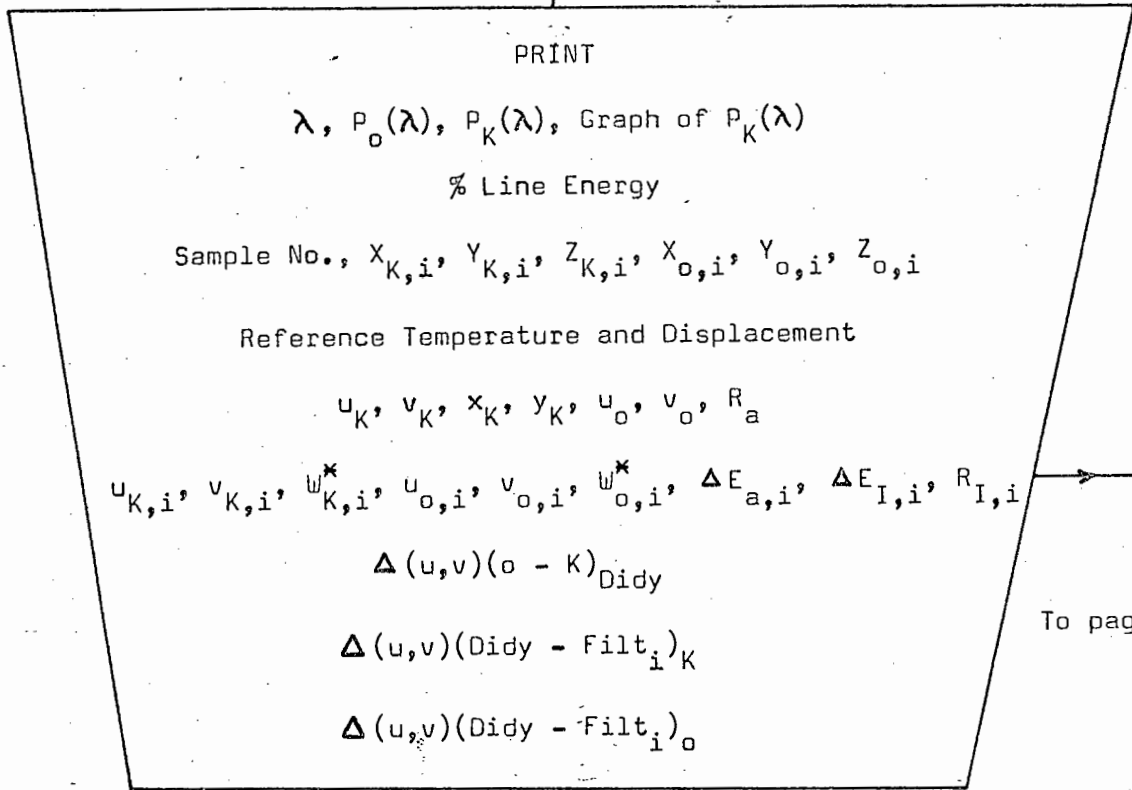
$$\begin{aligned} \Delta E_{a,i} &= \left\{ [(u_{K,i} - u_{o,i}) - (u_K - u_o)]^2 + [(v_{K,i} - v_{o,i}) - (v_K - v_o)]^2 \right\}^{1/2} \\ R_a &= 100 - 460 \sum_{i=1}^8 \Delta E_{a,i} \\ \Delta E_{I,i} &= \left\{ [w_{K,i} - w_{o,i}]^2 + 13^2 [w_{K,i}(u_{K,i} - u_K) - w_{o,i}(u_{o,i} - u_o)]^2 + \right. \\ &\quad \left. 13^2 [w_{K,i}(v_{K,i} - v_K) - w_{o,i}(v_{o,i} - v_o)]^2 \right\}^{1/2} \\ R_{I,i} &= 100 - 4.6 \Delta E_{I,i} \end{aligned}$$

$$\begin{aligned} \Delta(u,v)(\text{Didy} - \text{Filt}_i)_o &= \left\{ (u_{o\text{Didy}} - u_{o,i})^2 + (v_{o\text{Didy}} - v_{o,i})^2 \right\}^{1/2} \\ \Delta(u,v)(\text{Didy} - \text{Filt}_i)_K &= \left\{ (u_{K\text{Didy}} - u_{K,i})^2 + (v_{K\text{Didy}} - v_{K,i})^2 \right\}^{1/2} \\ \Delta(u,v)(o - K)_{\text{Didy}} &= \left\{ (u_{o\text{Didy}} - u_{K\text{Didy}})^2 + (v_{o\text{Didy}} - v_{K\text{Didy}})^2 \right\}^{1/2} \end{aligned}$$

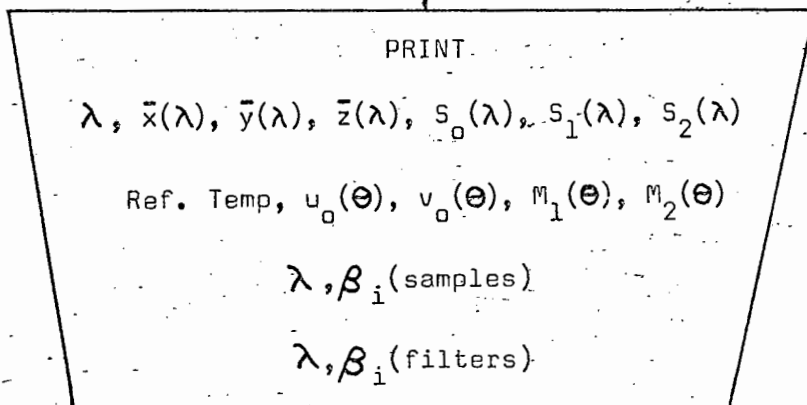


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STOP

APPENDIX 3

Determination of $\tau(\lambda)$ for the "universal" multi-comparison device II.

A3.1 Arrangement

The spectroradiometer⁽²⁵⁾ was set up as in Fig. 53. A large anastigmat L_1 of about 110 mm diameter and 305 mm focal length serves as collimating lens. Two 60° prisms (110 x 90 mm) in tandem are followed by an achromatic lens L_2 of 127 mm diameter and 610 mm focal length. The exit slit D can move by means of a micrometric setting x along the spectral surface which is a plane for practical purposes over the range of interest, between 380 nm at $x = 0$ and 780 nm at $x = 60$ divisions. Both the height and width of the exit slit D and the entrance slit d are adjustable. An EMI photomultiplier tube serves as a detector which moves with the exit slit. It has associated with it a 2 kV stabilised power supply. The dynode voltage can be switched to different values to adjust the sensitivity of the photomultiplier.

The output was connected (Fig. 54) via a 120 k Ω resistor R to a universal shunt and spot galvanometer. The voltage developed across R was recorded using a digital logging system, which logged this voltage by means of a typewriter. It was found that a 2 μ F condenser connected across R provided optimum reduction of the minor variations observed on the digital voltmeter. The spot galvanometer served as a useful check to avoid exceeding the rating of the photomultiplier tube.

A projector lamp (Fig. 53) was focussed onto the entrance slit using lens L_3 , and was suitably shielded to prevent stray light entering the

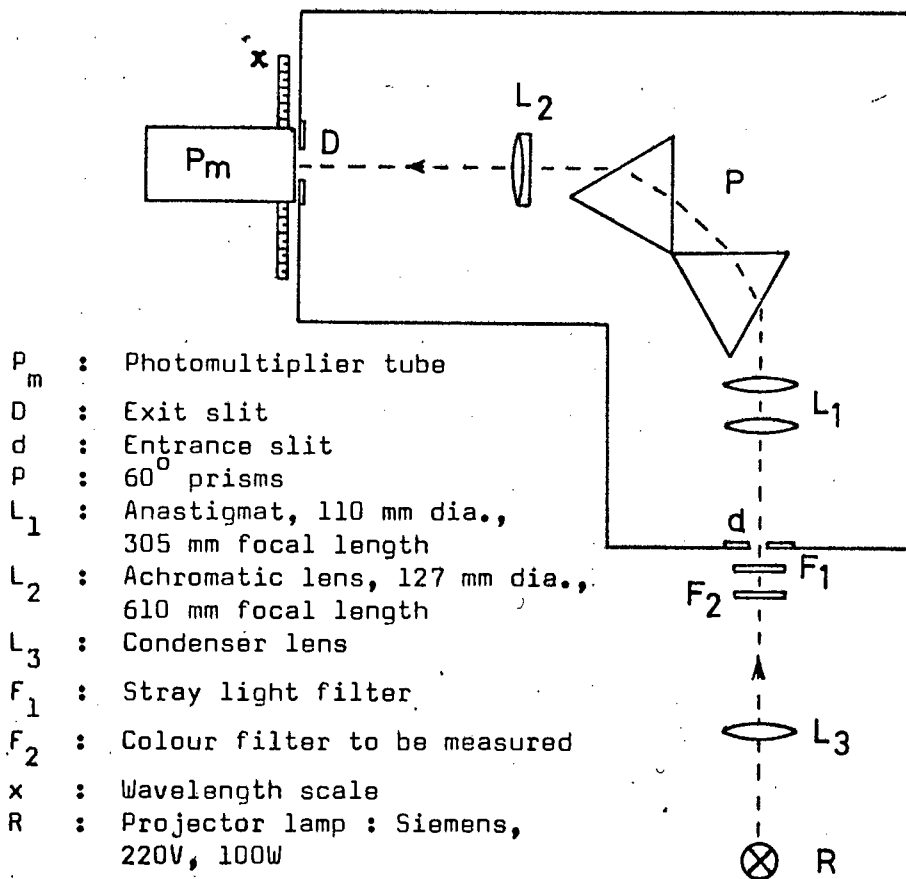


Fig. 53. Schematic diagram of spectroradiometer

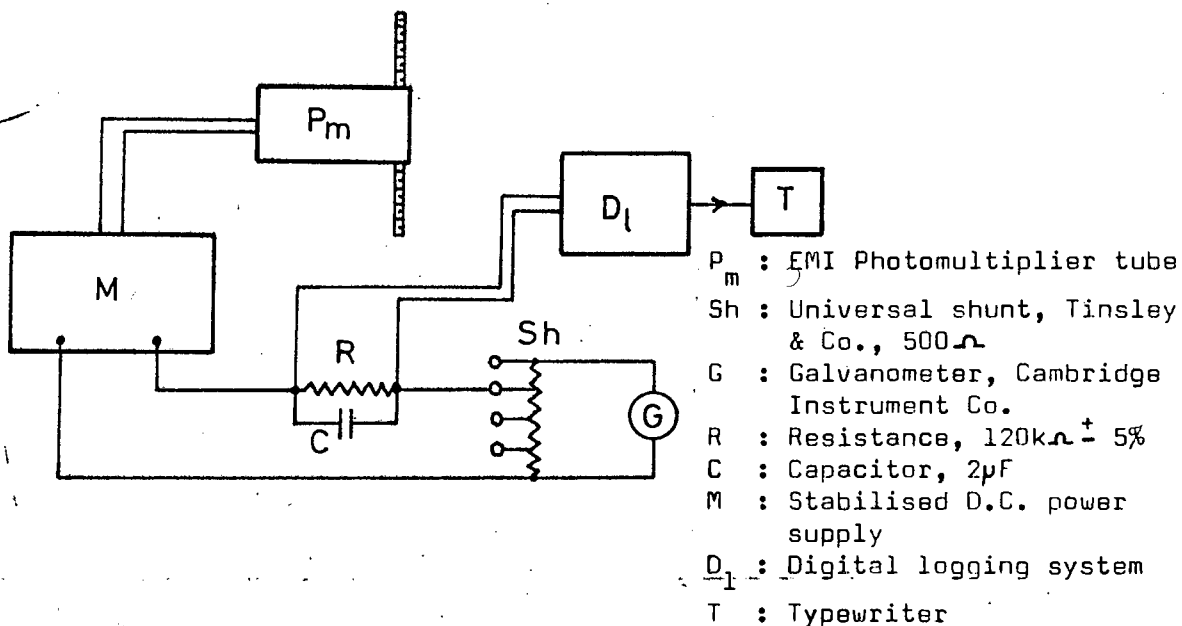


Fig. 54. Output connections of spectroradiometer

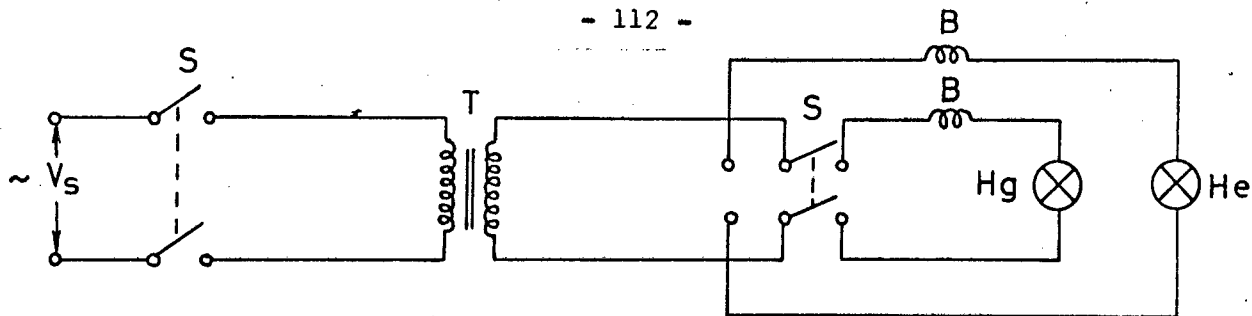
monochromator. The filter to be measured, F_2 , was placed in a device which enabled the filter to be removed from or inserted into the path of the light beam focussed onto the entrance slit. Filter F_1 was a stray light filter.

A3.2 Wavelength Calibration

The calibration of x position versus wavelength was obtained using both a mercury-cadmium-zinc lamp and a helium lamp (Fig. 55). The mercury green line of wavelength 546.1 nm, extremely strong and easily located, was set at 45.40 divisions by adjusting screws on the base of the photometer. The x positions of the more powerful lines of the Hg-Cd-Zn lamp were recorded, as were the lines of the He lamp which provided useful values in the shorter and longer wavelength regions. The wavelengths of the lines were taken from tables⁽²⁶⁾. The x position of a line was obtained by taking the arithmetic mean of two identical readings on the flanks of the lines at approximately 80% of the peak value (see Records, section R2.2). In Figs. 57 and 58 the measured x positions of the lines have been plotted against wavelength. Hartman's equation

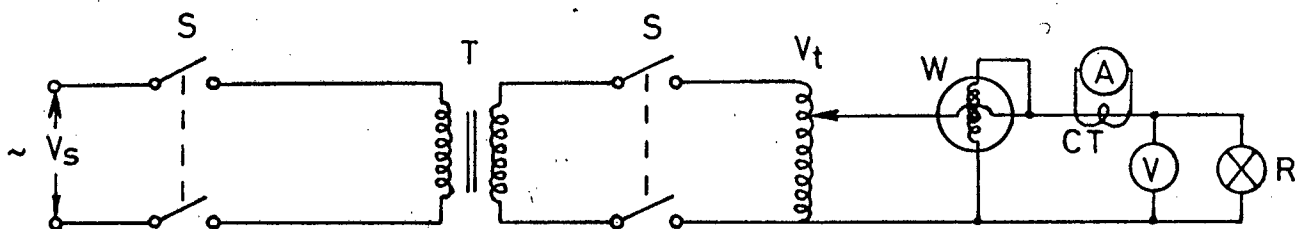
$$(\lambda - \lambda_0)(x_0 - x) = \text{constant} \quad \dots\dots\dots (A3.1)$$

was used to obtain the equations for three different dispersion curves from which x values at selected intervals could be calculated. One curve was used in the long wavelength region, one in the middle wavelength region and one in the shorter wavelength region, the selected λ -values for which are shown in Figs. 57 and 58. The equation for each curve was derived by inserting the measured x positions and known λ -values of three lines into an existing computer programme⁽²⁷⁾ to obtain the values of λ_0 and x_0 .



- V_s : 230V A.C. regulated supply from Foster Electronic Motor Control Unit
- T : Foster Constant Voltage unit - input 190-250V, 500VA, 50HZ
output $230 \pm 0.5V$, 2.18 amps
- B : Ballasts
- Hg : Mercury/Zinc/Cadmium lamp, Philips 93145E, 0.9 amps
- He : Helium lamp, Philips 93098E, 0.9 amps
- S : Switches

Fig. 55. Circuit diagram for lamps used in determination of dispersion curve.



- V_s : 230V A.C. regulated supply from Foster Electronic Motor Control Unit
- T : Foster Constant voltage unit - input 190-250V, 500VA, 50HZ
output $230 \pm 0.5V$, 2.18 amps
- S : Switches
- V_T : Variac, Zenith Electrical Co., 1.65VA, 0-220V
- W : Wattmeter, Cambridge Instrument Co.
- CT : Current transformer, Gossen & Co., 0.5 : 5A
- A : Ammeter, 0-5A
- V : Digital voltmeter, Rochar
- R : 220V, 100W Siemens projector lamp

Fig. 56. Circuit diagram for lamp used in transmission factor measurements.

Fig. 57. Dispersion curve (measured), 380 - 560 nm.

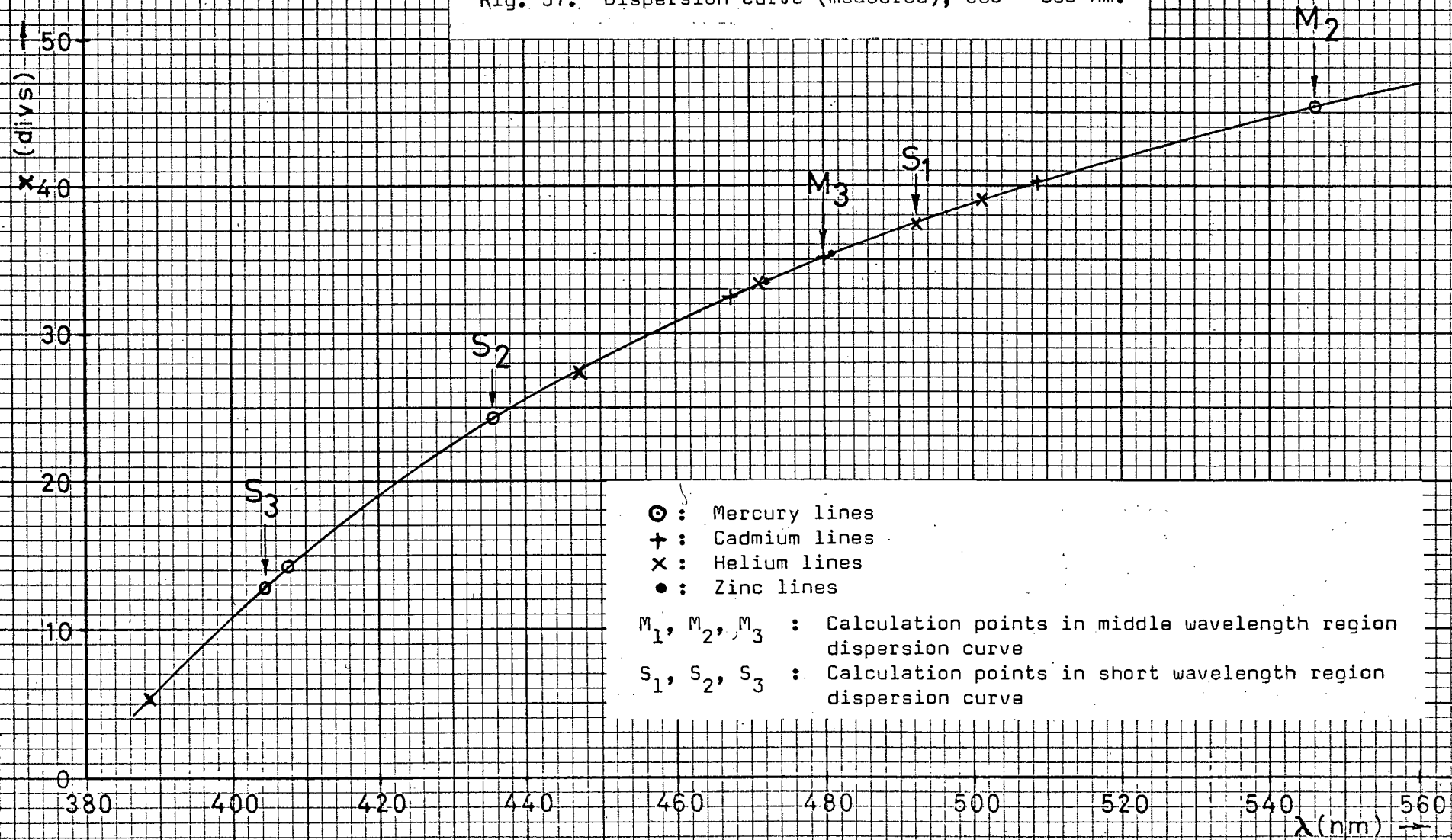
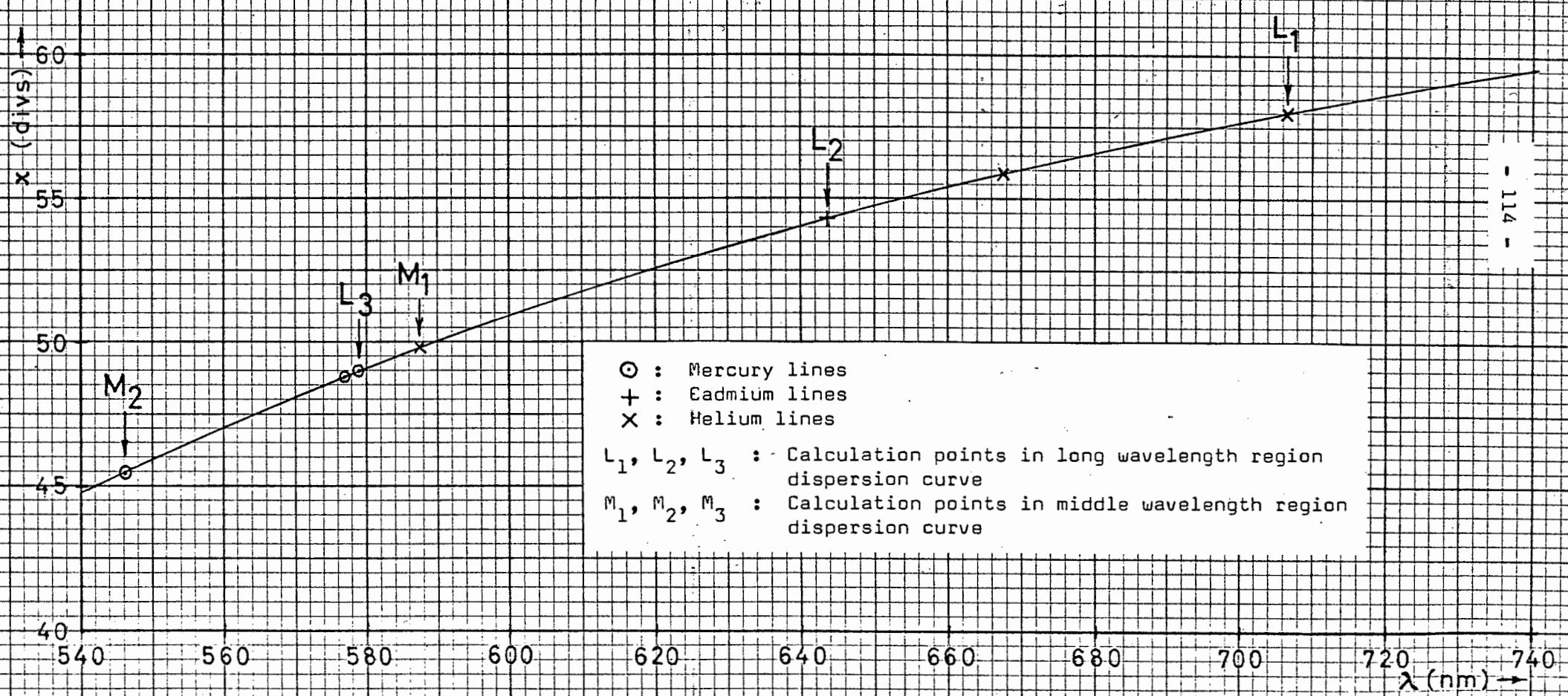


Fig. 58. Dispersion curve (measured), 540 - 740 nm.



\circ : Mercury lines
 $+$: Cadmium lines
 \times : Helium lines
 L_1, L_2, L_3 : Calculation points in long wavelength region dispersion curve
 M_1, M_2, M_3 : Calculation points in middle wavelength region dispersion curve

Values of x at 5 nm intervals, as well as the dispersion at these wavelengths, were then determined from the derived equations. These three calculated curves enabled more accurate x values to be obtained than could have been done from one curve based only on three line measurements.

A3.3 $\tau(\lambda)$ Measurement of filters

The circuit was connected as in Fig. 56. The lamp voltage of the projector lamp was kept constant at 210V throughout the measurements (i.e. slightly underrun). The output voltage across resistor R was recorded. Two readings were taken, with and without the filter to be measured in the path of the light beam at wavelengths from 730 to 380 nm. The ratio of the two gives the transmission factor of the filter at that particular wavelength. This was done for the test field and all the comparison fields of UM. II, as well as for the individual filter components.

Stray light filters were used only in the red and blue regions for the stage colour filters and comparison fields, but throughout the spectrum for the test field (didymium) measurement. This was done since stray light is most likely to be serious where the reading is relatively small compared with readings in the rest of the spectrum⁽²⁸⁾, and the didymium glass exhibits a series of peaks and troughs throughout its $\tau(\lambda)$ curve (Fig. 1). The seriousness of stray light in a particular spectral region can be reduced by inserting a filter mainly transmitting in this region.

Readings were taken at 10 nm intervals for the stage colour filters, but at 5 nm spacing for the didymium glass which, in some wavelength regions, showed large variations in $\tau(\lambda)$ over an interval of 10 nm.

As a check, measurements were done on UM. II comparison field III both with the colour filters inserted between the glasses and with the colour filters placed in front of the glasses (Fig. 59). The measurements of the latter appeared to be slightly lower particularly in the longer wavelength region, as may be seen in Fig. 59. Values calculated from the product of $\tau(\lambda)$ measured for the colour filters alone and $\tau(\lambda)$ for the glasses lay in between the abovementioned two curves in most regions of the spectrum. These differences in $\tau(\lambda)$ could be a result of reflections at the glass-air surfaces. Some of these reflective surfaces would disappear with different clamping arrangements of the glasses and colour filters. Measurements were done for the other filter fields with the colour filters inserted between the glasses, as this is the arrangement used in the construction of the device.

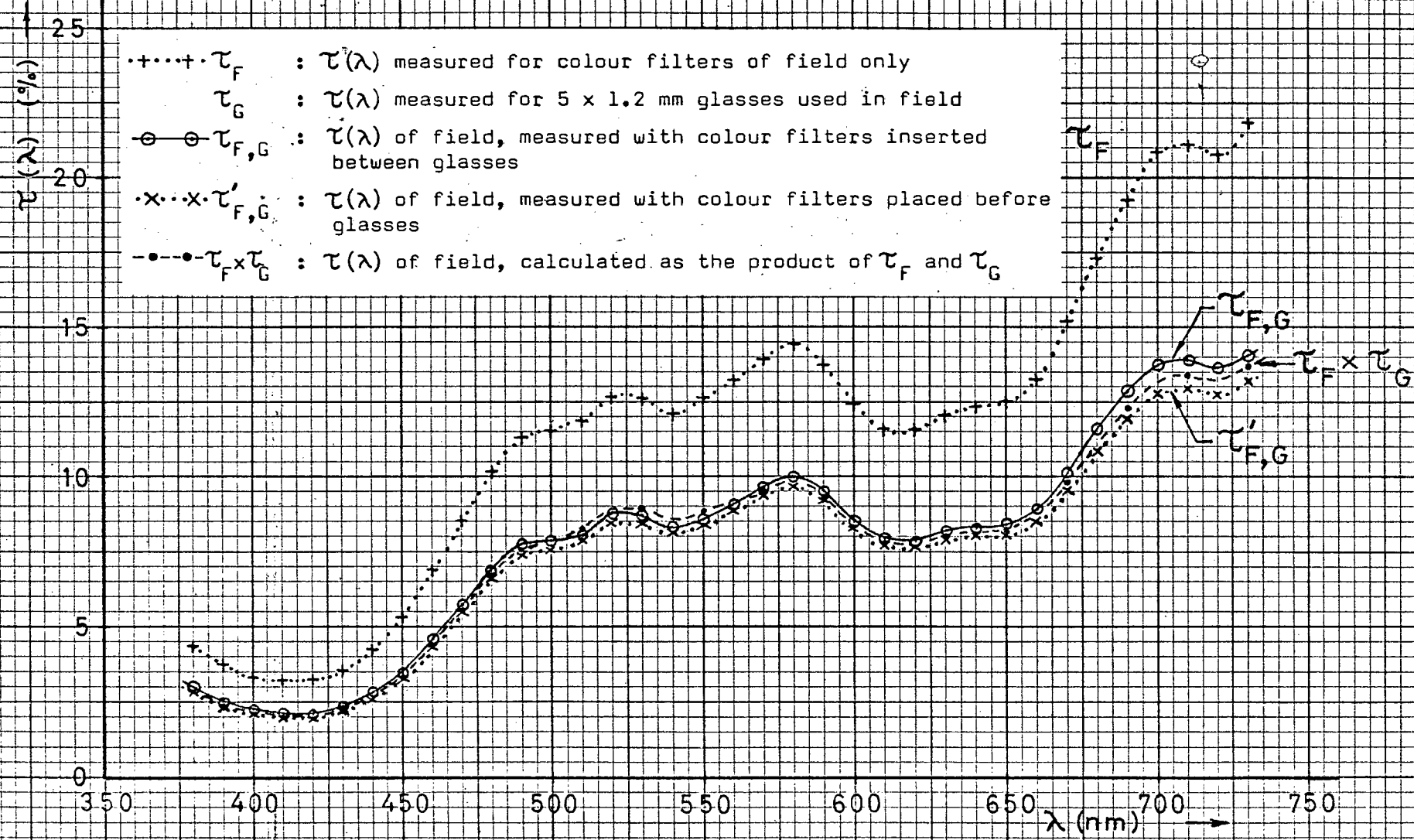
Further measurement checks were made using equation (4.1), namely

$$\tau(\lambda)_{1, 2, \dots, i} = \tau(\lambda)_1 \times \tau(\lambda)_2 \times \dots \times \tau(\lambda)_i \dots \dots \dots (4.1)$$

where i is the number of filters measured. Some measurements were within 1% of the calculated values, others e.g. to within 6% (Records, section R2.1). The largest percentage errors in measurement were found at very low values of $\tau(\lambda)$, where small discrepancies were not considered very important.

In addition, the linearity of the spectroradiometer⁽²⁹⁾ in the blue and green regions was verified using a linearity box (Records, section R2.1).

Fig. 59. Transmission curves for "universal" multi-comparison device II, comparison field III', showing differences in measurements.



APPENDIX 4

Determination of (x,y) and (u,v) co-ordinates of the filter devices

C.I.E. (x,y) chromaticity co-ordinates of the filter devices when observing different lamps were determined using the Lovibond-Schofield Tintometer. The tintometer contains a number of Lovibond permanent glass colour slides, covering the range 0.1 - 80 Lovibond units in the red and yellow primaries, and 0.1 - 10 in the blue primary colour. These slides are contained in a plastic box upon which is mounted a vertical viewing tube and a compartment for the C.I.E. Davis-Gibson light filter. This filter is a double compartment boro-silicate glass cell with two compartments each filled with appropriate solutions which transform the light from Illuminant A of the lamps into Illuminant C (daylight). These lamps are contained in an illuminating cabinet, and are accurately calibrated for colour temperature so that they may be operated at the necessary 2854K of Illuminant A. Light from both lamps falls on both the sample and the reference fields at 45° , and the sample is viewed at 90° , so that specular reflection does not interfere with colour appreciation.

The electrical equipment consists of a constant voltage transformer, a variable resistance and an ammeter, together with a foot switch to prevent the lamps being left switched on when not in use. The resistance is adjusted until the correct amperage of 9.2 amps is registered, as required by the lamp calibration certificate.

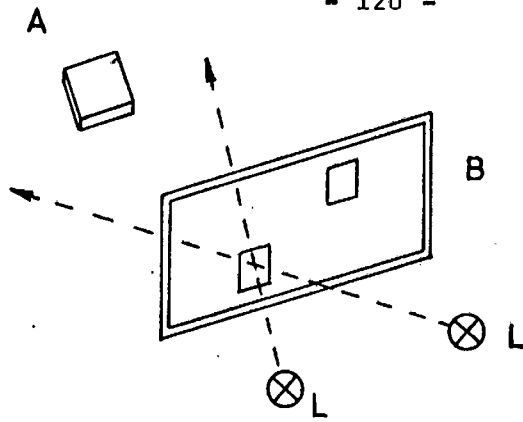
A magnesium oxide surface (the white standard of international convention) is fitted over the aperture of the reference field, and a magnesium carbonate block is placed about 12 inches behind the back-plate

of the light cabinet opposite the aperture for the sample field. The lamps will then illuminate the white reference background without affecting the block, because the beams from the lamps cross at the backplate and then diverge (see Fig. 60). The magnesium carbonate block is tilted at 45° to the backplate and is illuminated with the test source from above (see Fig. 61). The operator's eyes are shielded using a screen, and the filter device to be measured placed between the magnesium carbonate block and the backplate.

The colour of the sample is matched against the glasses by adjusting the glasses for hue and saturation, while the relative brightness is adjusted by means of a Rothamsted device. It is not advisable to gaze into the eye-piece longer than necessary, as discrimination decreases with fatigue. When the slides are satisfactorily selected, the two halves of the field will appear identical. Not more than two of the three series of Lovibond colour slides should be used. When the sample is accurately matched, the colour readings on the Tintometer and the reading on the brightness scale are noted. Carefully note whether this reading is positive (black) or negative (red).

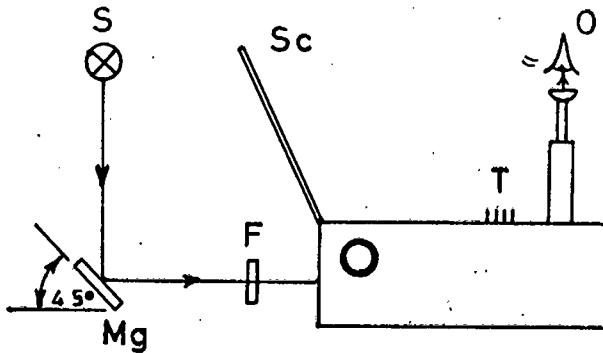
In order to obtain the C.I.E. chromaticity co-ordinates, the point of intersection of the two lines representing the two Lovibond values are found on the conversion graph printed on metal. Nylon threads, suspended through two holes in the metal graph, are supplied to act as cursors. These are moved until they pass through this point of intersection. The x and z C.I.E. co-ordinates are read off where the cursors cross their respective scales. In order to obtain the y co-ordinate, the x and z values are added and subtracted from 1.

To obtain a rapid transformation of the (x,y) values to the (u,v)



- A : Area under review not affected by lamps
- B : Backplate
- L : Calibrated lamps

Fig. 60. Tintometer lamp arrangement



- S : Test source
- F : Filter device to be measured
- Sc : Screen
- O : Observer
- Mg : Magnesium carbonate block
- T : Tintometer filters

Fig. 61. Determination of chromaticities of a filter field under different lamps, using a Tintometer.

U.C.S. co-ordinates, an $(x,y) \rightarrow (u,v)$ nomogram was used, the details of which are described in Appendix 1.

Using the above method (x,y) co-ordinates were obtained for various single-comparison filter instruments for observers H.E. and M.C.

APPENDIX 5

Composition of initial single-comparison filter devices

H.E. I

Test Field: 1 x 5 mm thick Didymium glass (Schott BG 36)
1 x "Cinabex" No. 17 Steel Blue stage colour filter
1 x "Cinemoid" No. 17 Steel Blue stage colour filter
Comparison
Field: 1 x "Cinemoid" No. 60 Pale Grey stage colour filter
1 x 0.61 neutral density filter in combination with
neutral filter of unknown density

H.E. II

Test Field: 1 x 5 mm thick Didymium glass (Schott BG 36)
2 x "Cinemoid" No. 17 Steel Blue stage colour filters
Comparison
Field: 2 x "Cinemoid" No. 55 Chocolate Tint stage colour filters
1 x 0.20 neutral density filter

Large Demonstration Model

Test Field: 1 x 4 mm thick Didymium glass (Chance ON 16)
1 x 1.6 mm thick pale blue-green heat absorbing filter
(Chance ON 13)
1 x 0.1 neutral density filter
Comparison
Field: 1 x 0.61 neutral density filter

Original N.P.L. Model

Test Field: 2 x 4 mm thick Didymium glass (Chance ON 16)

Comparison
Field: 1 x "Cinemoid" No. 56 Pale Chocolate stage colour filter.

M.C. I

Test Field: 1 x 5 mm thick Didymium glass (Schott BG 36)
1 x "Cinemoid" No. 40 Pale Blue stage colour filter

Comparison
Field: 1 x "Cinemoid" No. 36 Pale Lavender stage colour filter
1 x "Cinemoid" No. 55 Chocolate Tint stage colour filter

M.C. II

Test Field: 1 x 5 mm thick Didymium glass (Schott BG 36)
1 x "Cinemoid" No. 45 Daylight stage colour filter
1 x "Cinabex" No. 50 Pale Yellow stage colour filter
1 x 0.2 neutral density filter

Comparison
Field: 1 x "Cinemoid" No. 56 Pale Chocolate stage colour filter
1 x "Cinemoid" No. 60 Pale Grey stage colour filter

M.C. III

Test Field: 1 x 5 mm thick Didymium glass (Schott BG 36)
1 x "Cinemoid" No. 17 Steel Blue stage colour filter
1 x 0.1 neutral density filter

Comparison
Field: 1 x "Cinemoid" No. 56 Pale Chocolate stage colour filter
1 x 0.2 neutral density filter

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