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1. Introduction

Net radiometers are extensively used for the measurement of the difference of the incoming and outgoing electromagnetic radiation, either at the earth's surface or above. It is common to discriminate between shortwave radiation (direct or indirect sunlight) and longwave radiation (thermal radiation emitted by the earth's surface, or the atmosphere), because there is very little spectral overlap between these two entities. Since net radiometers are sensitive to both kinds of radiation, they have to be calibrated for shortwave radiation and for longwave radiation. At the KNMI we have a facility for shortwave calibrations, but we can not do longwave calibrations. It is assumed that the responsivities are the same.

Since many years we do measurements with a Funk type net radiometer at Cabauw. More recently also a Fritschen Q*6 and a Schulze net radiometer are employed. Both the Funk and the Fritschen radiometer were shortwave calibrated in our laboratory, but the manufacturer's (Dr. Lange) calibration of the Schulze was used. The net radiation at Cabauw is also inferred from the sum of the four components using Kipp CM11 pyranometers and Eppley pyrgeometers.

From an ongoing analysis of the four measurements of the net radiation (Funk, Fritschen, Schulze and sum of the components) it was found that both the Funk and the Fritschen gave lower absolute readings when compared to the Schulze or the sum of the components, at day as well as at night. This led us to question our calibration procedure.

2. The KNMI calibration of net radiometers

Funk and Fritschen net radiometers are laboratory calibrated by the KNMI for shortwave radiation only. The method is in short the following (a detailed description is given by Frerichs, 1981).
The instrument to be calibrated and the reference net radiometer (a Funk from Middleton, sn. 1176) are placed on a turntable under a halogen lamp at a distance of 1 m in a temperature controlled optical laboratory room. The lamp is fitted with an air cooled cold filter and a shutter (Fig.1). At the position of the instruments, the radiation intensity is about 500 W/m^2. The instruments are ventilated with an air stream of 2-3.5 m/s. The lower domes of the net radiometers - are covered with double walled metal caps, through which water flows from a thermostatted bath. While the lamp is burning, but its radiation being blocked by the shutter, the temperature of the bath is adjusted such that the radiometer outputs are about zero Volt. Next, during 2 minutes a series of measurements are taken with the shutter open. Two more series of the same duration as the first series with closed and open shutter are made. The table is turned by 180 degrees, so the instruments exchange places, and again three series of measurements are done. Then the instrument to be calibrated is turned upside down and the above sequence is repeated. Finally, the results are averaged and the ratio of the responivity of the instrument to be calibrated and the reference is calculated.

The reference Funk was calibrated in 1981 by the Belgian Meteorological Institute (KMI). They quote a shortwave responsivity of 40.82 microvolt per W/m^2 at a radiation intensity of 175 W/m^2. This value has been used by the KNMI up to present. According to the KMI, the reference instrument has a non-linear response of 0.02% per W/m^2 between 0 and 175 W/m^2

(higher intensities were not considered). If this non-linear behaviour is extrapolated to the intensity used in our calibration facility, 500 W/m^2, it would mean that the responsivity of the reference instrument is notably decreased. This causes no errors as long as the instrument to be calibrated has the same non-linear behaviour. In field use non-linear response never was taken into account by the KNMI. Moreover, if a different instrument like the Fritschen is considered, a correction for the difference in non-linear response of the two instruments should be, but never was, applied.
It is further of interest that the KMI found a longwave responsivity of the reference instrument of 39.62 microvolt per W/m^2 and an asymmetry between the upper and lower side of the instrument of 1.5% for shortwave radiation and 3.6% for longwave radiation. Presumably, the above quoted shortwave responsivity of 40.82 microvolt per W/m^2 is the average value of the upper and the lower surface. According to the manufacturer, the response values are 39.1 and 39.5 microvolt per W/m^2 for shortwave and longwave radiation, respectively (the shortwave value as quoted by the manufacturer has been devided by 1.022 to account for the difference between the IPS scale and the more recent WRR scale (Froelich and London, 1986)). Radiation intensities were not specified. These values are 4.2% (shortwave, 175 W/m^2) and 0.3% (longwave) less than the KMI values.

The calibration procedure adopted by the KNMI thus gives a relative value. However, the quality of the reference is not guaranteed. Therefore, we sought for independent ways of calibration. In the following will be discussed:
a. The response of the reference Funk by comparison with our reference Kipp pyranometer, at various levels of radiation intensity.
b. The same for a Fritschen.
c. The response of a Funk and a Fritschen by means of shading against the sun.

d. The effect of ventilation on the response of the Funk and the Fritschen.

3. Investigations of response

a. The response of the reference Funk

The calibration facility described above was used, with our Kipp CM11 reference pyranometer taking the place of the reference Funk, and the reference Funk at the other position. A glass plate of 5.5 mm thickness was positioned about 10 cm above both instruments in order to block the infrared radiation from the 'cold' filter and the shutter. Both devices are appreciably above room temperature during the calibration proceedings .
As the glass plate is still somewhat heated by the incoming radiation, the temperature of its bottom side (facing the instruments) was monitored with a Heimann infrared thermometer.
The radiation intensity was varied between 95 and 460 W/m2 by changing the lamp voltage, and changing the distance between the lamp and the radiation sensors. A disadvantage of this method might be that the radiation spectrum changes, but this is considered to be of minor importance since the transmission spectrum of the glass Kipp domes, as well as that of polyethylene (of which the Funk and Fritschen domes are made) are reasonably flat (spectral transmission data are given by the Kipp CM11/14 manual and the Schulze manual; no spectral data could be found for the Funk or the Fritschen domes).
Due to the temperature increase of the glass plate an extra infrared radiation was produced of about 1.3% of the shortwave radiation. This amount of radiation was added to the shortwave radiation impinging on the Funk only. In Fig.2a the response of both sides of the Funk is given. It is seen that:

1. the responsivity of the Funk decreases with increasing radiation intensity. Between 100 and 300 W/m^2 the decrease of 0.02% per W/m^2 as quoted by the KMI may fit the observations, but at higher intensities it levels off. From an analysis of Halldin and Lindroth (1992) follows a response loss of 6% at 454 W/m^2 for a Middleton Funk, giving 0.013% per W/m^2.
2. the responsivity is less than the KMI value. At 185 W/m^2 we find 39.39 microvolt per W/m^2 (upper side), whereas the KMI value (after correction for non-linearity) is 40.74, a difference of 3.4%. The manufacturer's calibration of 39.1 microvolt per W/m^2 fits well within our observations (see Fig.1a).
3. the difference in responsivity between the upper and lower side is increasing with radiation intensity, from 1.4% at 95 W/m^2, to 2.8% at 460 W/m^2. The former value is in accordance with the KMI value of 1.5%. Only the upper side is of interest because the reference Funk is always in its upright position during a regular calibration procedure.

b. Response of the Fritschen net radiometer sn. 92318

The procedure is the same as for the reference Funk. Fig.2b displays the results. It is noted that:
1. also the responsivity of the Fritschen decreases with increasing level of radiation, be it that the decrease is less pronounced than with the Funk. Going from 190 to 460 W/m^2, the decrease is 1%, whereas the Funk's response decreased by 3% over the same radiation interval. At 460 W/m^2 the responsivity is 73.25 microvolt per W/m^2 (average of the upper and lower surface), wheras the KNMI calibration, ignoring the non-linearity of the Funk and using the KMI value of 40.82 microvolt per W/m^2, gave 77.82 microvolt per W/m^2 - a difference of 6.3%. The manufacturer's value is 75.2 microvolt per W/m^2, and fits marginally within our observations (Fig. 1b).
2. the asymmetry between upper and lower surface is about 2.5%, and virtually independent of the radiation level.

c. Results of the shading experiments

The shading experiments were done in Cabauw, where we have a permanent set-up of various radiation instruments, among which a Kipp CM11 pyranometer and a Funk and a Fritschen net radiometer. Simultaneously the Kipp and the Funk, or the Kipp and the Fritschen, were shaded by means of 15 cm diameter disks held at a distance of 1.5 m from the instruments. A bright day with no clouds and low turbidity was chosen (25 July 1995). The shading-non shading period was 20 minutes, and repeated over a period of one hour. Data were collected at a rate of 10 Hz. From these data, the value of the net radiation and of the shortwave radiation just before and after shading were determined, making allowance for the response times of the instruments. A sample is: net radiation (Fritschen) before shading 496 W/m^2, after shading -194 W/m^2; the Kipp gave 829 and 85 W/m^2, respectively. The ratio of the radiation jumps is here 0.927. Shortly after the shading experiments the net radiometers were dismounted for calibration. Averaging the shading results and using this calibration, it was found that both the Funk's readings and the Fritschen's readings were 6% lower than the readings of the Kipp.

d. Effect of ventilation

In field use the Funk and the Fritschen are heavily ventilated; the air speed around the domes is 15-30 m/s. The main purpose of the ventilation is to prevent dewfall on the domes. To this purpose, a much lighter (and slightly heated) ventilation would suffice, however. The reason why in the past this strong ventilation was preferred is not clear. It could be that one whished to keep the instrument as good as possible in thermal equilibrium. Anyhow, the ventilation in the field is way different from the ventilation during calibration (2 to 3.5 m/s). This could lead to systematic differences. For instance, Fritschen and Fritschen (1991) report a sensitivity decrease of 4.3% at a wind speed of 7.5 m/s, relative to the sensitivity at zero wind speed.

In order to see whether this effect plays a role in our situation, the ventilation of the Fritschen was switched off for a period of one month and the differences before and after this action were analysed. As a reference the sum of the radiation components was taken. It was found that during the week after the ventilation was switched off the responsivity of the Fritschen was 3% larger than the week before. However, looking at the hours before and after swiching off the ventilation, no apparent change was noticed. Equally, no change was seen when the ventilation was switched on. During the week after switching on the responsivity was 1% less than the week before.

Next to this outdoors test, a test in the optical laboratory was done. The reference Funk and a Fritschen were compared to the reference Kipp as outlined in section 2, but now with inclusion of the same ventilation equipment as used in the field. The radiation intensity was about 360 W/m^2. With the lamp switched on and the shutter open, the optical laboratory room was allowed to stabilize its temperature for about one hour. Then a series of measurements was done without ventilation, which took about 15 minutes, a second series with ventilation, the third series without and finally the last series with ventilation. At all times, the usual ventilation giving an airstream of 2-3.5 m/s was kept on. Unlike in the previously reported procedure, the net radiometers and the Kipp were not exchanged in place, nor were runs done with the Fritschen turned upside down. Also the time interval between measurements with the shutter open and closed was greater (about 15 minutes) than the two minutes of the regular procedure, resulting in a larger temperature excursion of the glass plate. The correction for the glass plate temperature amounted to 2-4% here, whereas it was 1% previously. After correction the results are the following (responsivity in microvolt per W/m^2):

	1st (off)	2nd (on)	3rd (off)	4th (on)	previous (off)
Funk	38.6	37.8	38.2	38.0	38.4
Fritschen	75.9	72.5	72.7	72.7	72.8

There is little difference between the 2nd, 3rd and 4th series of measurements for each instrument, but the responsivity of the Funk decreases 2.1% between the 1st and the 2nd series, and the Fritschen decreases by 4.4%. Typically, different calibrations of the same instrument reproduce within 1%. When compared to the responsivities found earlier, the 1st series of the Funk exhibits a larger responsivity, but the other 3 series are about equally less. The previous calibration of the Fritschen fits best with the 2nd to 4th series. (The previously obtained responsivities were multiplied by 1.01 because of the inhomogeneity of the field of irradiance).
If we reject the first series, no effect of the ventilation seems to be present. But there is no a priori reason why the first series should deviate from the ones following. One may speculate that there is some factor, whether instrumental or in the calibration set-up, that we do not control. A process that comes to mind in this respect is the convective heat transport from the sensor surface to the domes. According to Fritschen and Fritschen (1991), this heat transport is about equal to the thermal conduction through the transducer for a Q*6 radiometer. It is not unlikely that the actual size of the convective heat transport depends, next to the temperature differences between the transducer and the domes, on other factors like the temperature distribution of the instrument housing. It is not without reason that pyranometers are commonly provided with double domes. If this explanation is accepted, it puts error bars of at least a few percent around all calibrations and field measurements. However, the fact that laboratory measurements usually reproduce within 1% is not in favour of this explanation. Regarding the calibration procedure using the Kipp as reference, one is particularly sensitive to changes in ambient infrared radiation. In our

situation ambient infrared radiation is largely controlled by the glass plate over the instrument and an error of, say, 4% is far more than can be explained by changes in environmental temperature. We can not at the moment offer a satisfying explanation for the deviating first series, and thus have to be careful in drawing conclusions from these measurements.

It is concluded that these experiments do not clearly demonstrate an effect of the ventilation on the responsivity. Quite another matter is that the heavy ventilation causes a rapid growth of a layer of dirt on the domes. Even after one day the effect is often noticeable. Cleaning the domes with water and a cloth does not remove all the dirt, especially from the fragile Funk domes. Besides that, we are not able to clean the domes every day. It seems therefore better to reduce the ventilation speed to, say, 3 m/s. Such a ventilation suffices to keep away dew, without having the disadvantage of a rapid scaling of the domes.

4. Discussion

We summarize the main results:

-from laboratory comparison of the reference Funk and the reference Kipp, it is found that the responsivity of the Funk at 460 W/m^2 is 7% less than the value adopted by the KNMI up to now

-the same kind of comparison gives that the responsivity of the Fritschen is 6% less than the one following from the KNMI calibration

-from shading against the sun experiments it follows that both the Funk and the Fritschen measure 6% less than the Kipp

-an effect of ventilation speed on the responsivity of the Fritschen is not clearly demonstrated.

-the manufacturer's calibrations of both the Funk and the

Fritschen fall within the range of the present observations. Neither of the manufacturers specified relevant radiation intensities, however.

From the above results it is concluded that the responsivity of the reference Funk at about 500 W/m^2 is 6-7% less than the value used hitherto. The error is partly due to a difference between the KMI calibration and the present calibration, and partly due to ignoring the non-linear response of the reference Funk. KNMI calibrations of Funk radiometers over the past 10 years do not show any trend. Thus, it can be assumed that the reference Funk did not change in sensitivity over the last decade of years.
Decreasing the responsivity by, say, 6% at all radiation levels would mean an over-correction of the Funk at low radiation because of the non-linear response. The so induced error is never larger than +5 W/m^2, and can be neglected in view of other instrument limitations. Regarding the Fritschen, the error is much less because of its better linear behaviour.

5. Recommendations

1. The responsivity of the reference Funk has to be decreased by 6%.

2. Measurements since 1985 with net radiometers calibrated by the KNMI have to be corrected by +6%.

3. The ventilation of the net radiometers should be reduced to about 3 m/s. In order to prevent dew, the air stream must be heated to some degrees Celsius above ambient.

Acknowledgement

The laboratory measurements were carried out by Rob van Krimpen. Harry Carolus aided in the shading experiments.

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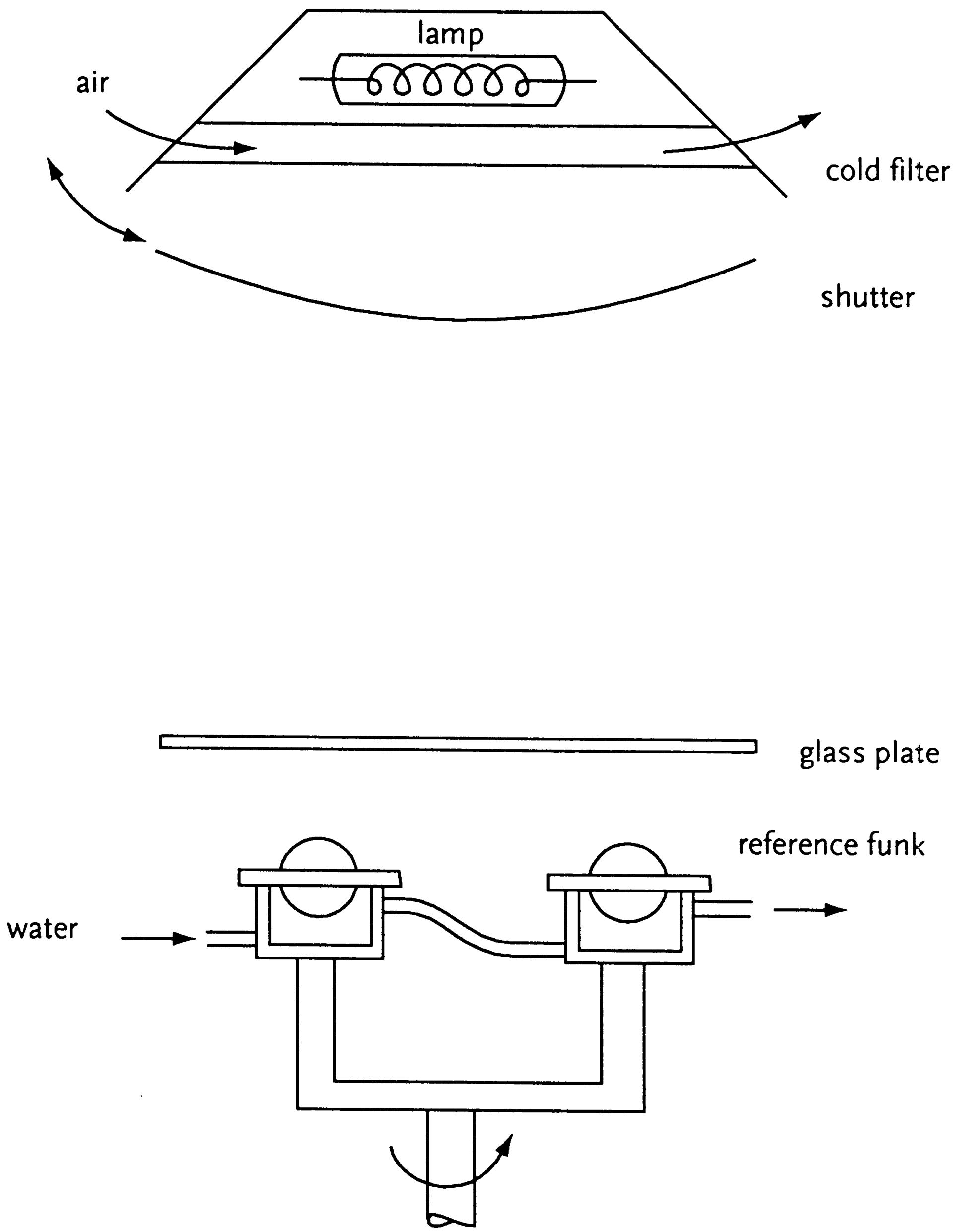
Figures

Fig.1 Schematic lay-out of the calibration set-up.

Fig.2a. Responsivity of the Funk as a function of shortwave irradiance. Diamonds: lower surface; squares: upper surface. The drawn line represents a decrease of the sensitivity by -0.02% per W/m^2. The dotted line represents the manufacturer's calibration; the appropriate radiation intensity is not known.

Fig.2b. Responsivity of the Fritschen. For symbols, see Fig. 2a.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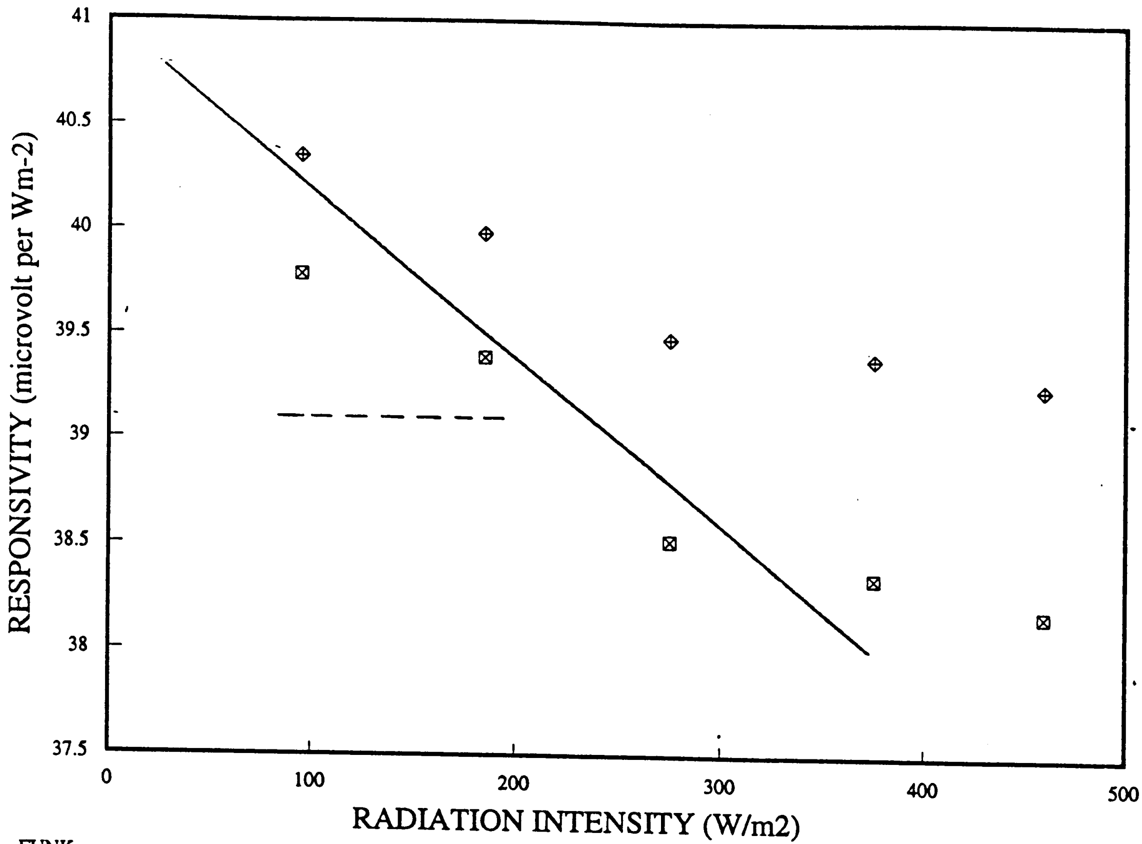
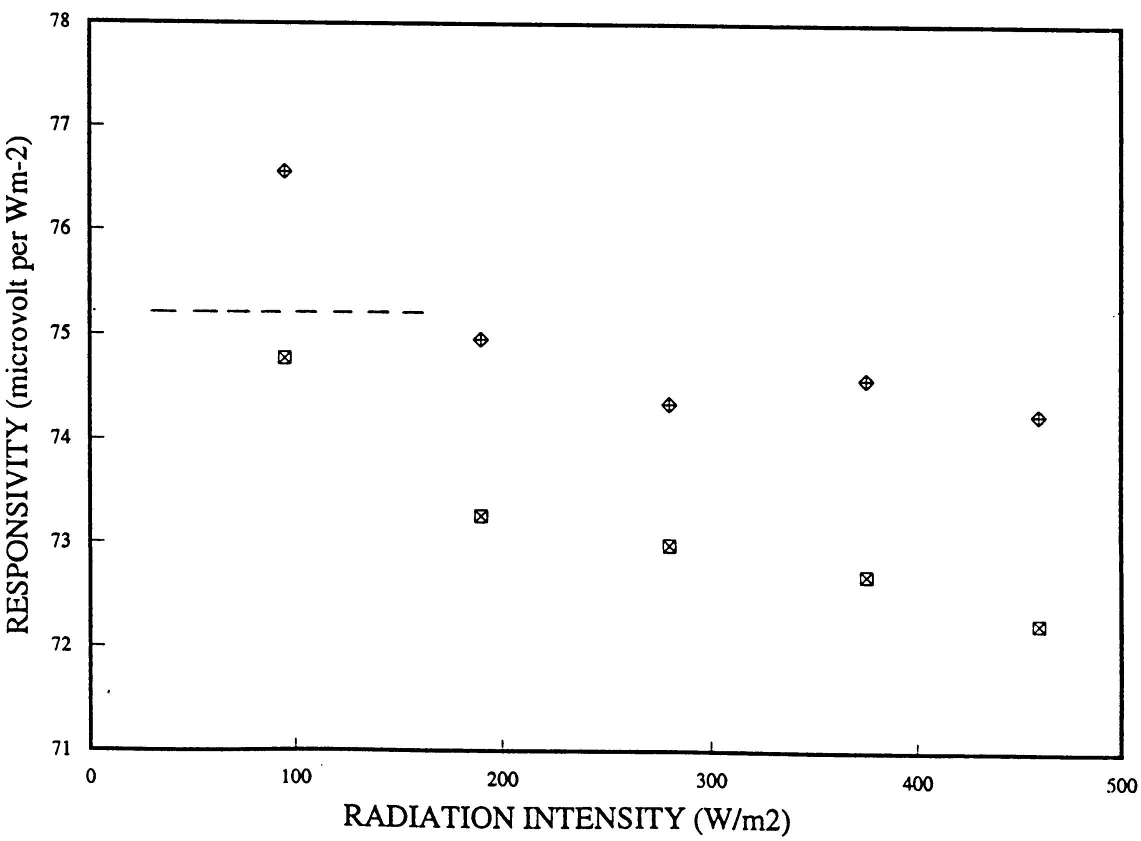
air
cold filter
shutter
glass plate
reference funk
water

Fig. 1



FUNK

Fig. 2a



FRITSCHEN

Fig. 2b