# Absolute linearity measurements on PV HgCdTe detectors in the infrared

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# Why is characterisation of detectors important?

- Because it allows the uncertainty component associated with a particular detector characteristic (linearity, uniformity, temperature coefficient, etc) to be estimated (and used to calculate the combined uncertainty).

  **No characterisation – no uncertainty budget**

- Detector suppliers exaggerate the capabilities of their products. They rely on the inability of their customers to verify their claims.

- Differences in the performance of nominally identical products.

- It allows the selection of the detector with the best performance.

# Parameters determining the performance of detectors

1. The relative spectral radiant power responsivity.
2. The absolute spectral radiant power responsivity.
3. The Noise Power Spectral Density and NEP/NEI
4. Spatial uniformity of response
5. Linearity/non-linearity of response
6. Temperature coefficient of response
7. Frequency of response
8. Stability with time/ageing or fatigue

## A detection system is linear

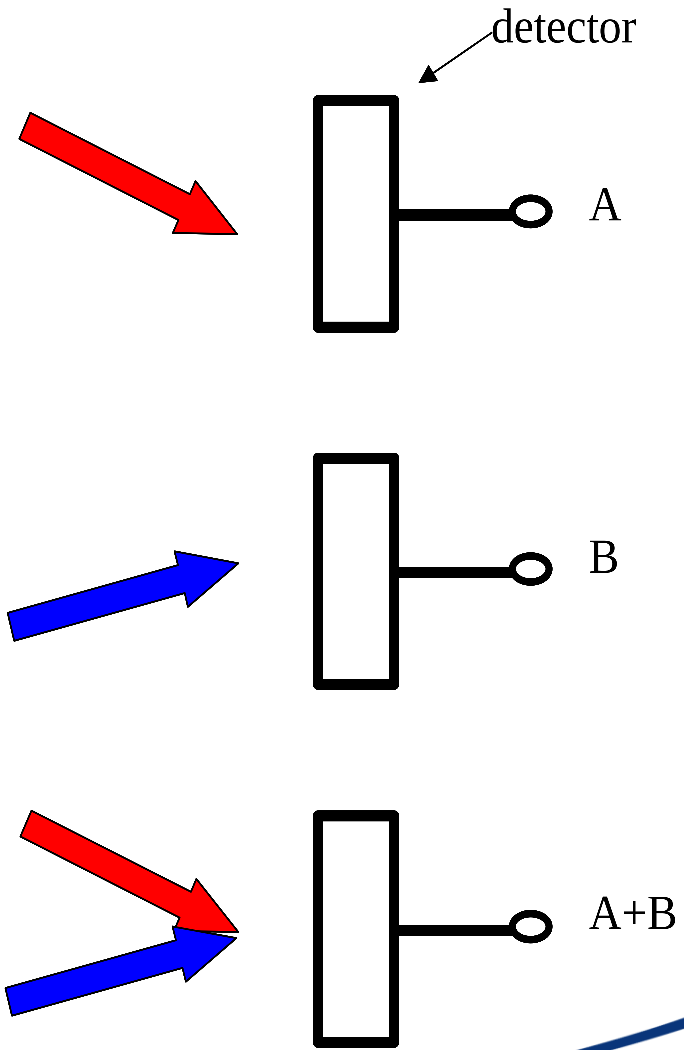
**If its output is directly proportional to the input**

**Linearity is a relatively unpopular measurement,**

**particularly in the infrared**

**Until recently there were no serious scientific publications on the linearity of infrared detectors (despite their widespread use)**

## At NPL we favour ABSOLUTE linearity measurement methods based on power/irradiance superposition.




Accomplished by superimposing two beams.

# Definition of the Linearity Factor

The linearity factor of a detector for an output of $(V_A+V_B)/2$ is given by:

Linearity factor =

$$L\left(V_{A+B}\right)=\frac{V_{A+B}}{\left(V_A+V_B\right)}$$

where $V_A$, $V_B$ and $V_{A+B}$ represent the zero-corrected signals from the detector when apertures A, B and A+B were open, respectively, with $V_A$ set to be approximately equal to $V_B$.

The linearity factor provides the average deviation of the responsivity from nominal over a range of 2:1 at that specific output voltage/power etc.

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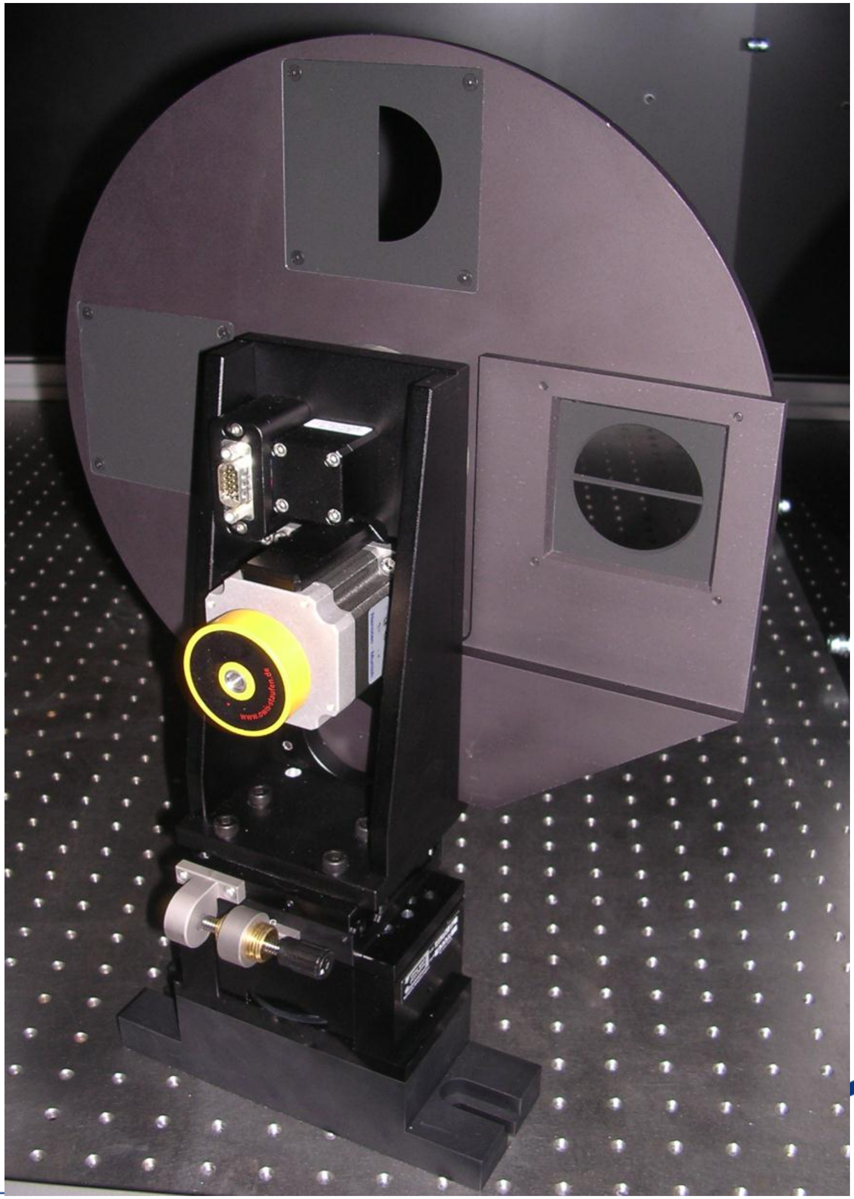
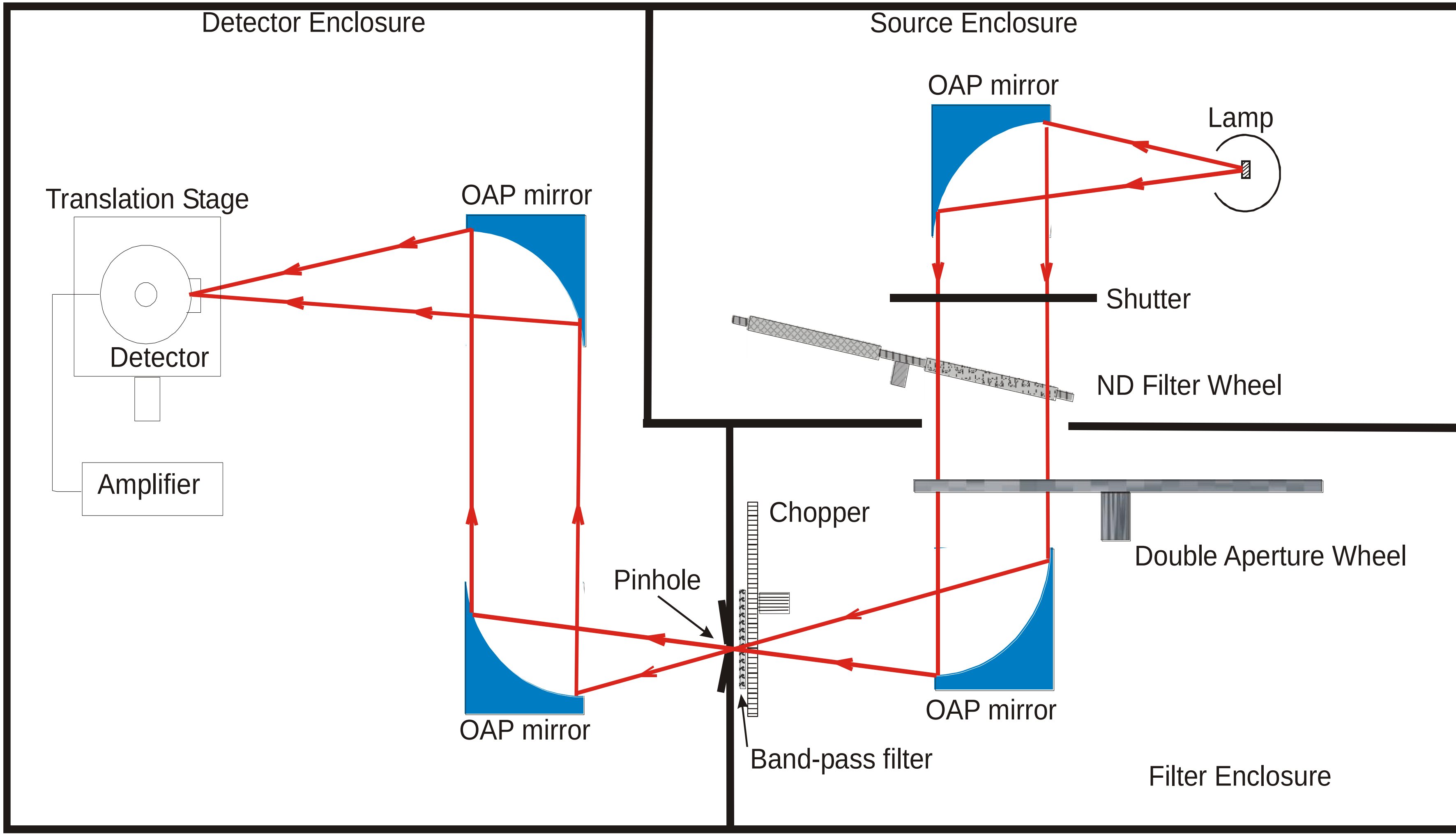
# The "double aperture" wheel



# Layout of the NPL detector linearity measurement facility

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# Advantages of the NPL linearity measurement facility

- It provides an **ABSOLUTE** linearity measurement.
- Ensures linearity characterisation in terms of **irradiance**.
- Uses reflective optics so it can cover a very wide spectral range (with ZnSe-based filters it covers the **0.6 µm to 20 µm** region).
- **It is fully automated.**
- The use of neutral density filters to change the radiant power means that the detector is illuminated with the **same angular characteristics** for all the radiant power levels (compare with the use of apertures to vary the radiant power/irradiance reaching the detector under test).

# Linearity factor of CMT01 detector at 10.3 μm as a function of radiant power

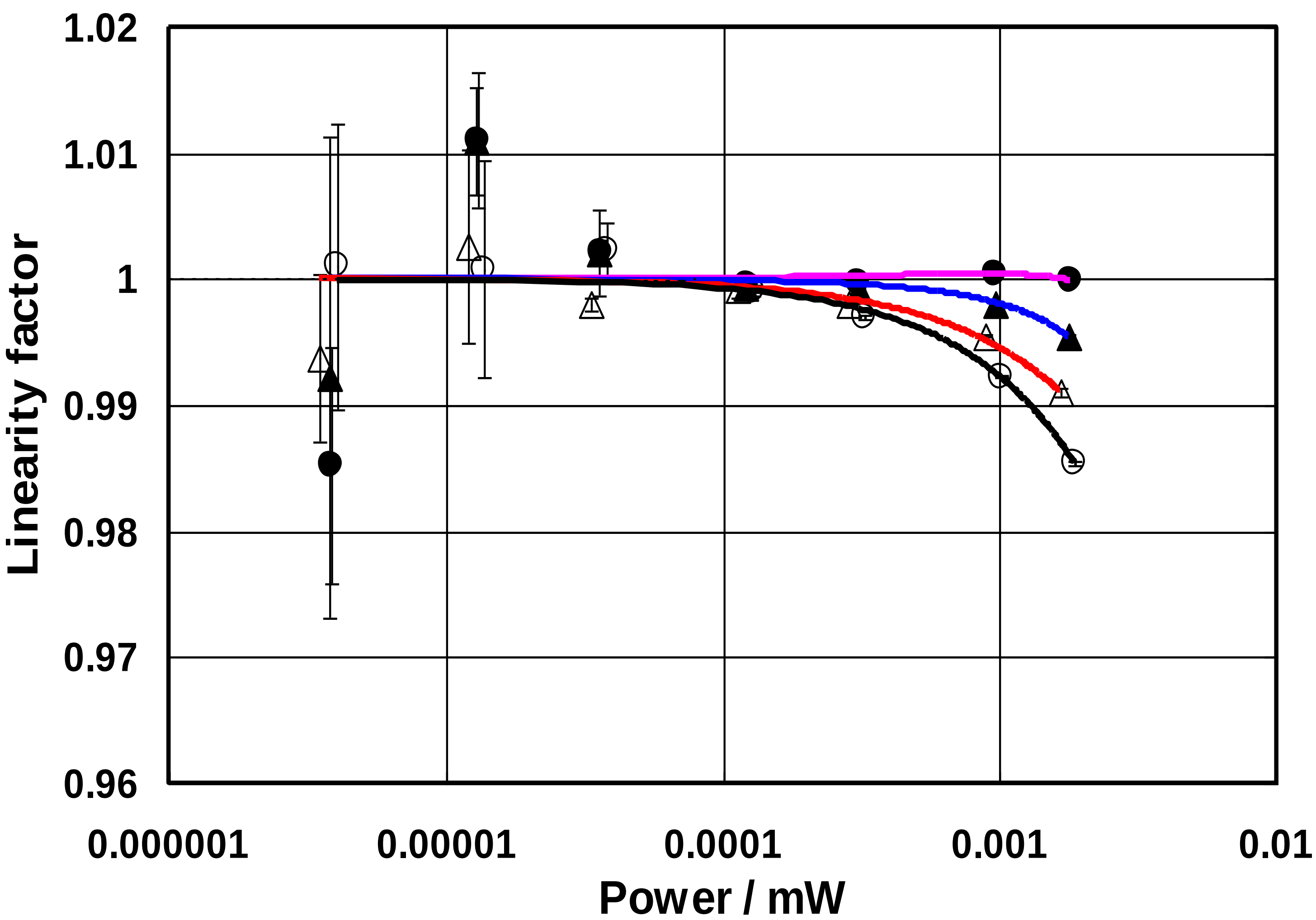
**E. Theocharous et al., *Applied Optics*, 43, 4182-4188, 2004.**

**Black: 1 mm**

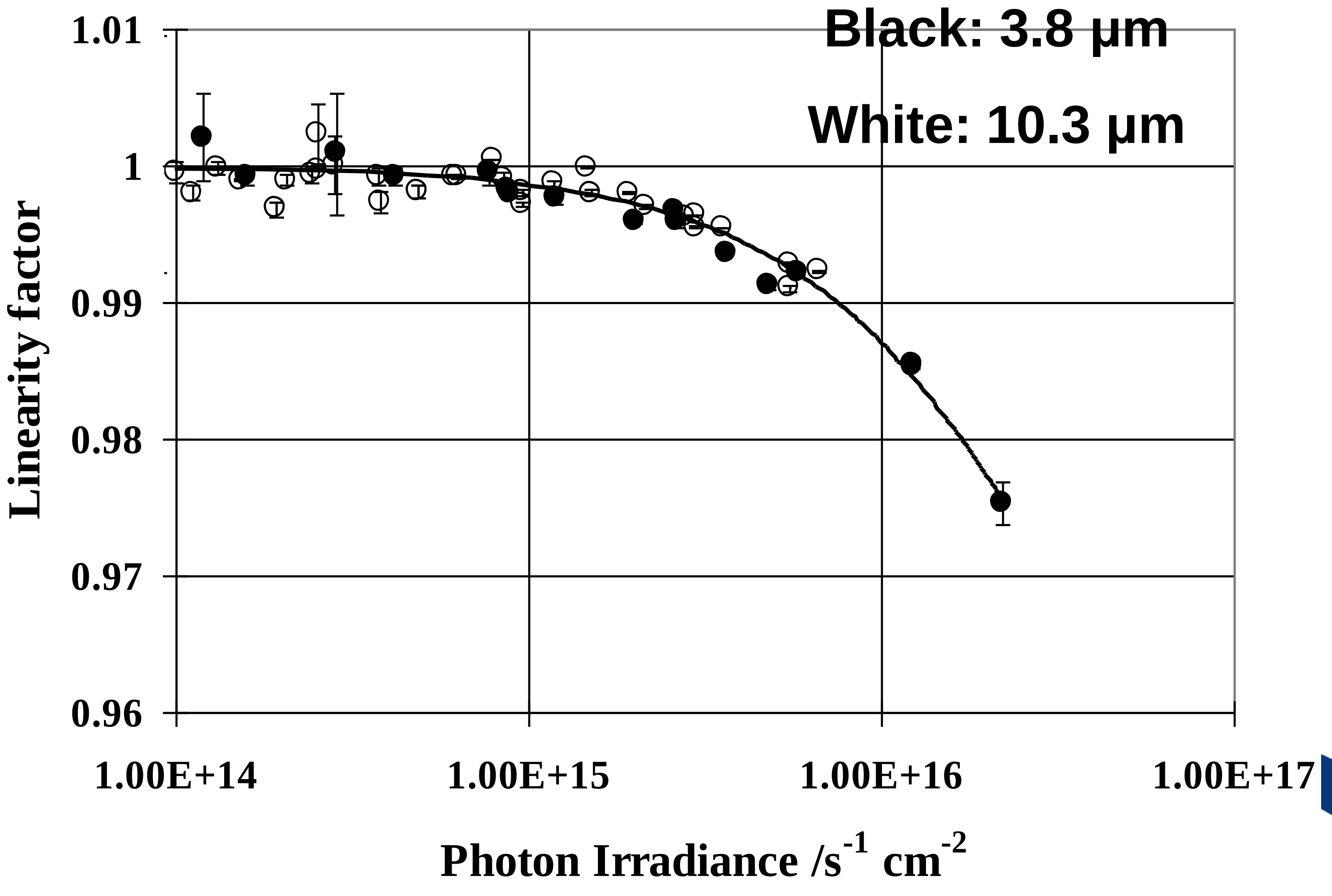
**Red: 1.4 mm**

**Blue: 1.8 mm**

**Purple: 2.8 mm**



## Linearity of CMT01 detector as a function of photon irradiance at 10.3 μm (○) and 3.8 μm (●).



# Is this behaviour to be expected?

- The density of the photo-generated charges is proportional to the photon irradiance.
- However, at higher charge carrier densities, there is a higher probability of recombination of charges (Auger recombination).
- Auger recombination is the dominant loss mechanism. Therefore, as the photon irradiance increases, the charge carrier lifetime decreases and therefore the non-linearity increases.
- Charge recombination is responsible for the non-linearity of PC HgCdTe detectors.

**Theocharous et al.**

**“Absolute linearity measurements on HgCdTe detectors in the infrared”**

**Applied Optics, 43, 4182-4188, 2004**

**E-mail e.theo@npl.co.uk for a copy**

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- **PV HgCdTe detectors** are widely used in FT spectrometry.
- They have superior noise characteristics compared to PC HgCdTe detectors
- No systematic study of their linearity of response has ever been published.
- This paper aims to rectify the situation.

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# PV HgCdTe detector characteristics

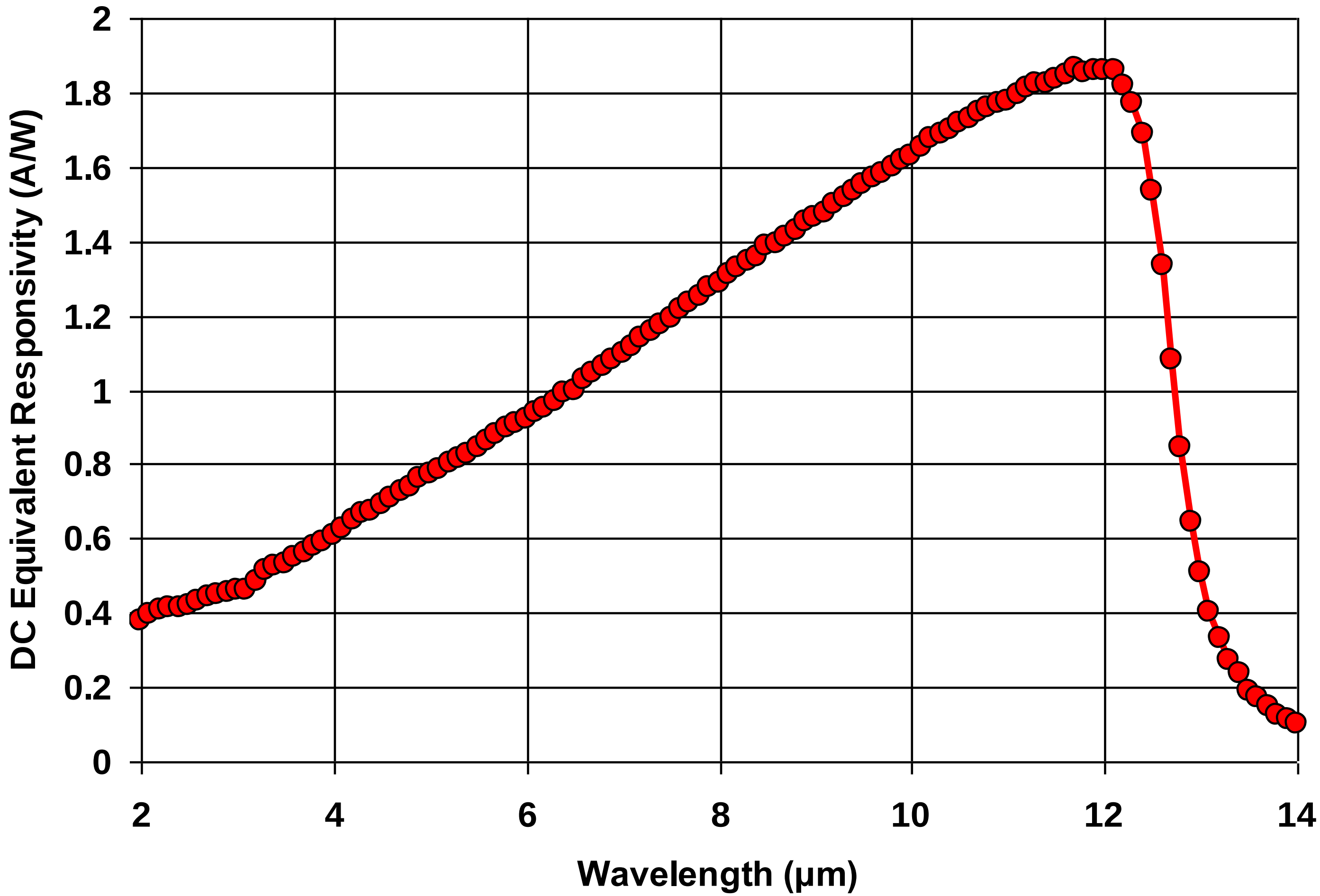
- 2 mm diameter active area.
- In side-looking Dewar.
- AR-coated ZnSe window.


- Cold shield limiting FoV to 60º (full angle).
- Dedicated trans-impedance amplifier with $10^4$ and $10^5$ V $A^{-1}$ gain settings.
- Output rectified by digital lock-in amplifier.

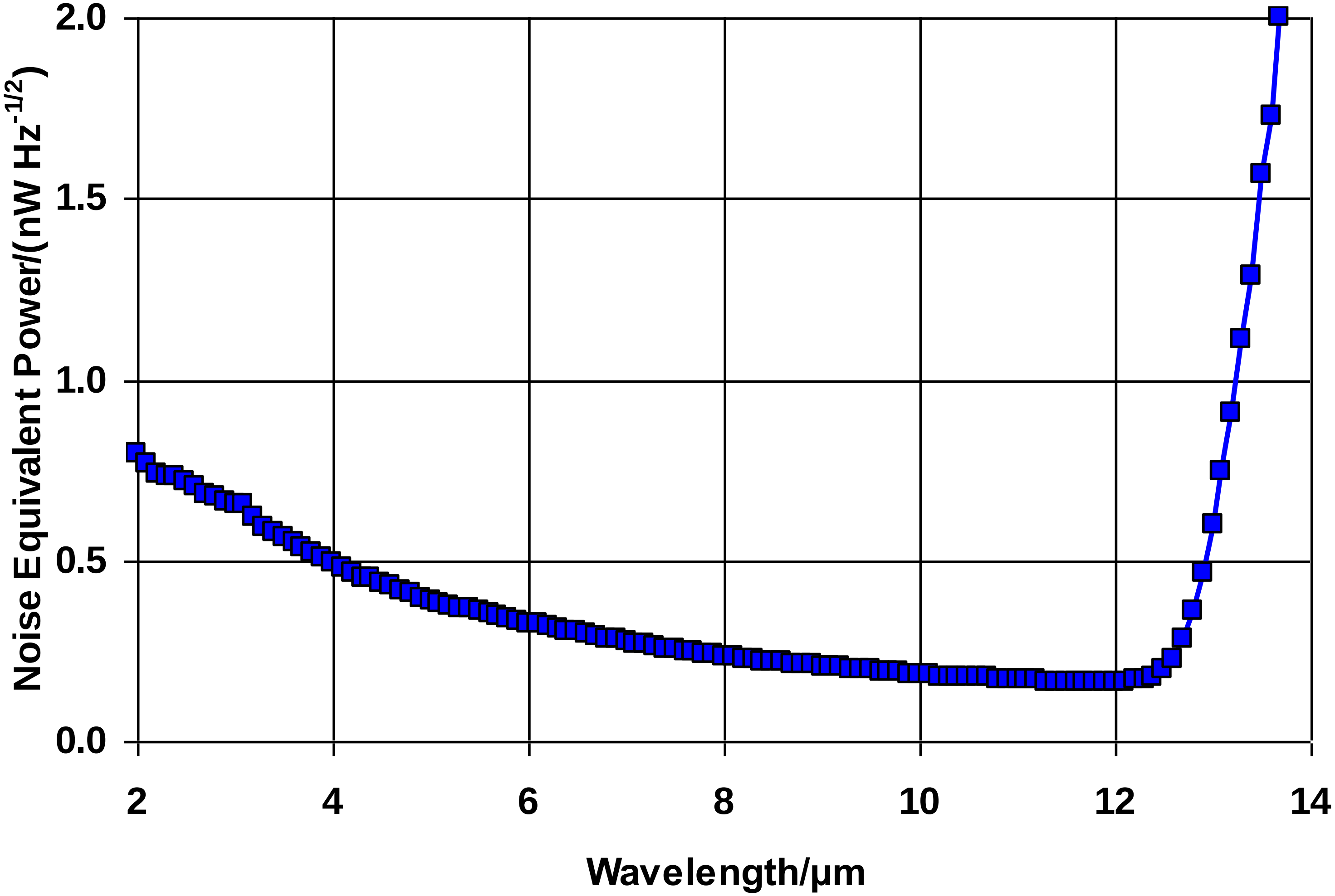
# Linearity characterisation settings

- **Sources used:**
  - a Glowbar source (10.3 μm) and
  - a sapphire-windowed filament lamp (2.2 μm & 4.7 μm).
- Source output was **spectrally filtered** by dielectric **bandpass filters**.
- Used **different area pinholes** which illuminated different areas on the active area of the test detector.
- Incident radiation modulated at 70 Hz.

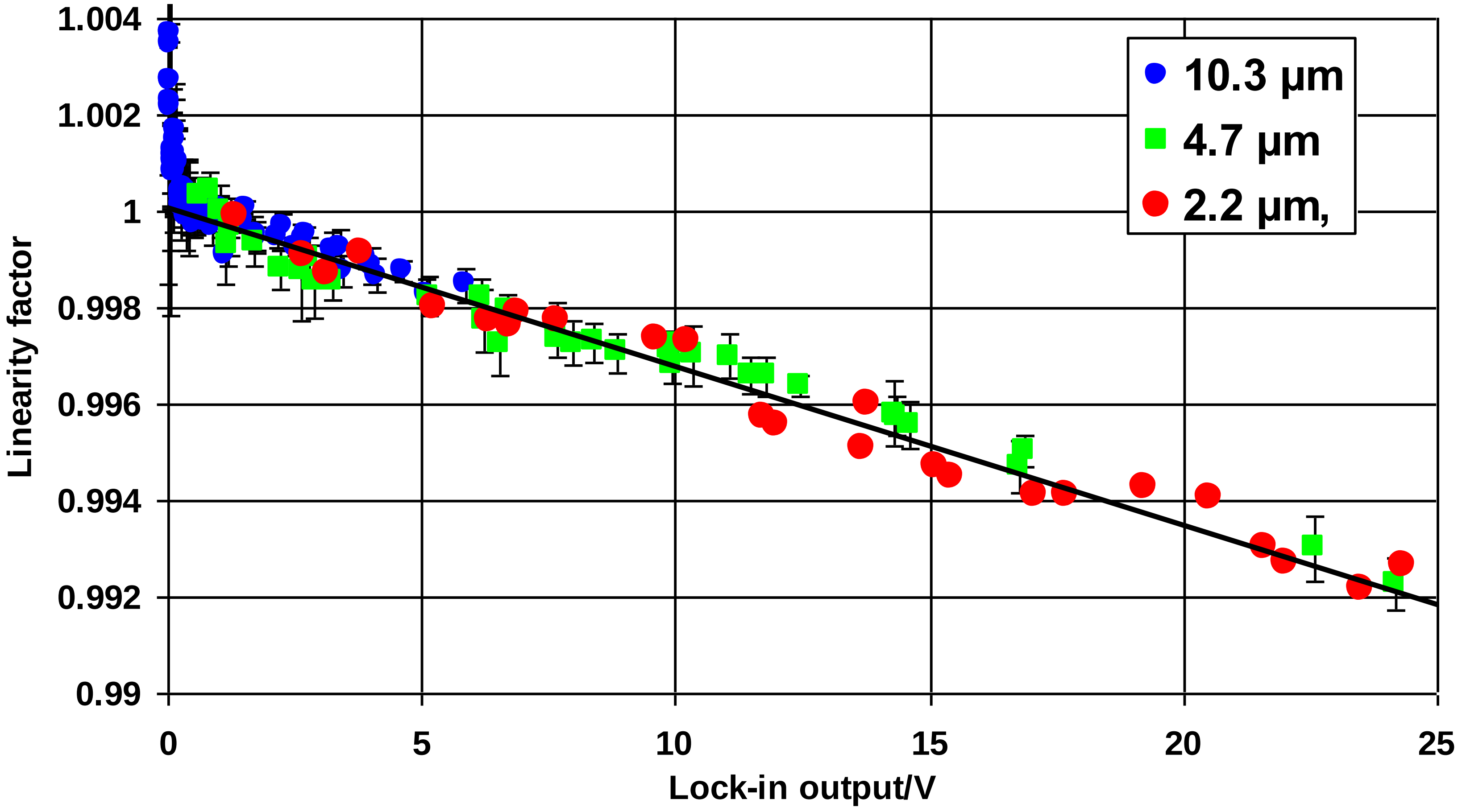
# Absolute spectral responsivity of PV HgCdTe detector, 1.5 mm diameter spot



# Noise Equivalent Power of PV HgCdTe detector



# Linearity characteristics of the PV CMT detector

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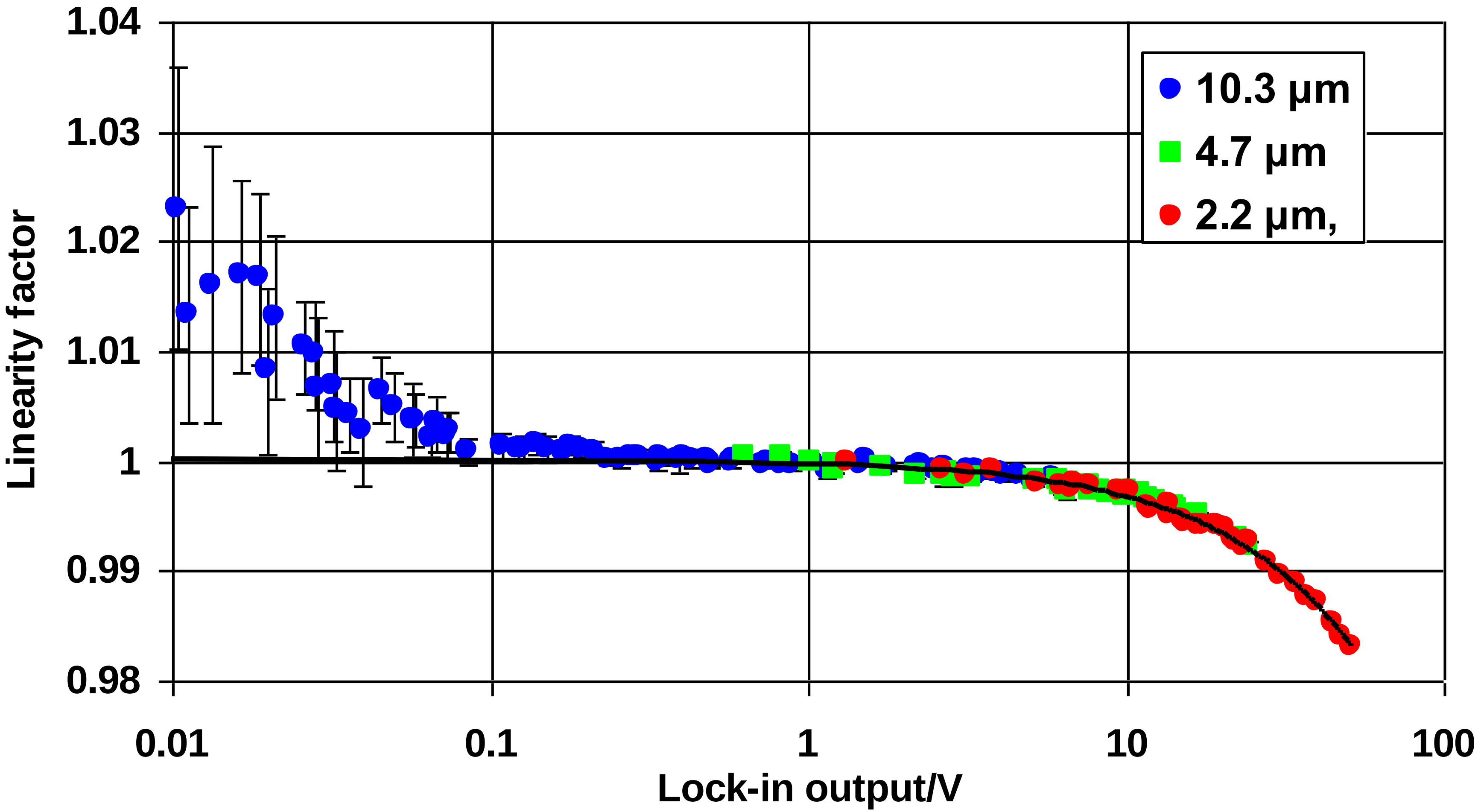
# Linearity characteristics of the PV CMT detector

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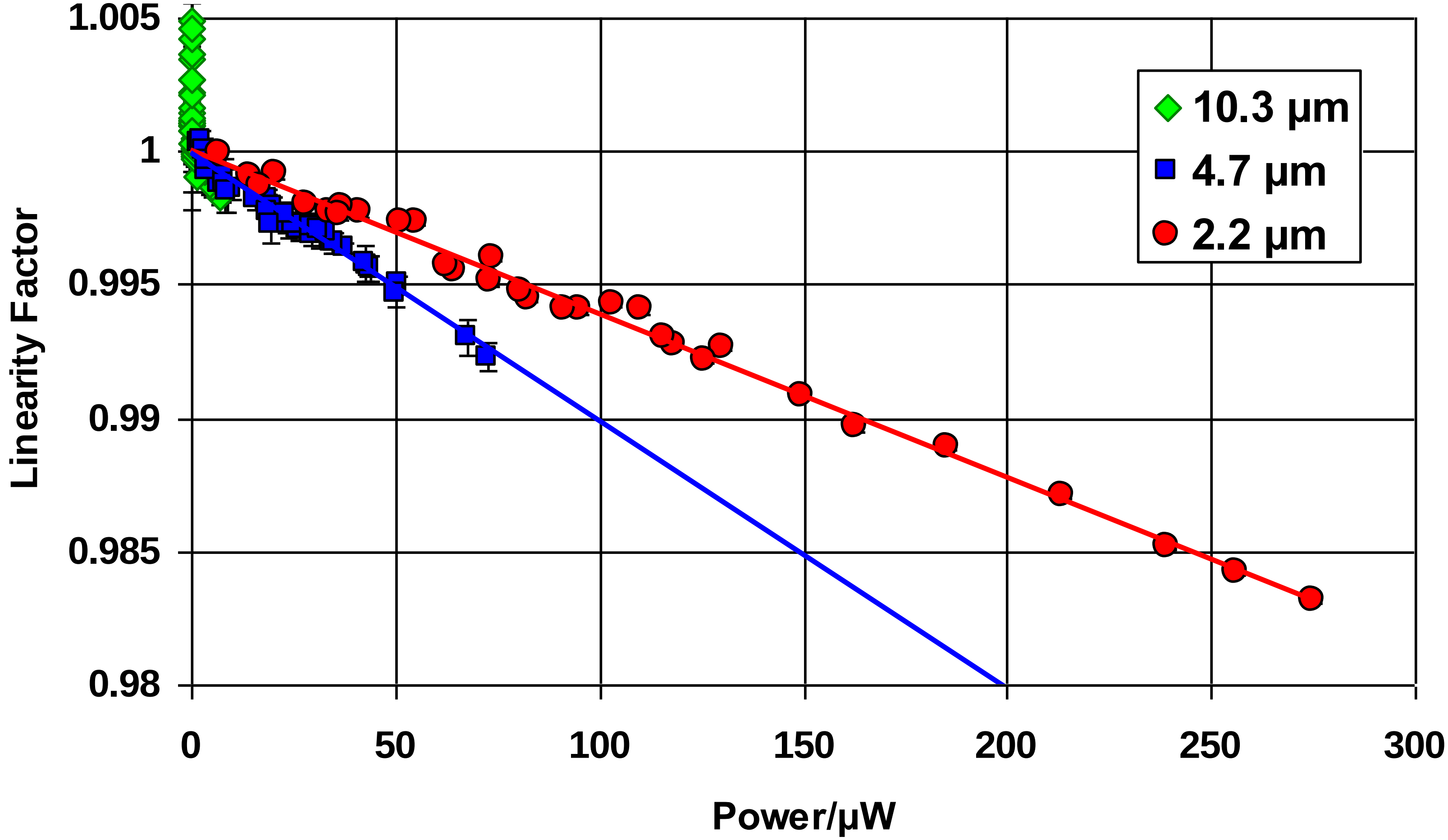
# Plots of the linearity data as a function of total radiant power incident on the test detector. The plots corresponding to different wavelengths do not overlap.

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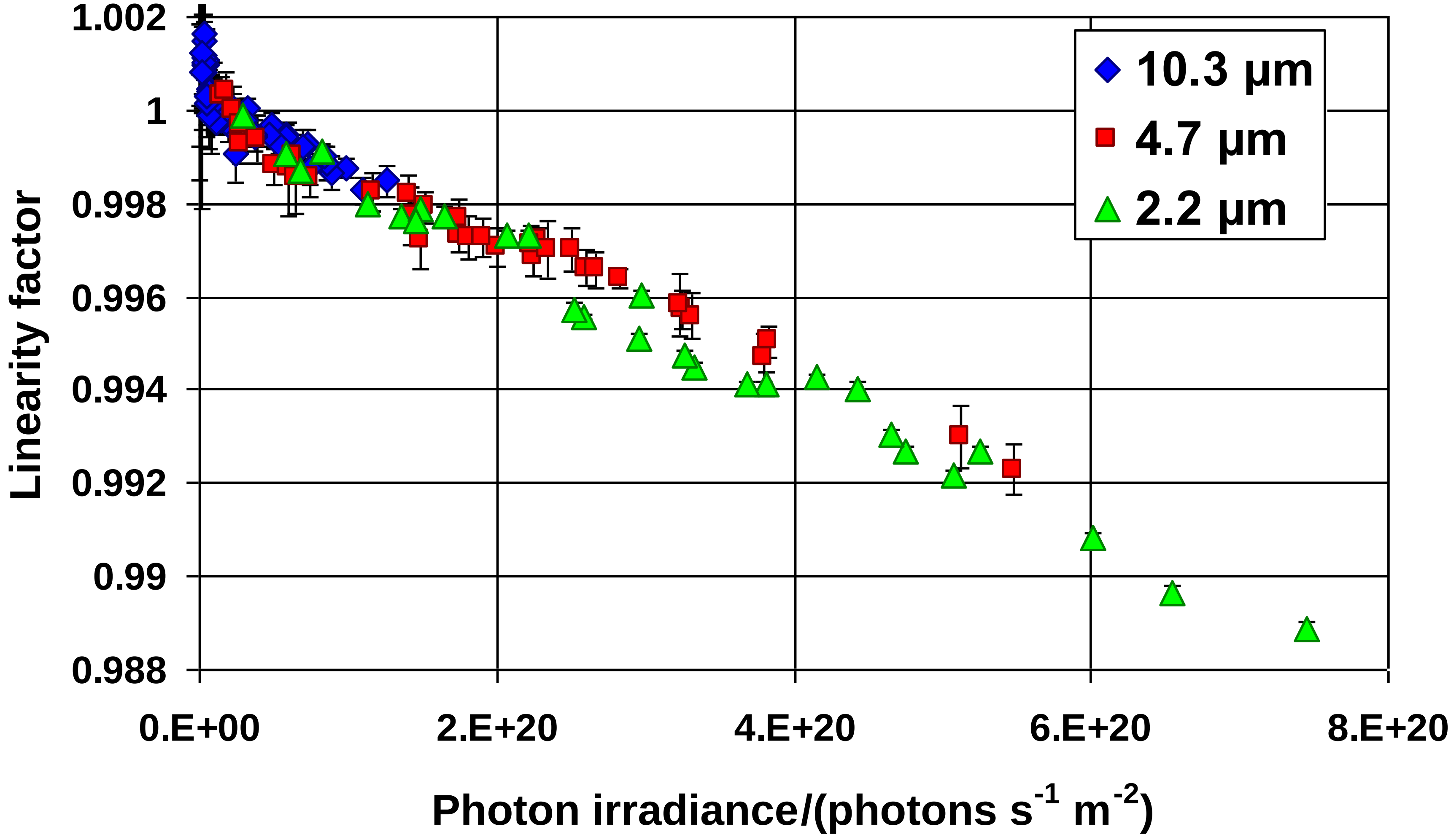
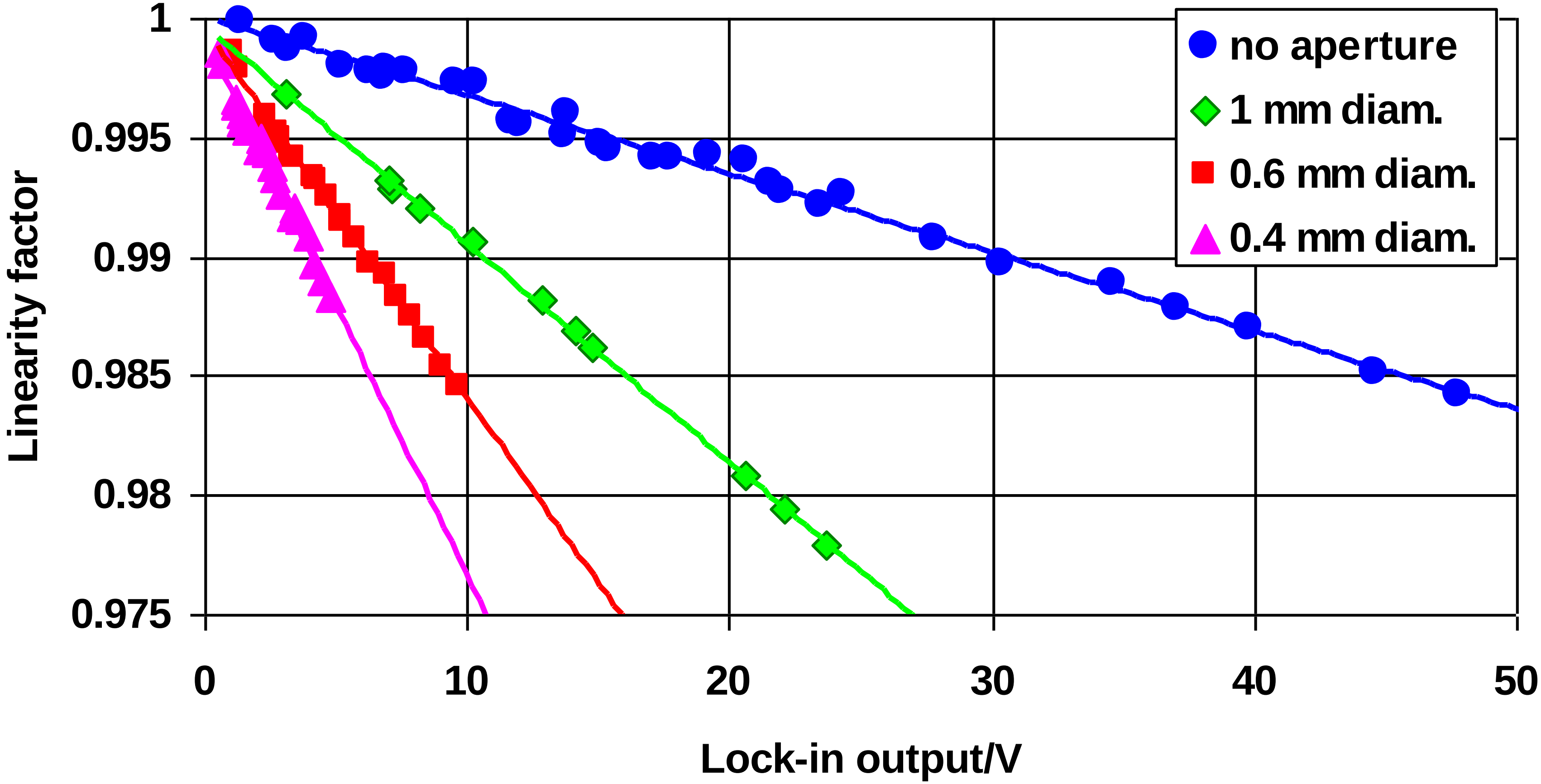
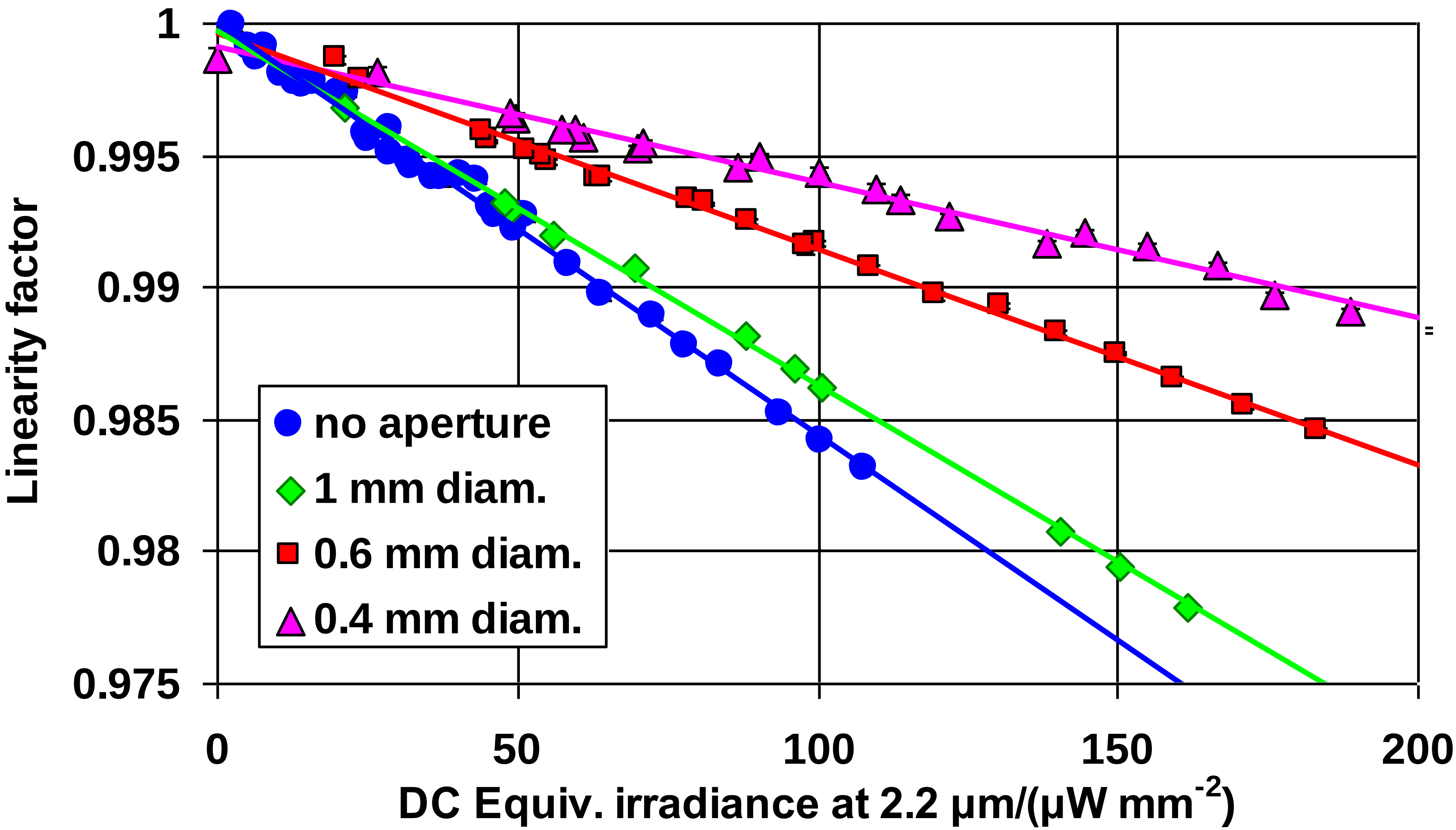
## When the same data are plotted as a function of photon irradiance the resulting plots show good overlap.



# The linearity factor of the PV HgCdTe detector measured at 2.2 μm, with a 0.4 mm, 0.6 mm, 1.0 mm diameter spots, as well as with the active area of the test detector overfilled.



# The linearity factor measured at 2.2 μm as a function of the DC equivalent irradiance

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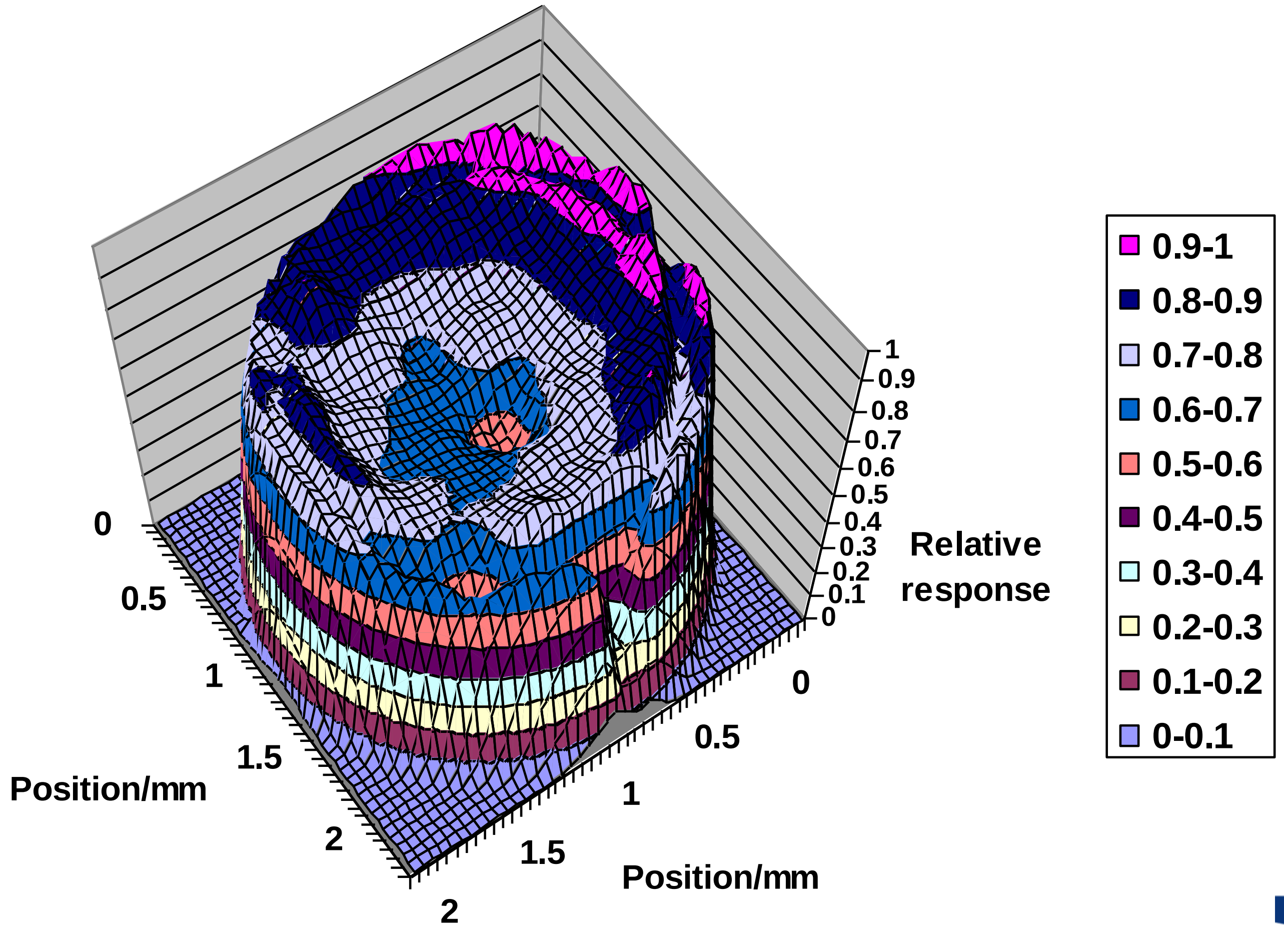
# Spatial uniformity of response of the PV HgCdTe detector at 2.2 μm, measured using a 100 μm diameter probe spot.

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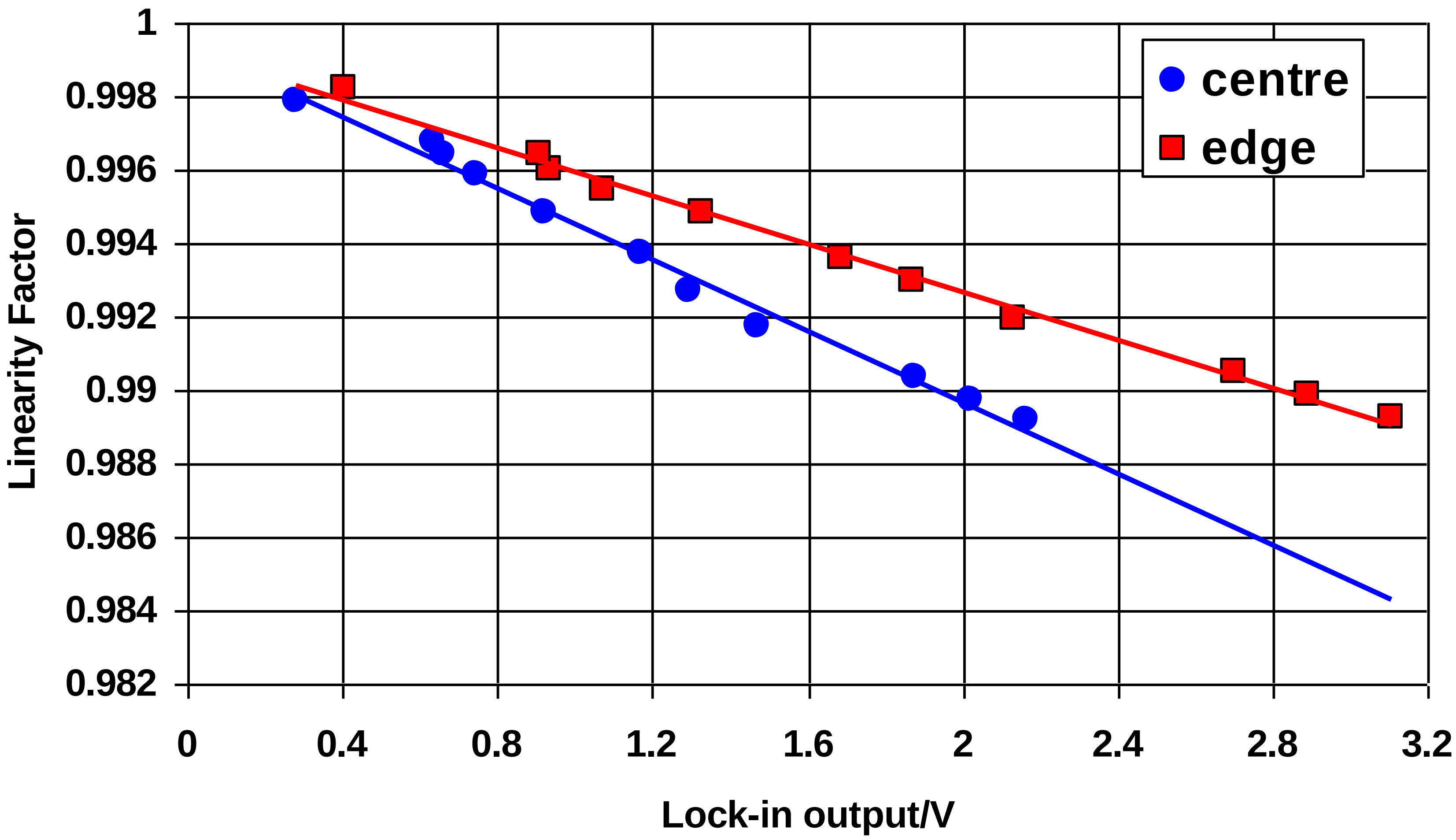
# Linearity factor as a function of lock-in output measured at the centre and near the edge of the active area of the test detector.



## The non-linearity of a photodetection system can be due to the detector itself, the amplifier itself, or BOTH.

- **It can also arise due to the lock-in amplifier**

**(E. Theocharous, "Absolute linearity characterisation of lock-in amplifiers" *Applied Optics*, 47, 1090-1096, 2008). Deviation from linearity limited to less than 0.1%.**

- The linearity of the trans-impedance amplifier was checked with a current source.
- The fact that the linearity characteristics depend on the area of illuminated spot confirms that the non-linearity originates within the PV HgCdTe detector.

# Contribution due to the thermal background

- All measurements correspond to an ambient temperature background.
- This is how the test detector will be used normally.
- This is not an issue with “visible” detectors but it is an issue for infrared detectors.

# The Theo$^2$ effect

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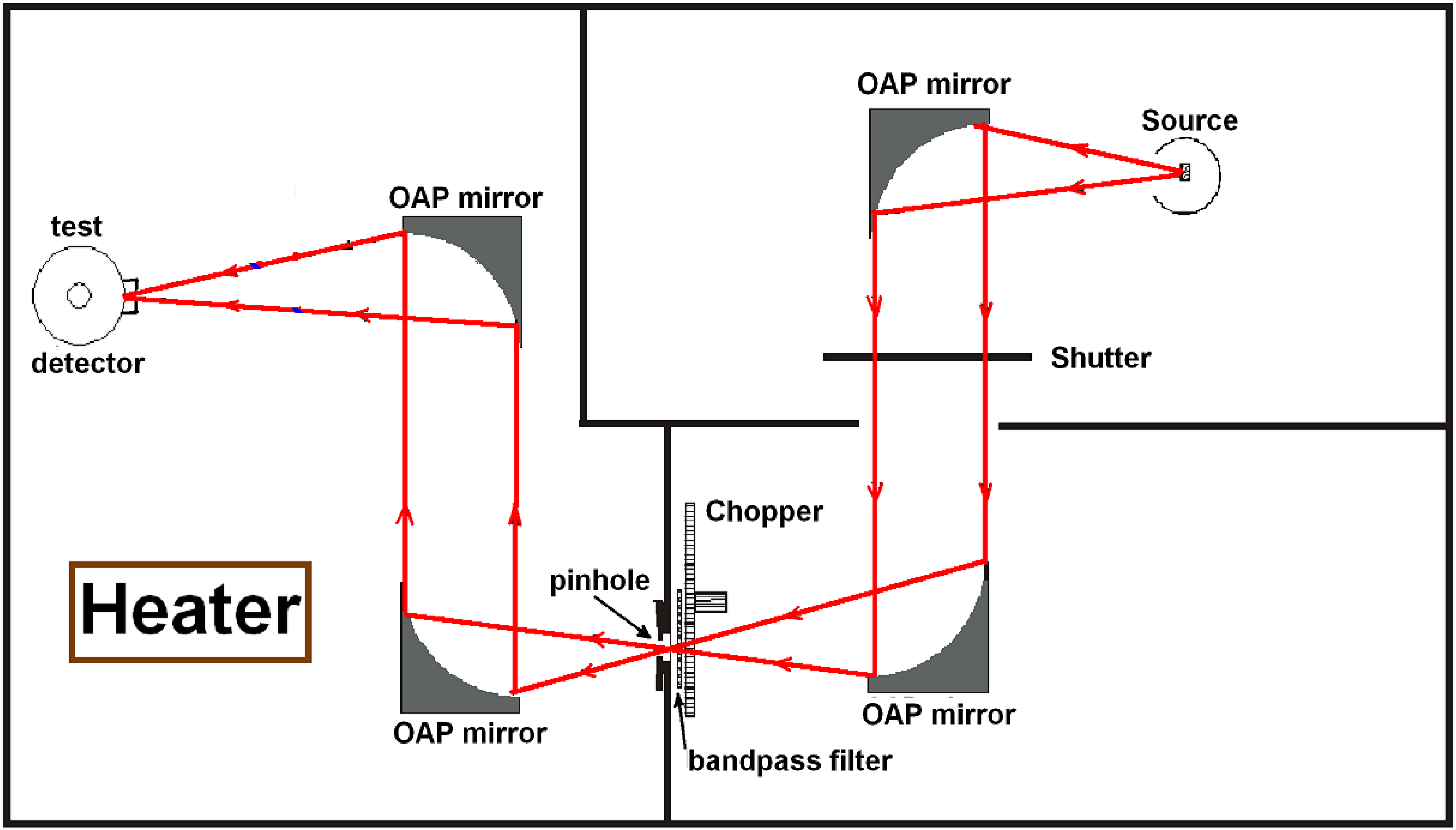
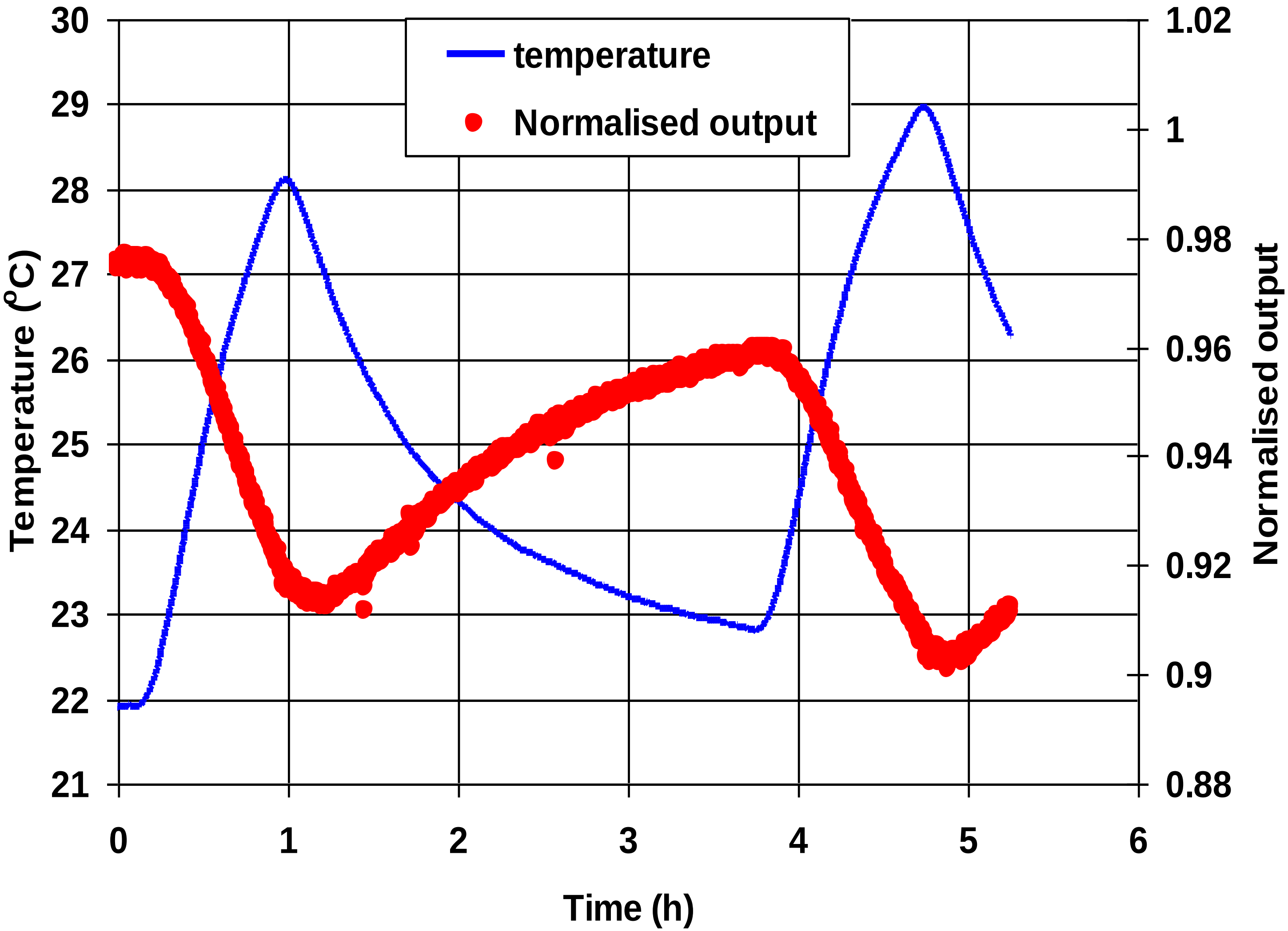
# NPL's detector stability measurement facility

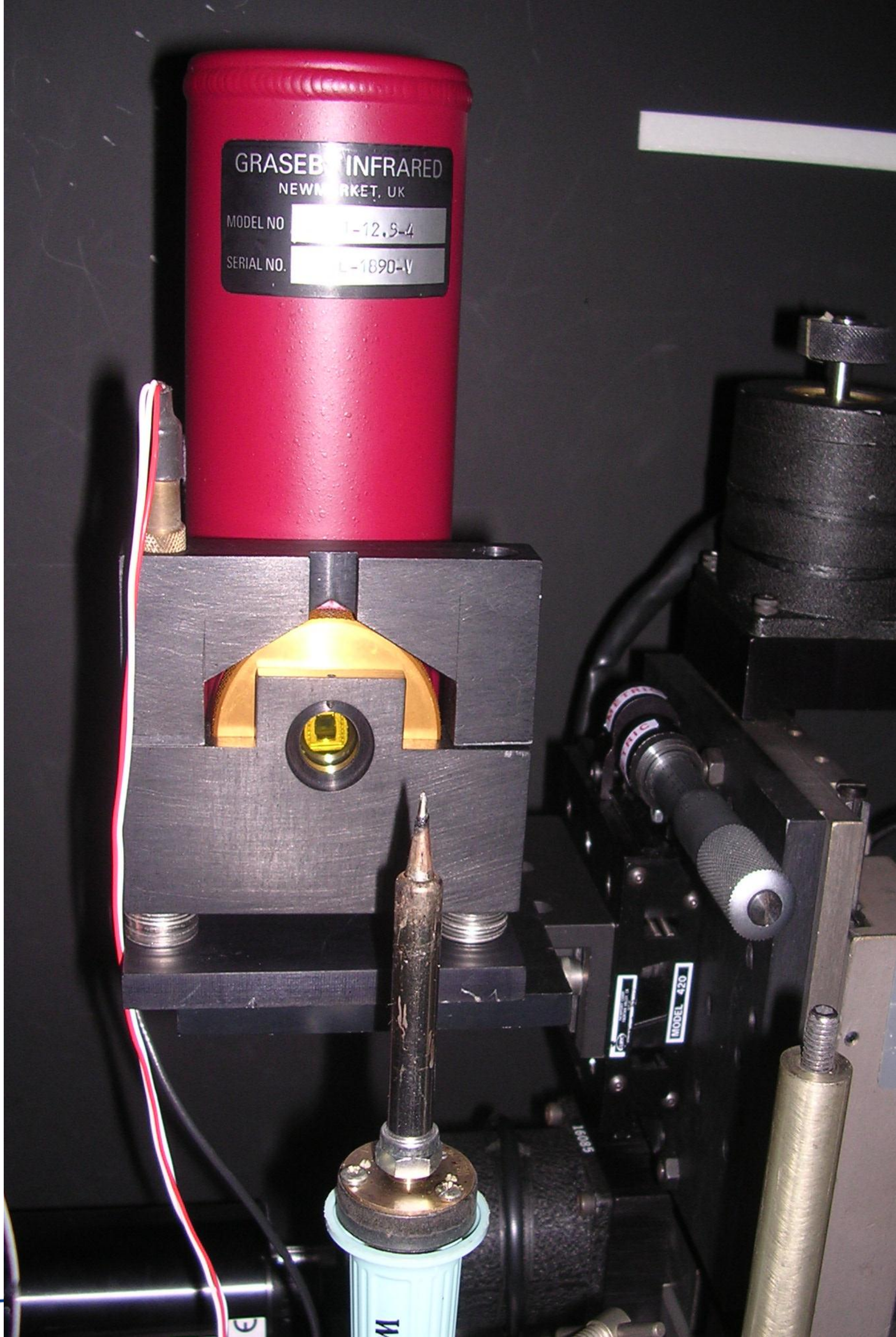


# The responsivity of a HgCdTe detector depends on the temperature of objects in its Field of View.

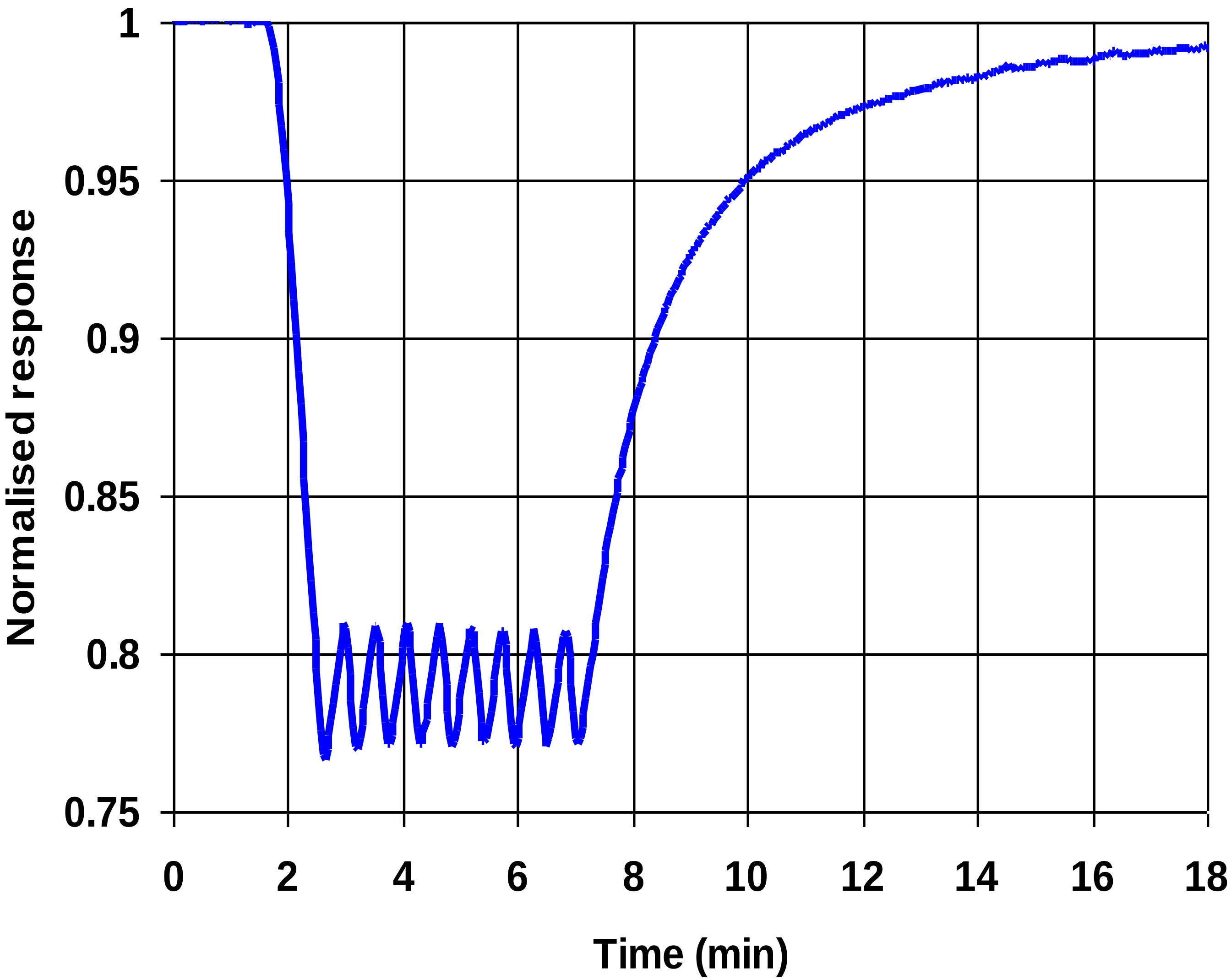


- **The responsivity of the HgCdTe detector was dependent on the temperature inside the chamber.**
- **It is not a "Temperature coefficient of response" effect because the detector wafer was maintained at "77 K".**
- **What was causing the drift?**

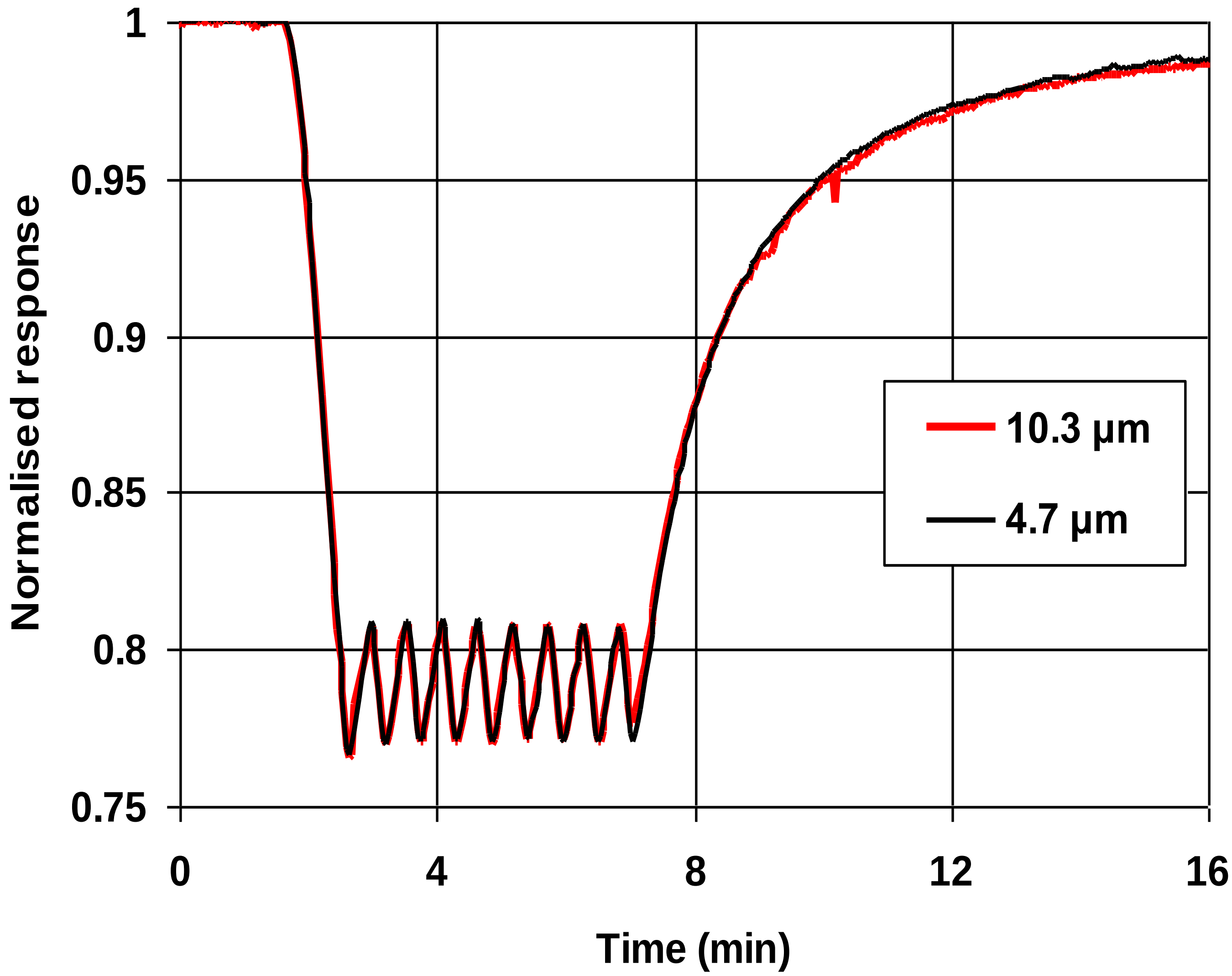
# The soldering iron test



# Change in the responsivity of a PC HgCdTe detector



# Drift is independent of wavelength

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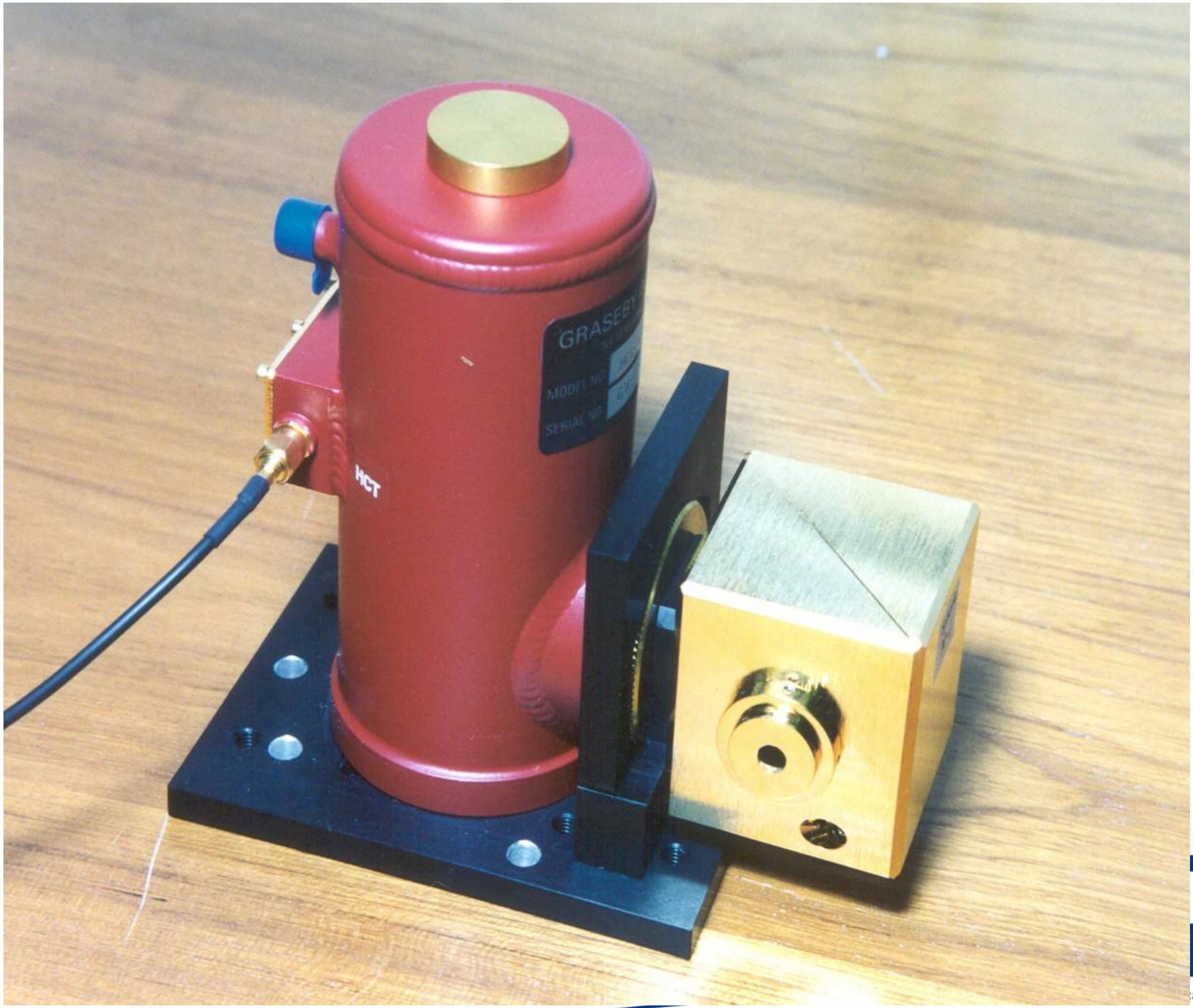
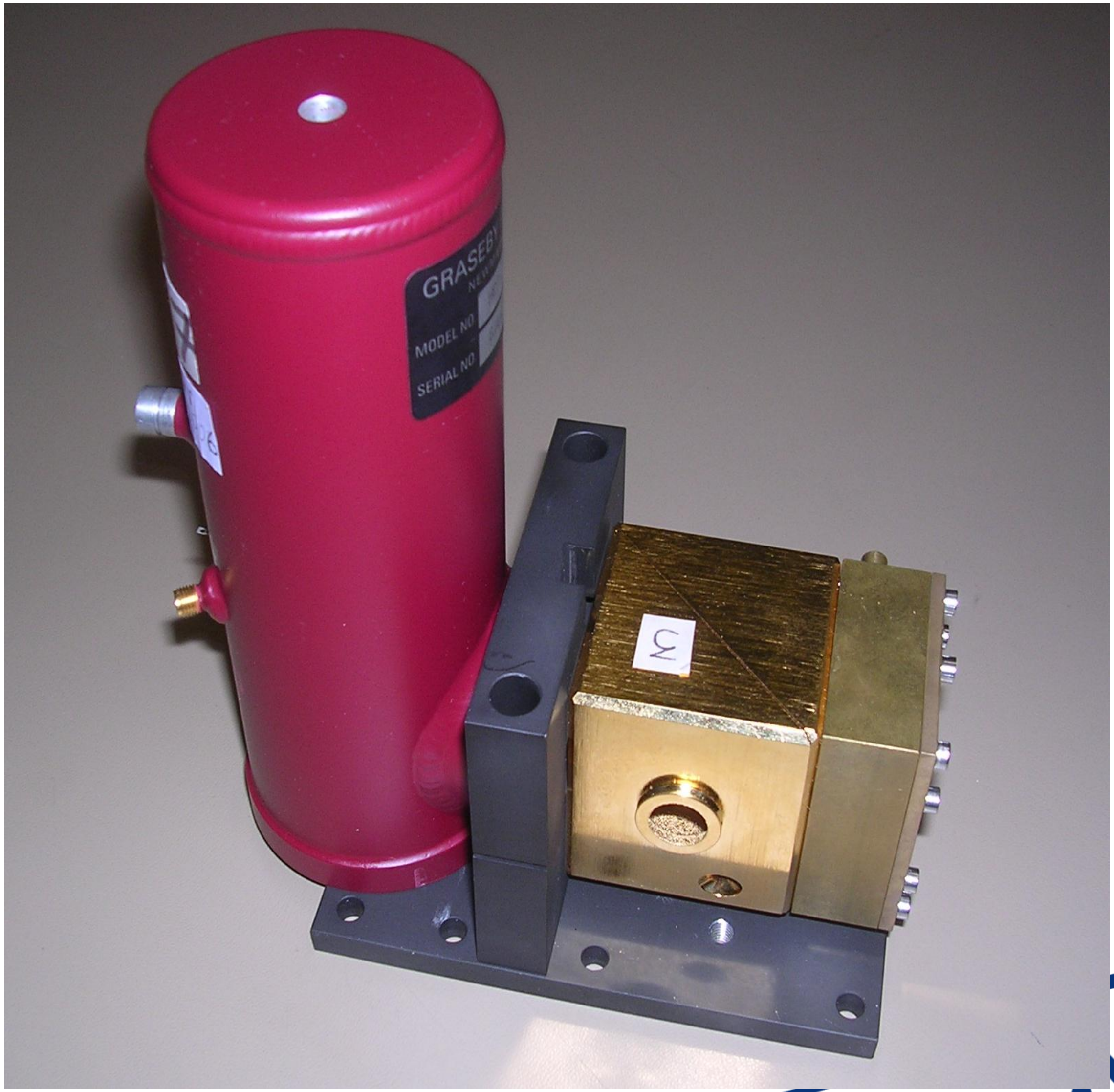
# HgCdTe-sphere detector



# HgCdTe-sphere detector with temperature controlled FOV

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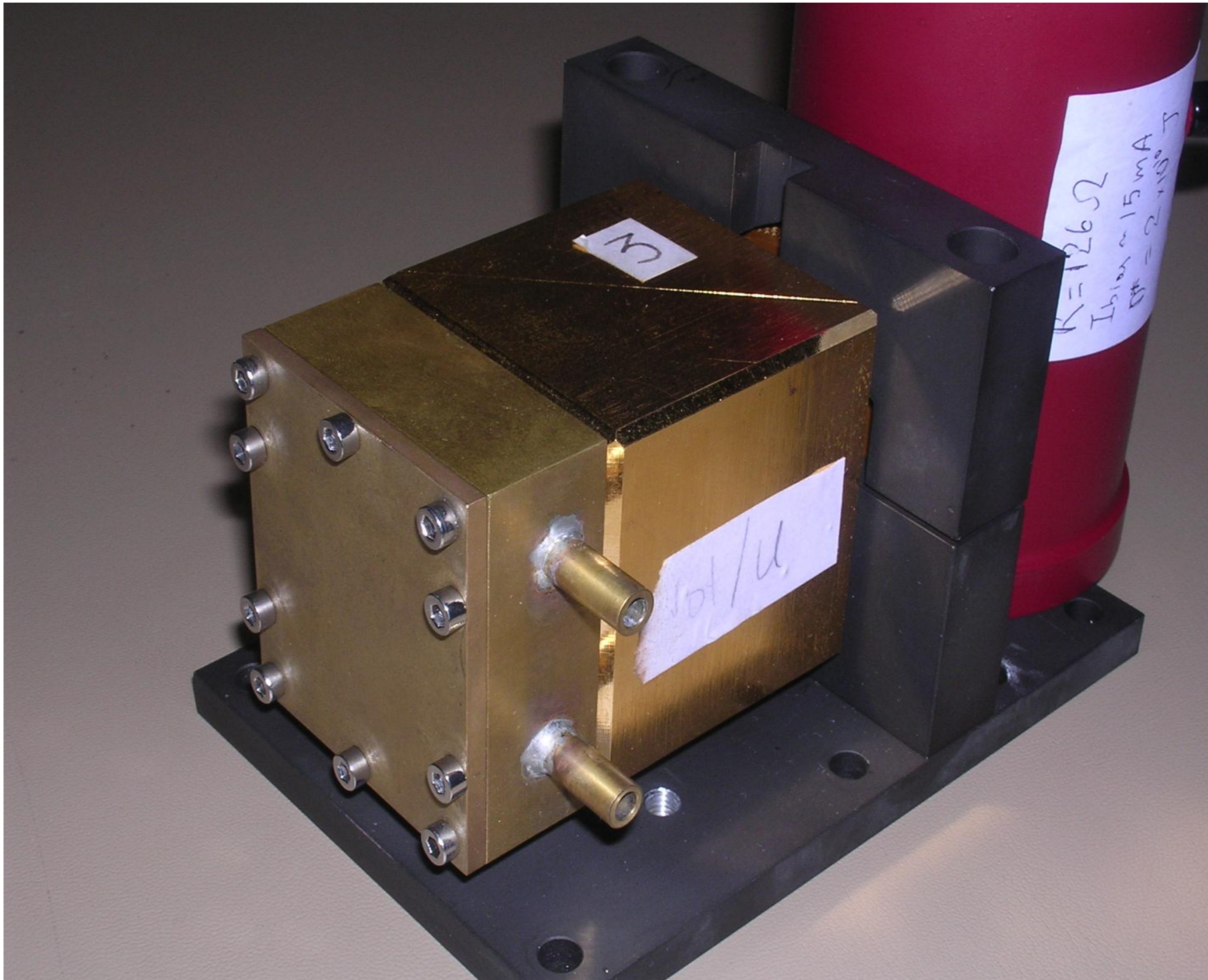
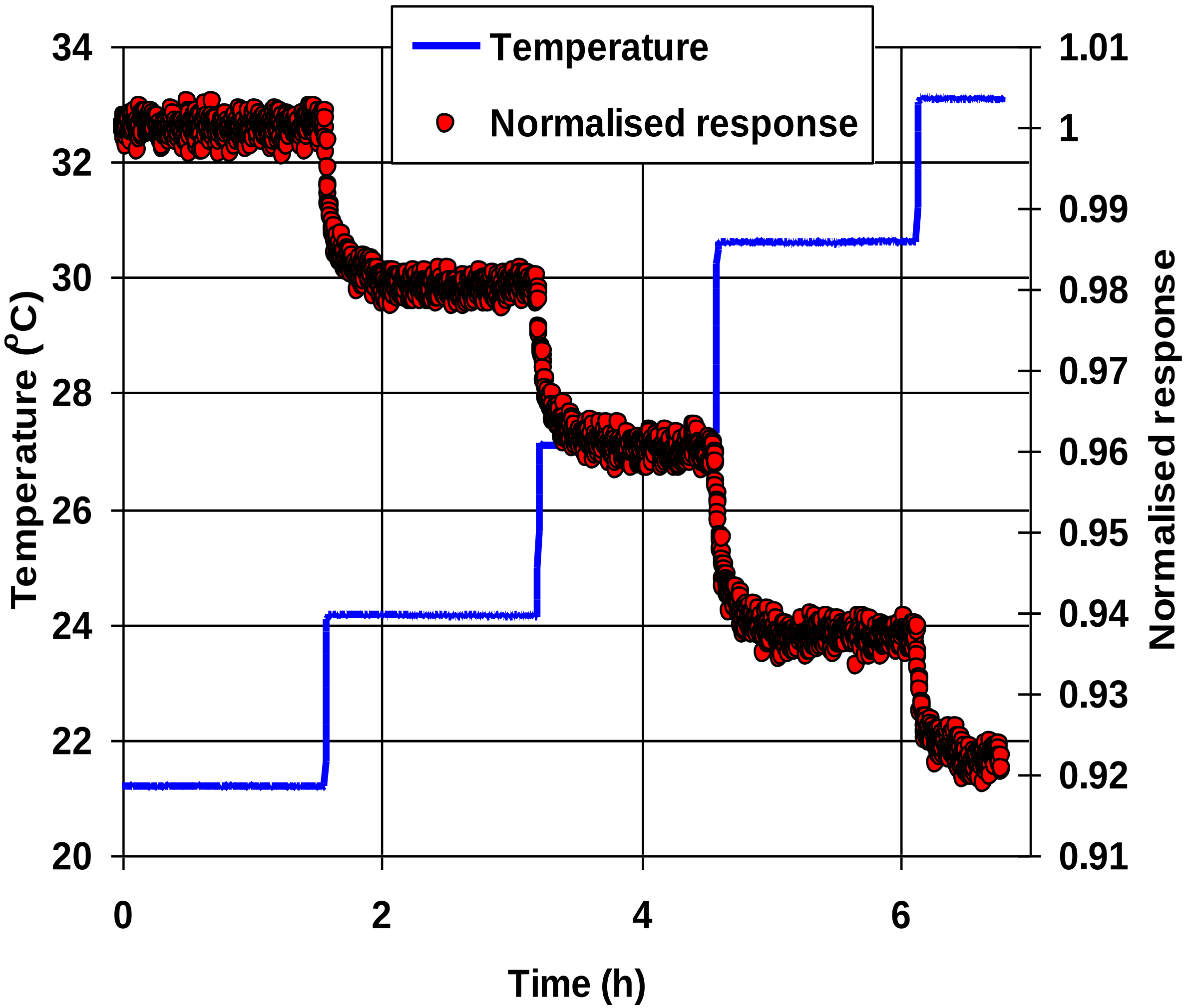
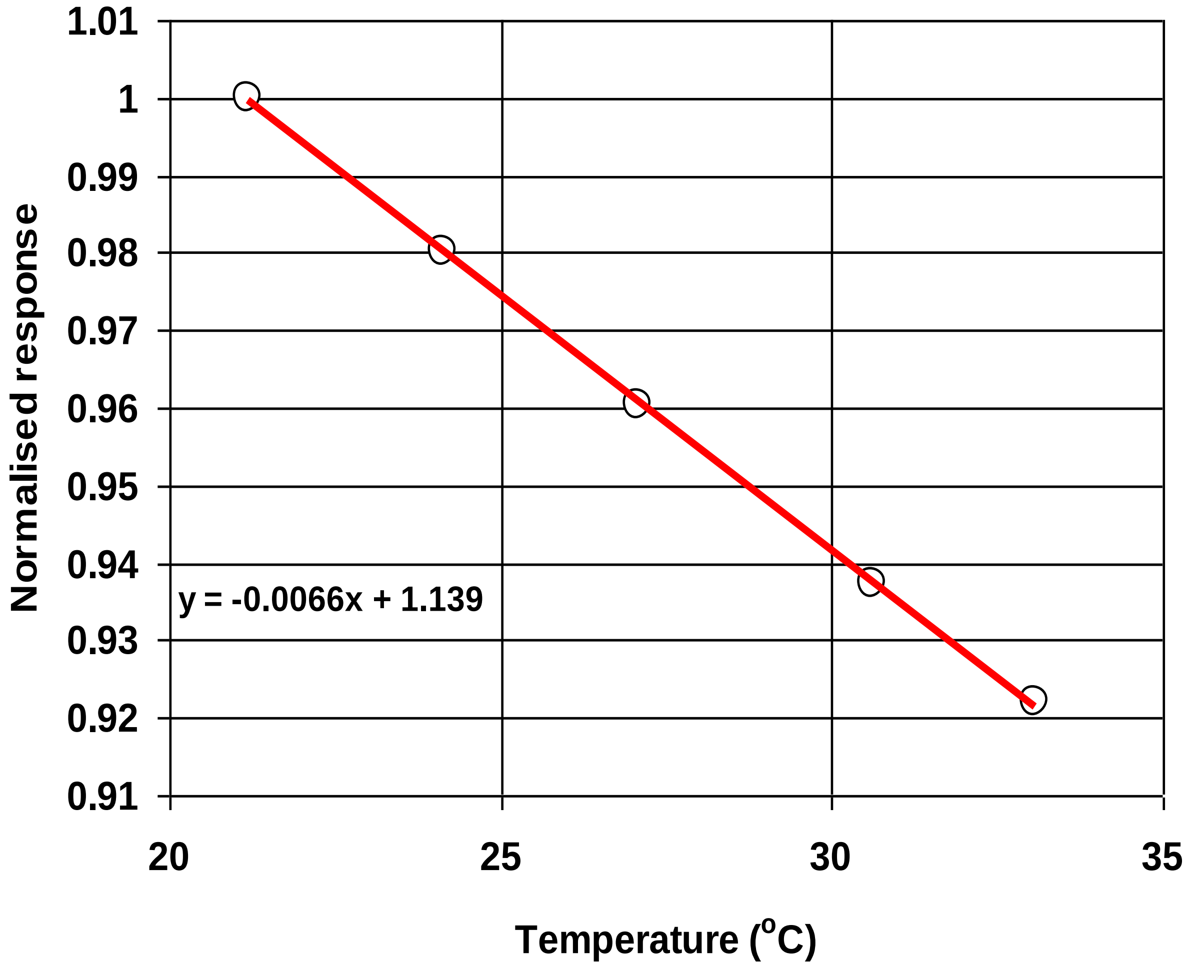
# Back view



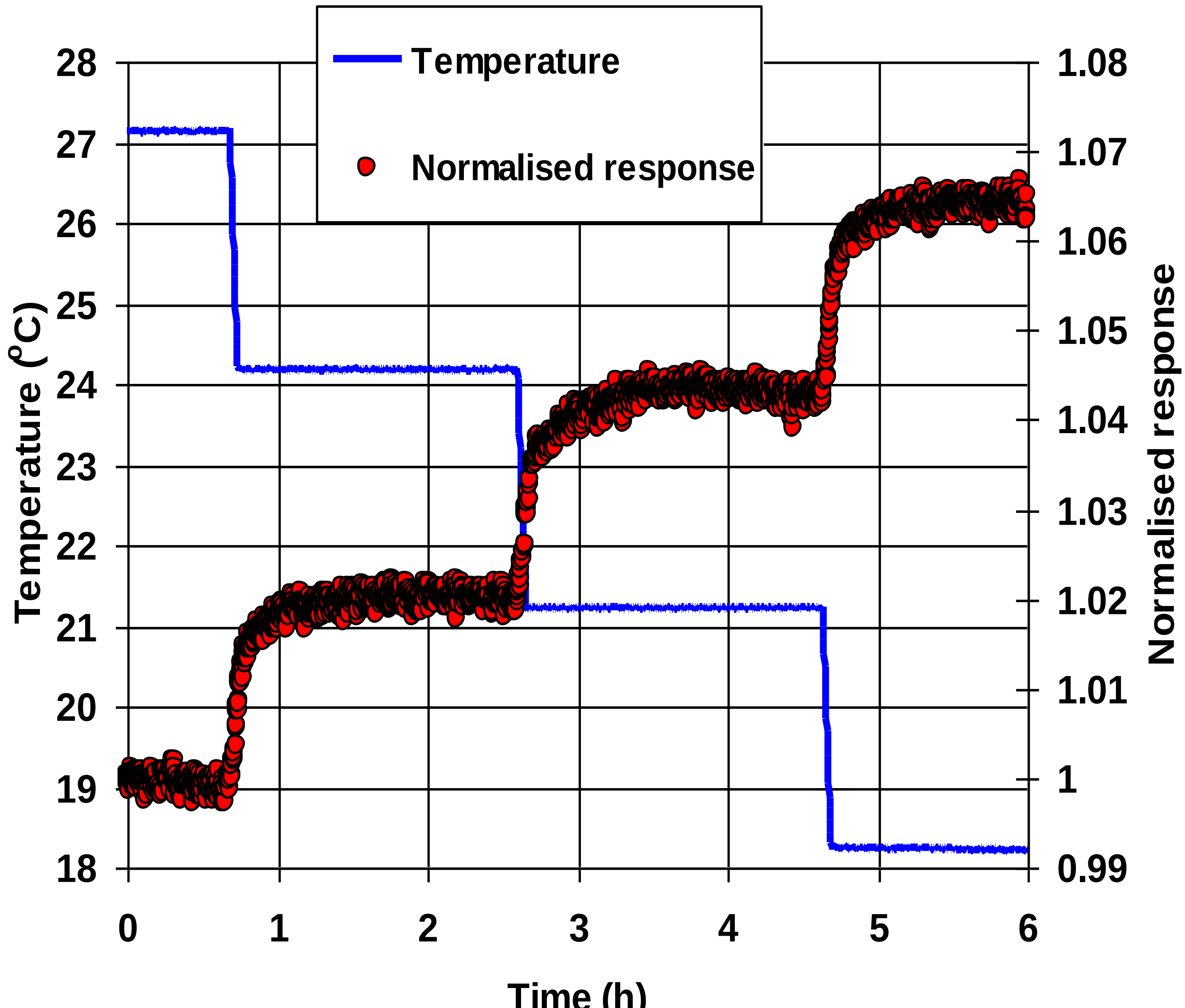
# As the temperature of the sphere increases, the responsivity of the HgCdTe detector decreases.



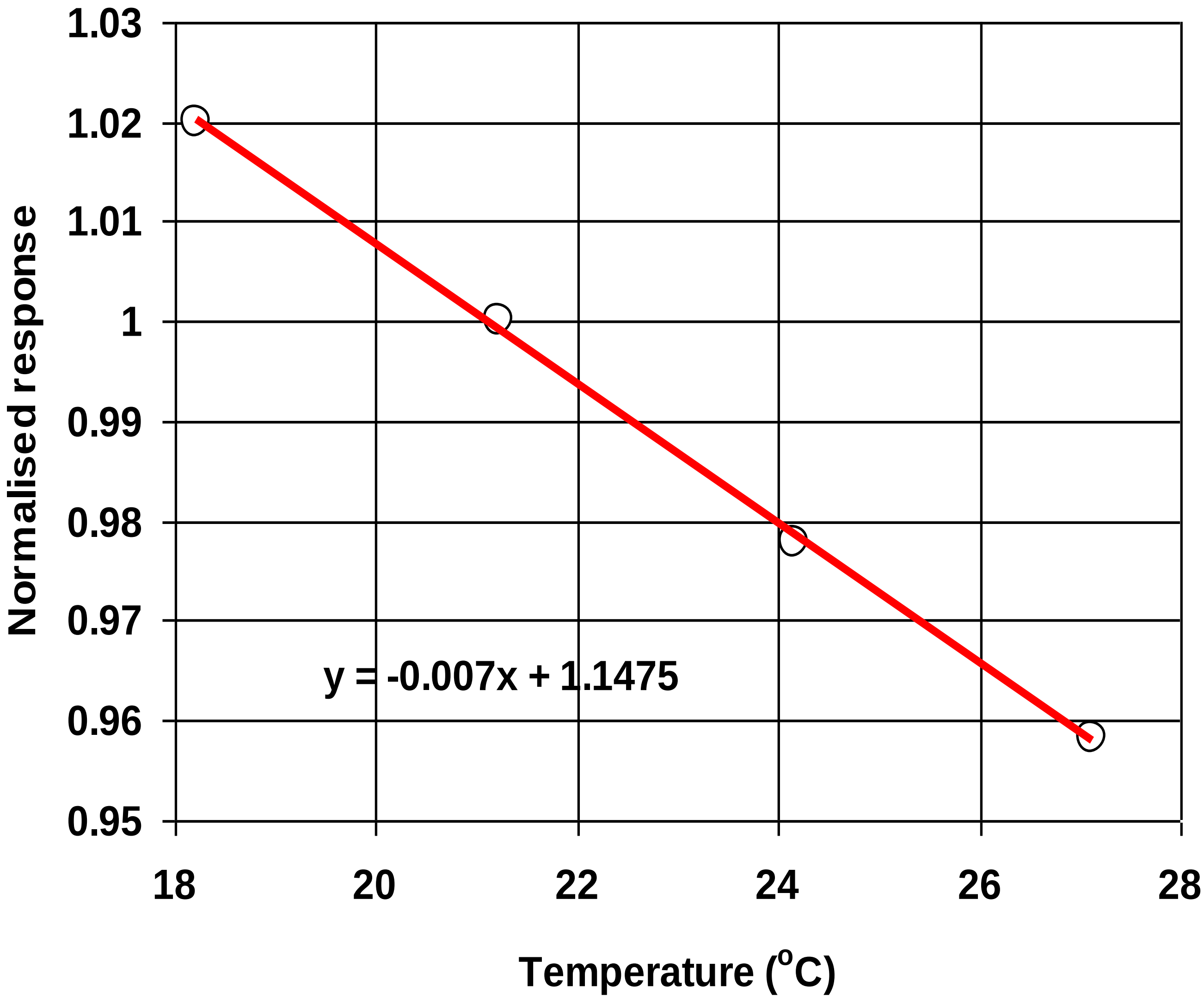
# As the temperature of the sphere increases, the responsivity of the HgCdTe detector decreases.



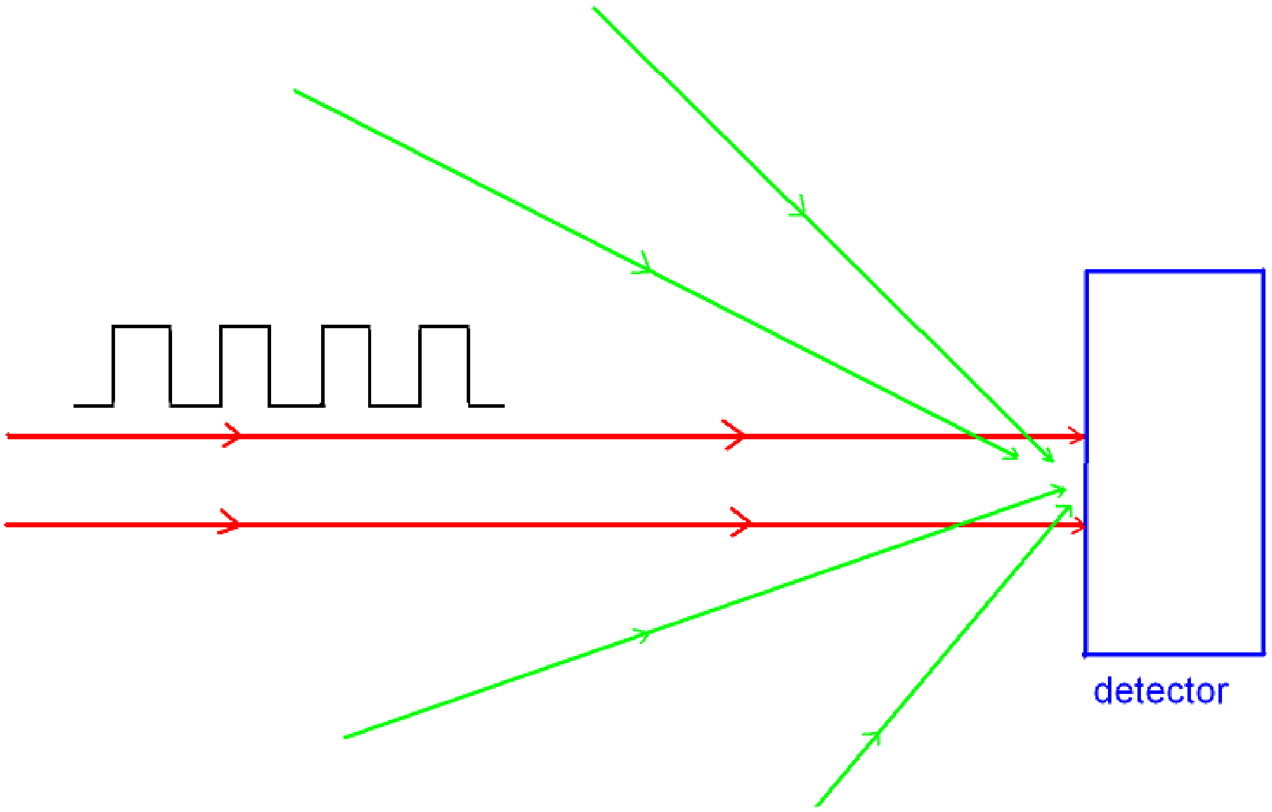
# Repeat with a different HgCdTe detector



# Slope is very similar



# The detector cannot recognise whether the photocharges are due to the modulated radiation or the background radiation

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E. Theocharous and O. J. Theocharous

"On a practical limit of the accuracy of radiometric measurements using HgCdTe detectors"

Applied Optics, 45, 7753-7759, 2006

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# Explanation of the "Theo$^2$ effect"

- Infrared radiation, whether modulated or unmodulated, incident on a HgCdTe detector generates free charge carriers.
- Auger recombination is the dominant loss mechanism and this loss mechanism is known to rise with the increasing density of charge carriers.
- This leads to the observed high non-linearity in the response of HgCdTe detectors (see Theo's linearity paper in Applied Optics).
- Note that both the modulated radiation being detected as well as the thermal background radiation produce free charge carriers which contribute to the non-linearity.
- The contribution due to the thermal background is not modulated and is therefore rejected by the phase sensitive detection utilised.
- However, its contribution to the non-linearity of response of the detector cannot be avoided.

# Explanation of the "Theo$^2$ effect"

- Examination of the irradiance values involved indicates that a PC HgCdTe with a 60$^o$ FOV (full angle) is subjected to a background irradiance of 40 W m$^{-2}$ in the 8 µm to 14 µm wavelength range. This assumes a background temperature of 20 $^o$C.
- Compare this with the irradiance values of a few W m$^{-2}$ normally supplied by the modulated radiation being detected.
- It is clear that the dominant source of free charge carriers is the irradiance due to the thermal background. It is also the dominant source the HgCdTe detector non-linearity.
- This is because the density of the free charge carriers generated by the thermal background is over an order of magnitude greater than that from the modulated radiation being measured.
- This confirms the importance of the irradiance due to the thermal background in the linearity of HgCdTe detectors and to the drifts associated with changes in the temperature of objects in their FOV.

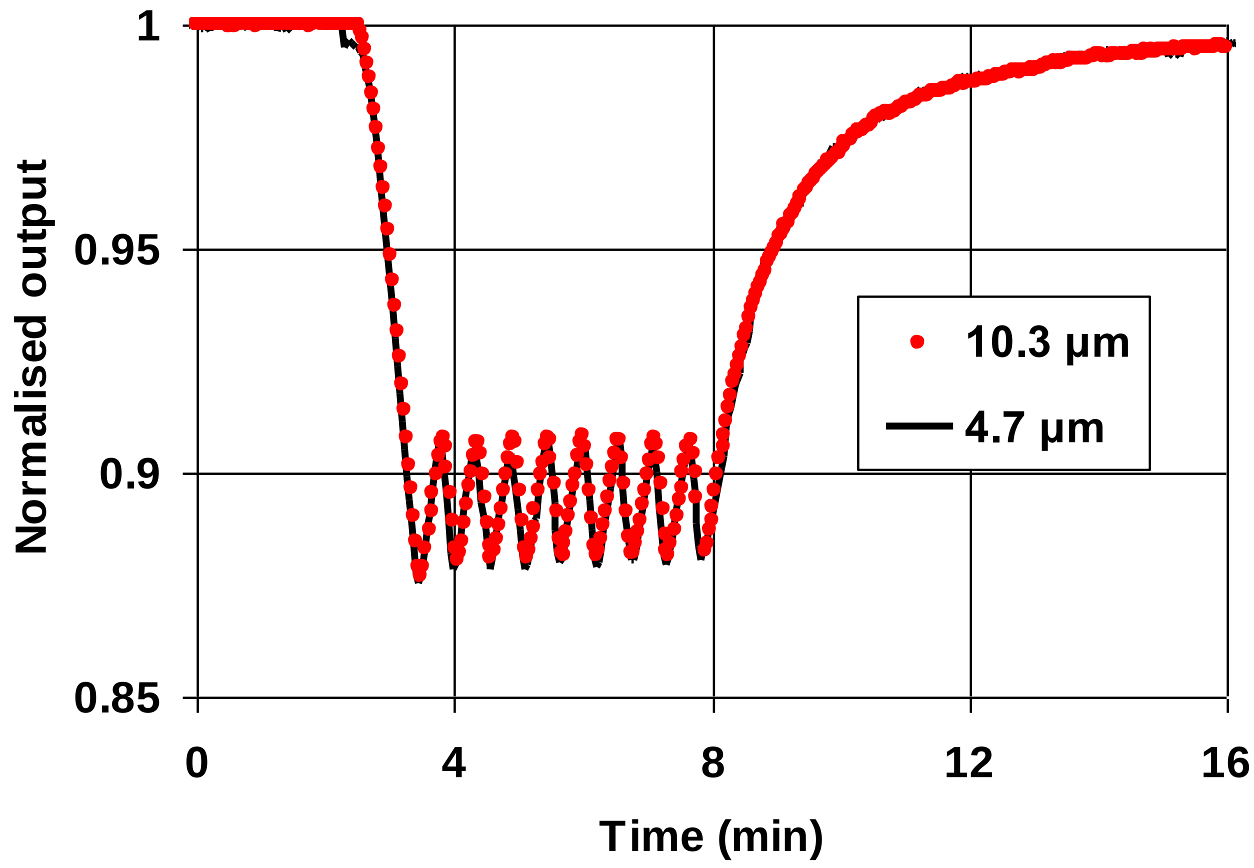
- Fluctuations in the temperature of objects in the FOV of HgCdTe detectors provides a **practical limit** to the accuracy with which radiometric measurements can be performed using HgCdTe detectors.
- Other infrared photodetectors will also suffer from a similar limit.
- See publication on the "Theo$^2$ effect" for full description.

## Where can we expect to “suffer” from the effects of the “Theo$^2$ effect”?

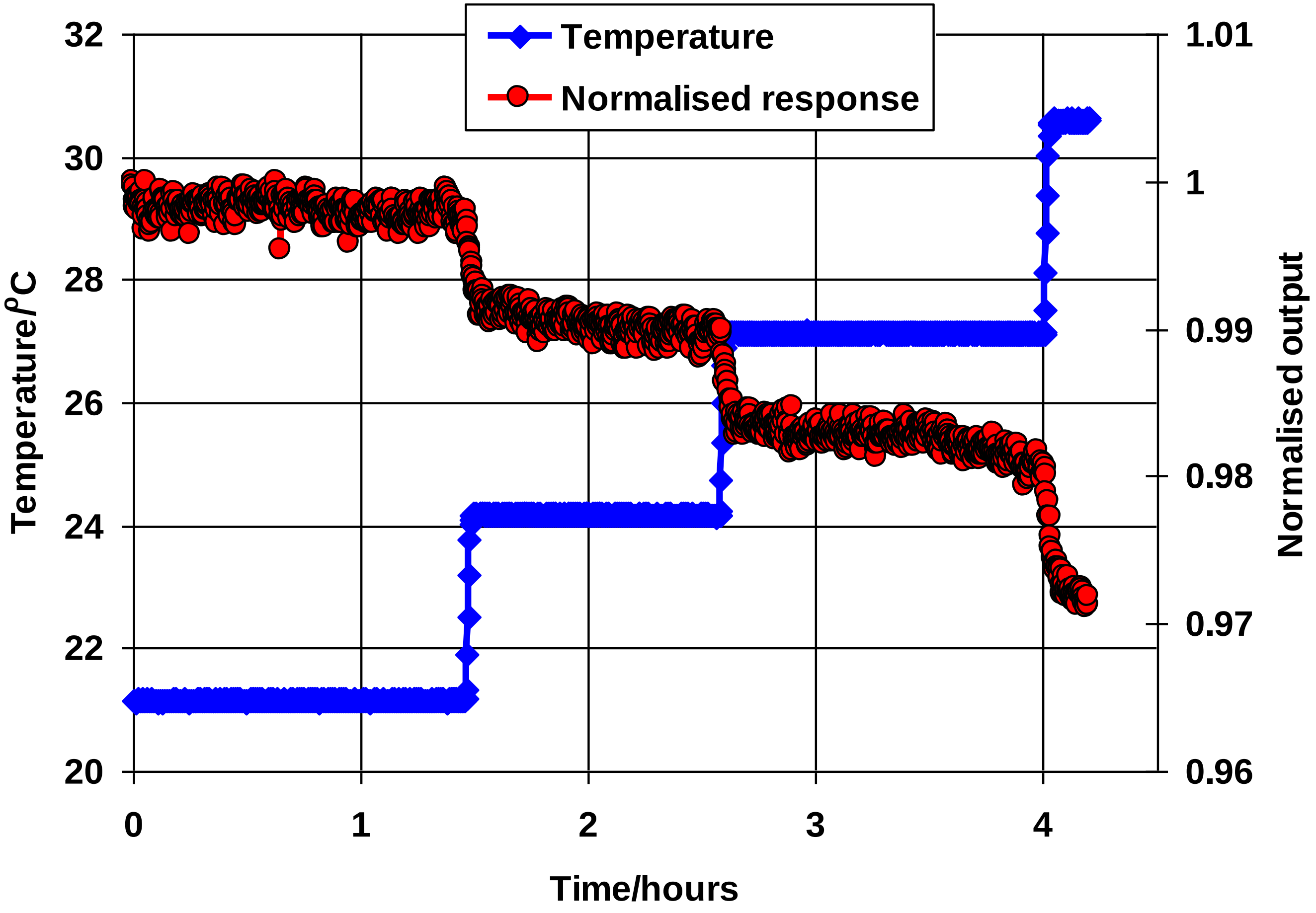
**<u>In ALL applications of HgCdTe detectors!</u>**

- **Earth Observation !!!!!!!!!!**
- **Radiometry**
- **Laser radiant power stabilisation**

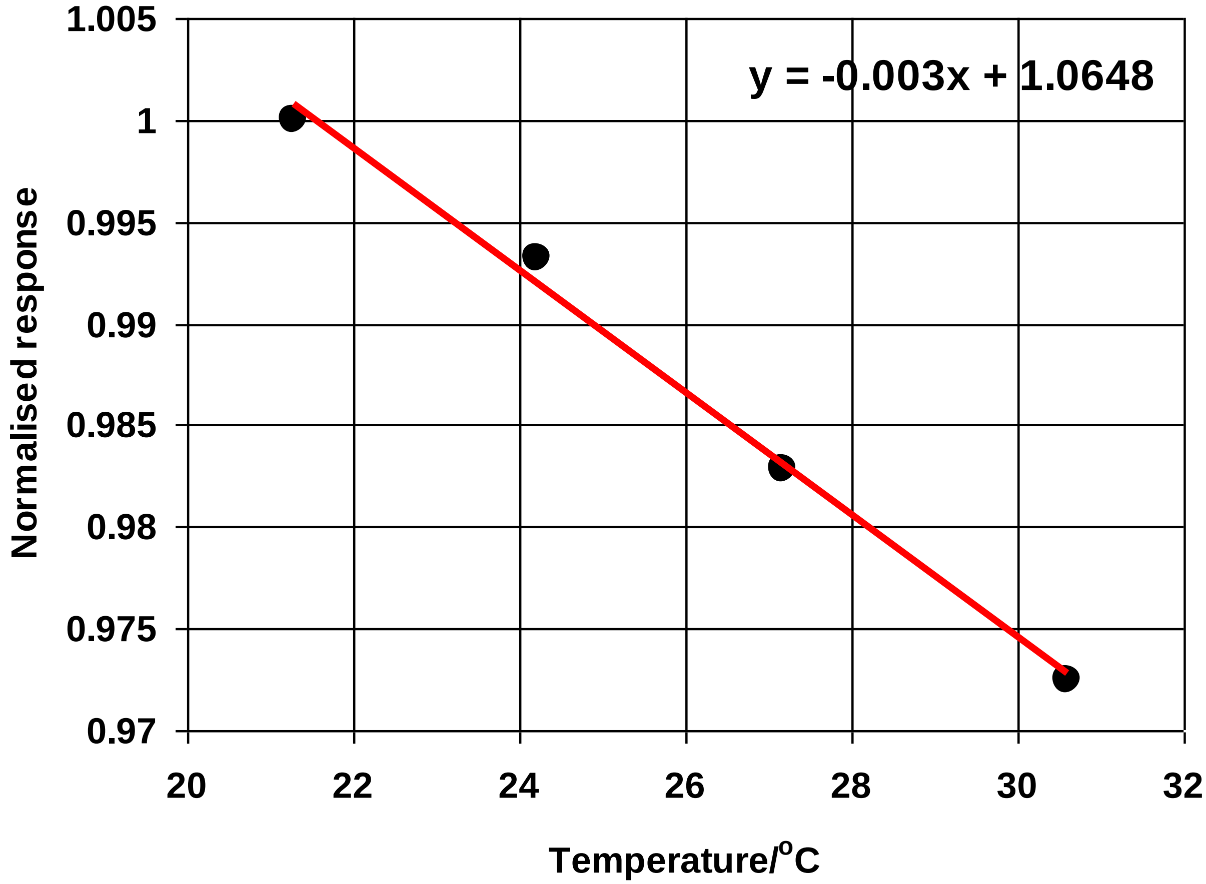
# PV HgCdTe soldering iron test. Identical percent change at 10.3 µm and 4.7 µm



# 2 mm PV HgCdTe detector



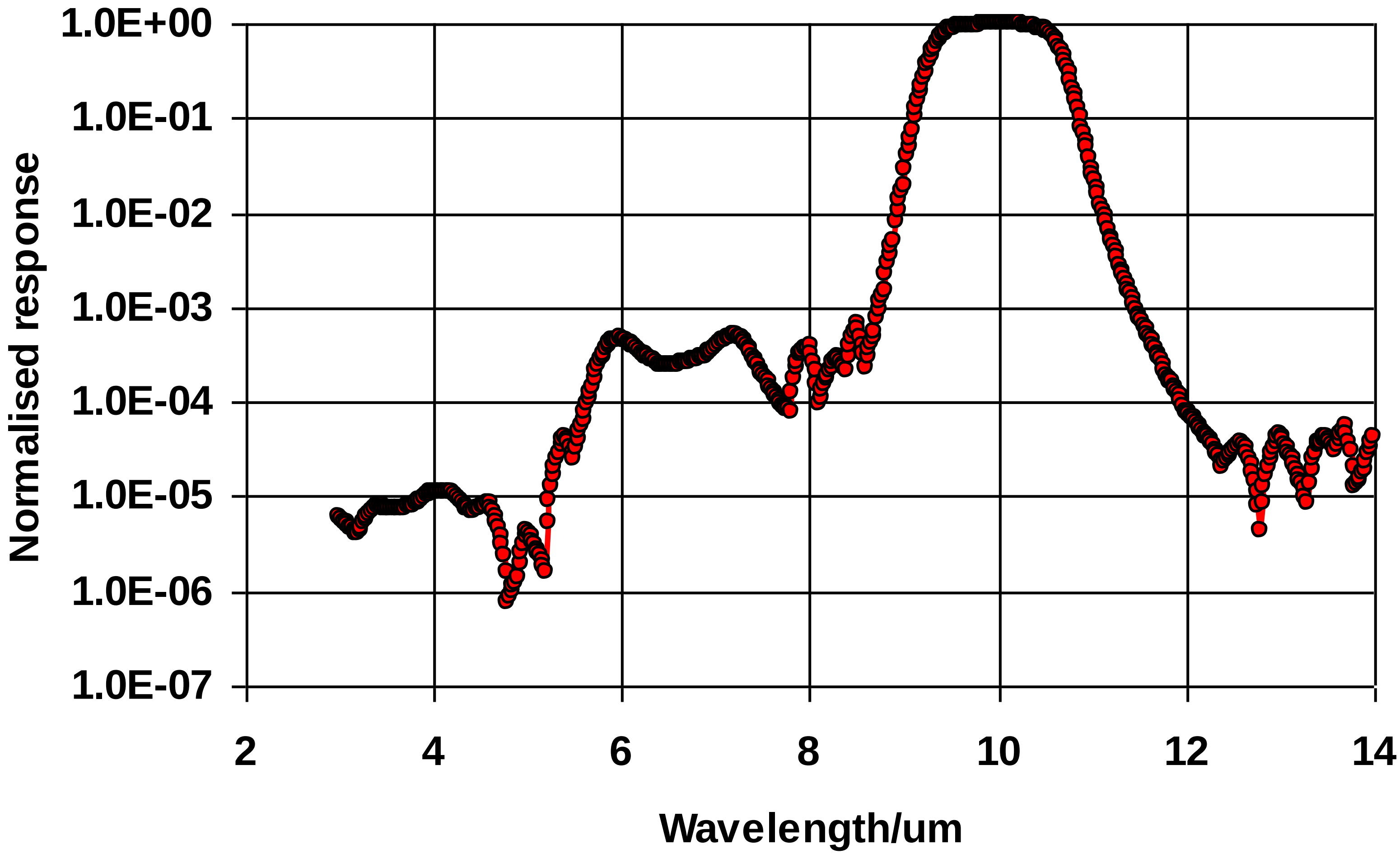
# 2 mm PV HgCdTe detector at 10.3 μm, slope less than half of that of PC HgCdTe



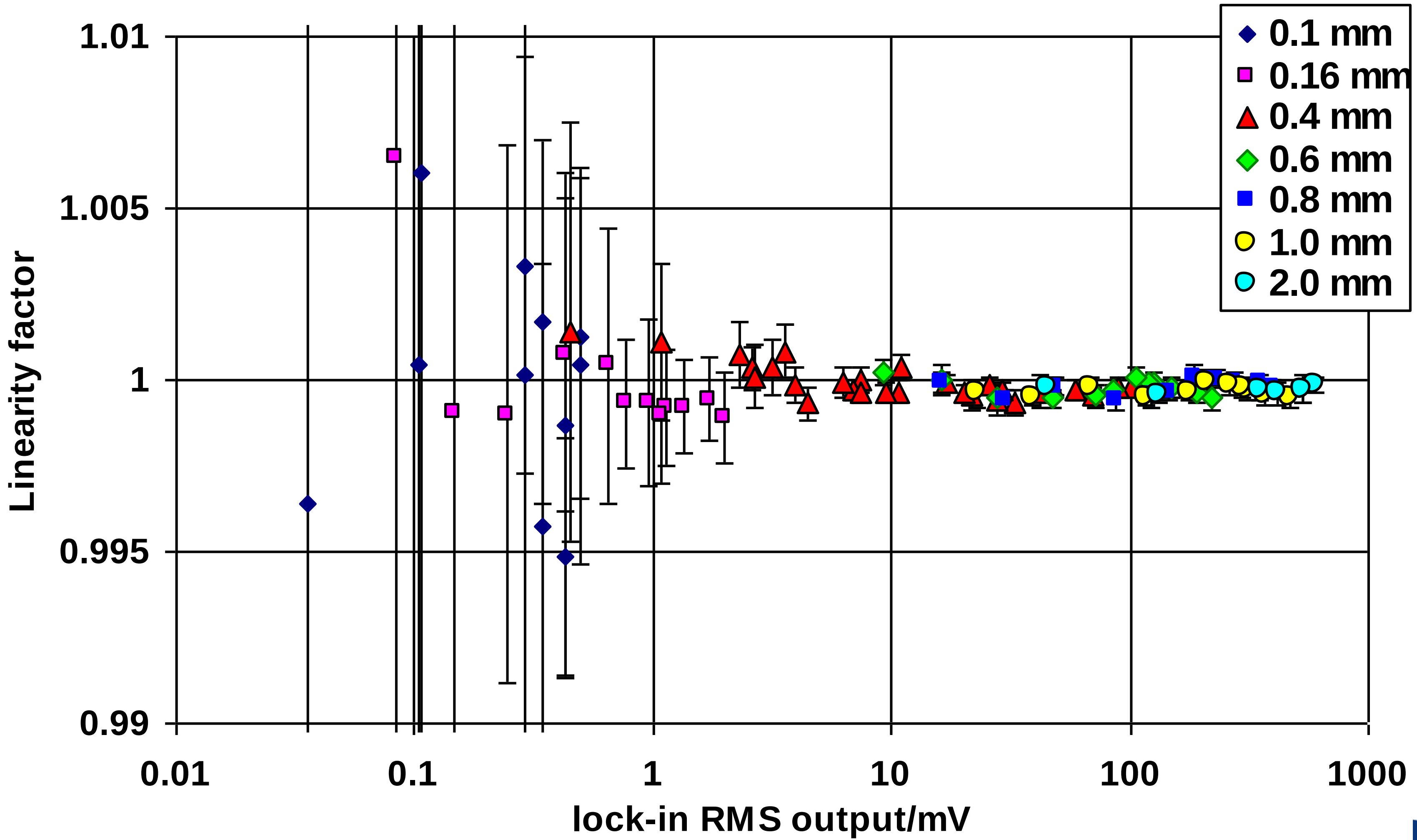
# How can we extent the linear range of operation of HgCdTe detectors?

- Reduce the thermal background reaching the detector:
  - Enclose detector in a “cold chamber”
  - Reduce temperature of objects in the FoV of the detector (reduce size of cold shield aperture)
  - Use cold filter

# Normalised response of HgCdTe Filter Radiometer



# Linearity characteristics of the 10.1 μm PV CMT filter radiometer

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# The introduction of the cold filter has two benefits:

1. Reduces noise due to the reduction of the thermal background being detected.

2. Improves linearity because it reduces the photo-generated charges produced by the thermal background, thus reducing the effect of the "Theo$^2$ effect".

Penalty: Limited spectral response range

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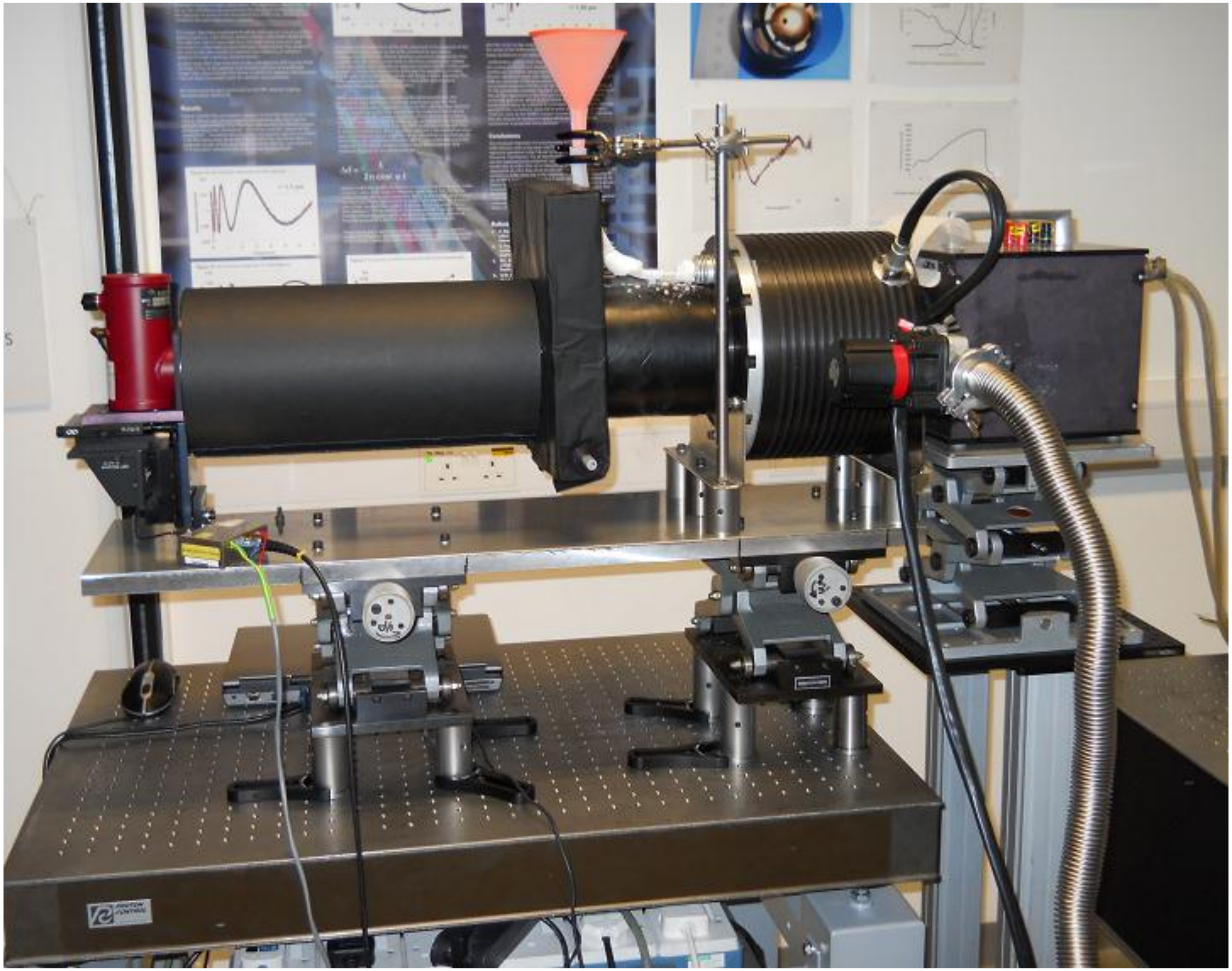

# Conclusions

The linearity characteristics of PV HgCdTe detectors were experimentally investigated in the infrared.

Measurements were completed with the test detector operating under conditions identical to those in which it would operate when used in typical infrared radiometric applications.

The non-linearity of the PV HgCdTe detectors was shown to be a function of photon irradiance rather than the total radiant power incident on the test detector.

The "Theo$^2$ effect" dominates the detector non-linearity.

# Methods of increasing linear range of operation of HgCdTe detectors:

Operate PV HgCdTe detectors with their active areas overfilled.

Adjust cold shield to give small FoVs (remove “hot” objects from the detector FoV)

Use “cold filters” whenever possible.

# Thank you for listening

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# Nine publications from NPL on detector linearity


1. **E. Theocharous, J. Ishii and N. P. Fox, "Absolute linearity measurements on HgCdTe detectors in the infrared", *Applied Optics*, 43, 4182-4188, 2004.**
2. **E Theocharous, "Absolute linearity measurements on PbS detectors in the infrared", *Applied Optics*, 45, 2381-2386, 2006**
3. **E. Theocharous and O. J. Theocharous, "Practical limit of the accuracy of radiometric measurements using HgCdTe detectors" *Applied Optics*, 45, 7753-7759, 2006.**
4. **E. Theocharous, "How linear is the response of your detector?", Europhotonics Magazine, February edition, Pages 33-35, 2007.**
5. **E. Theocharous, "Absolute linearity measurements on a PbSe detector in the infrared", *Infrared Physics and Technology*, 50, 63-69, 2007.**
6. **E. Theocharous, "Reply to comments on "Absolute linearity measurements on a PbS detector in the infrared"", *Applied Optics*, 46, 6495-6497, 2007**
7. **E. Theocharous, "Absolute linearity characterisation of lock-in amplifiers" *Applied Optics*, 47, 1090-1096, 2008.**
8. **E. Theocharous, "Absolute linearity measurements on a gold-black-coated deuterated L-alanine-doped triglycine sulphate pyroelectric detector", *Applied Optics*, 47, 3731-3736, 2008.**
9. **E. Theocharous, "Absolute linearity measurements on $LiTaO_3$ pyroelectric detectors", *Applied Optics*, 47, 3397-3405, 2008**


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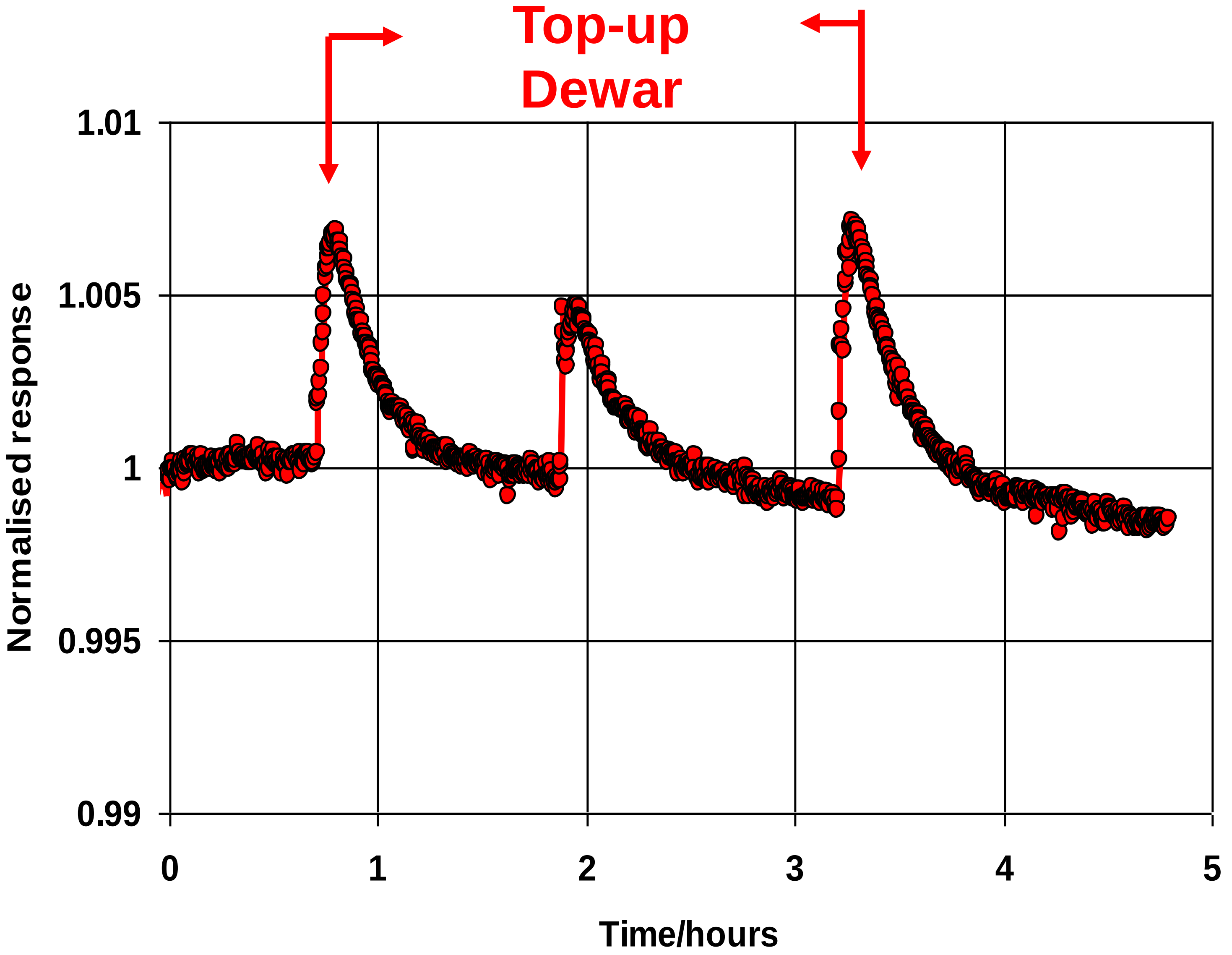
# Drift in a HgCdTe detector due to “topping up” of the Dewar (Infrared Physics & Tech. 48, 175-180, 2006)



# Larry Gordley Principal Associate, GATS, Inc. l.l.gordley@gats-inc.com

- I'm the PI for a differential absorption occultation experiment called SOFIE (Solar Occultation For Ice Experiment) designed to sound the atmosphere at polar mesospheric cloud levels (83 Km). The instrument developer selected MCT PC detectors for most of the channels, but failed to realize (as did the detector manufacturer Judson) that the predicted flux levels would drive the detectors into a severely non-linear region, given our under-fill design. When the first full up tests (in late July) showed extreme, intolerable, non-linearity, the budget and schedule constraints threatened the whole mission, which included two other instruments on the AIM (Aeronomy of Ice Mission). In a panic literature search on linearity of MCTs, at the airport on the way back from the depressing tests, Google pointed me to your paper. Now, armed with the realization of the dependence linearity on irradiance (as opposed to flux), I simply had the detectors moved to an overfill position (3mm shim) which brought the response into an easily manageable range of non-linearity. Tests yesterday validated the improvement, which has spawned both relief and celebration.
- Thanks a million and all the best.