# Development of a Versatile Radiometer-Photometer System

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# Outline

- Introduction/motivation
- Design considerations
  - Mechanical and optical design
  - Design of temperature control
  - Electronic design
- Quality tests
- Conclusions

# Introduction/motivation

- There is a need for a versatile radiometer-photometer system that can disseminate radiometric and photometric scales from the NMI level to the radiometric and photometric community with high sensitivity and low measurement uncertainty.
- The new system fills up an existing gap in detector-based scale propagations from UV to mid-IR

# Design considerations

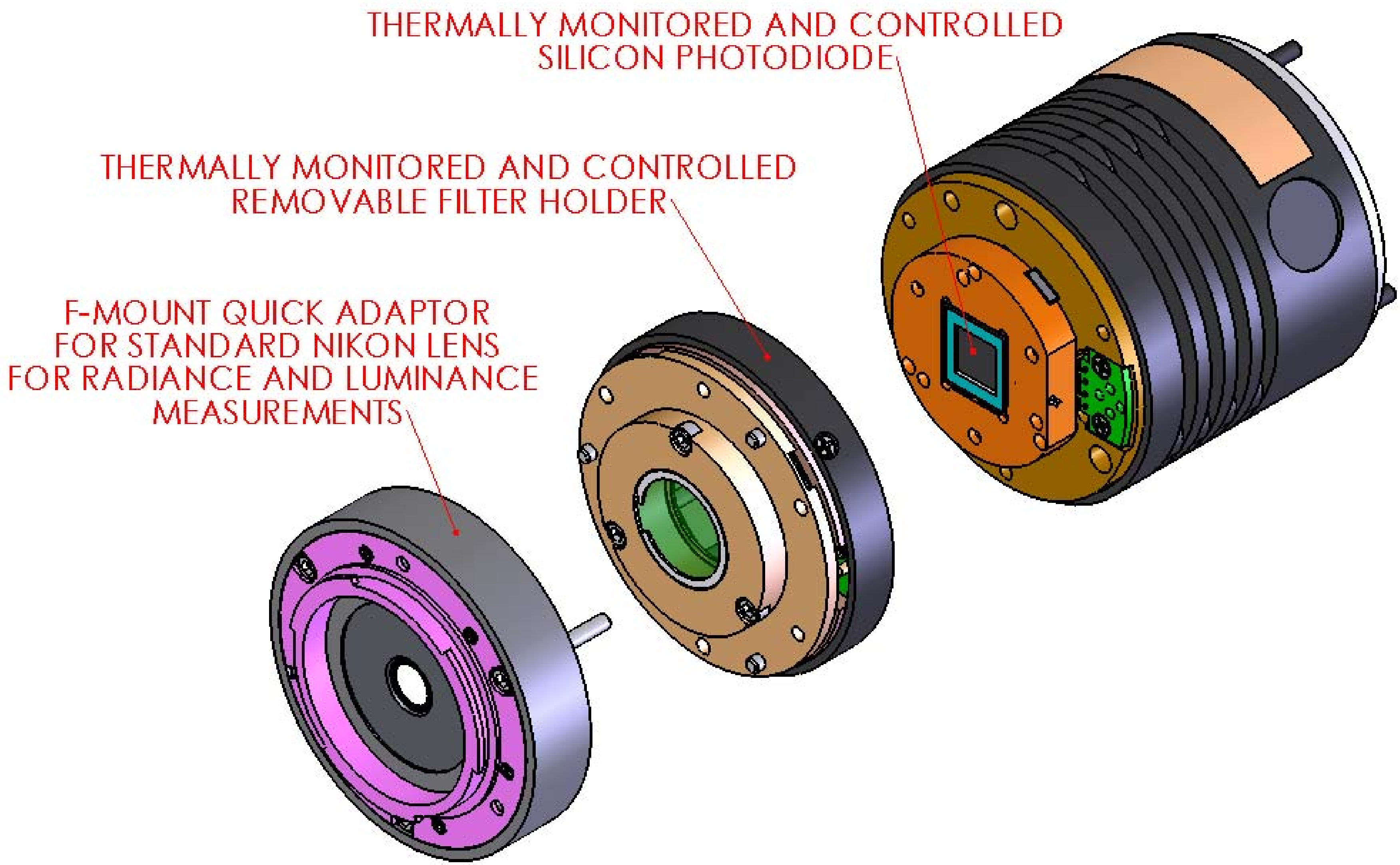
- Satisfy the increased requirements in the dissemination of NIST detector responsivity scales
- In addition to traditional spectral power responsivity, spectral irradiance and radiance responsivity measurements are to be performed
- Propagate the extended NIST responsivity scales to field applications with a minimal increase in measurement uncertainty
- The designs are made such that the combined measurement uncertainty is dominated by the uncertainty of the responsivity calibrations and not the performance of the radiometers.

# Mechanical and optical design

- Versatile measuring head
  - **Front geometry can be easily modified to measure**
    - **Power or luminous flux**
    - **Irradiance or illuminance**
    - **Radiance or luminance**
  - **Using**
    - **Apertures**
    - **Diffusers**
    - **Filters or filter combinations**
    - **Detectors (Si, passivated Si, InGaAs, extended-InGaAs etc)**

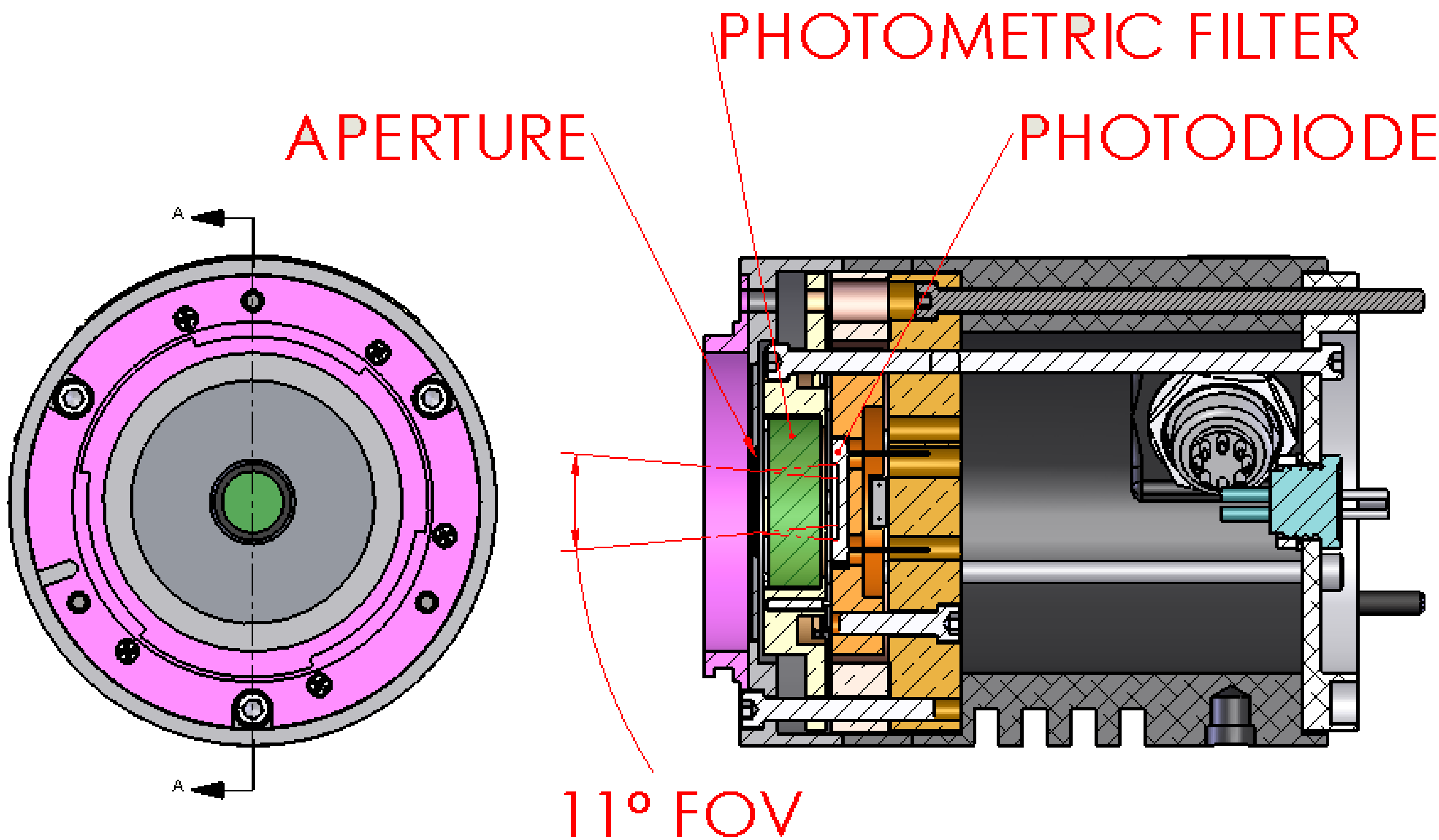
# Versatile measuring head

to measure power, irradiance, radiance and the photometric equivalents

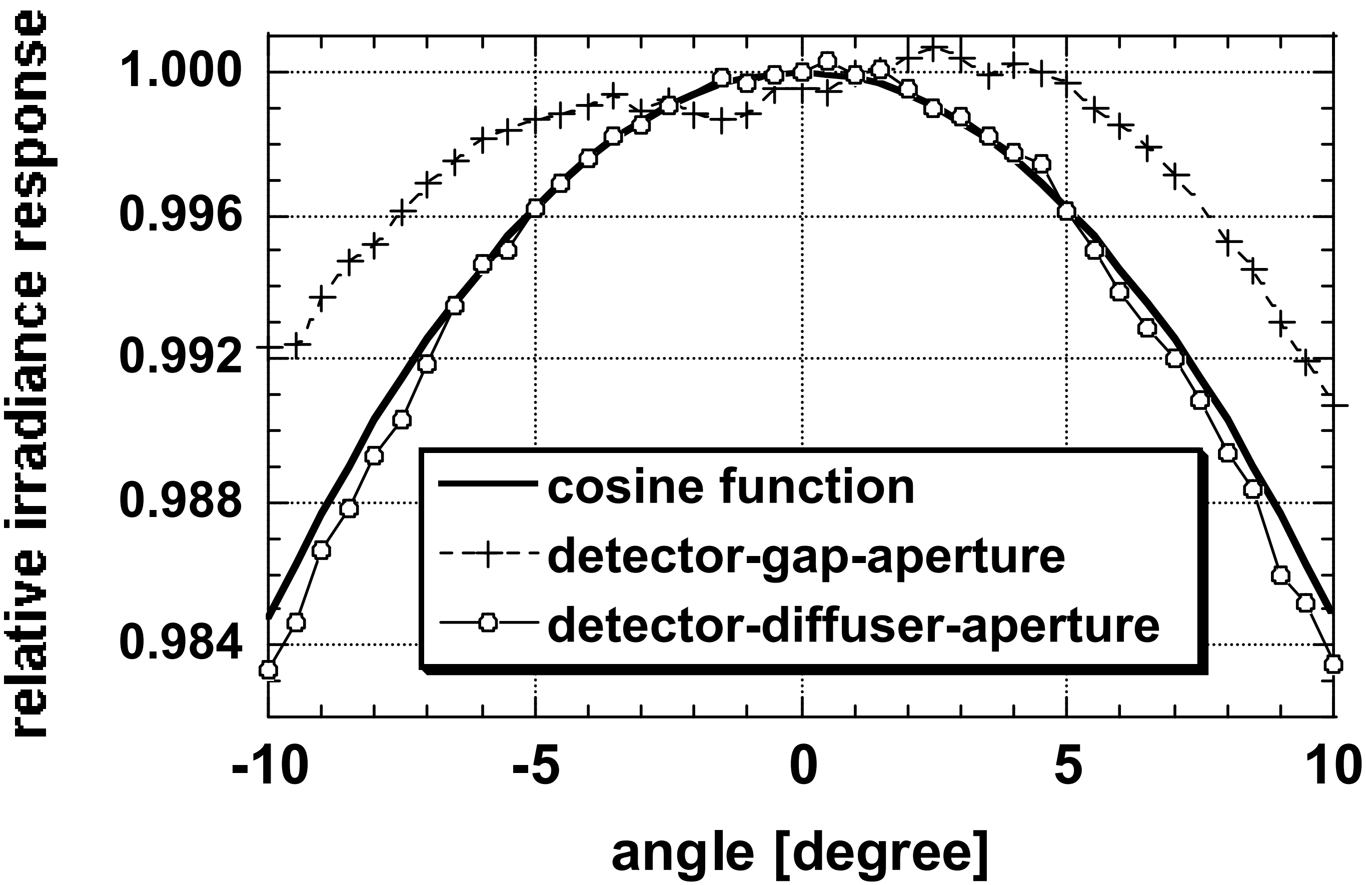


# Versatile measuring head

## Illuminance meter cross section and front view

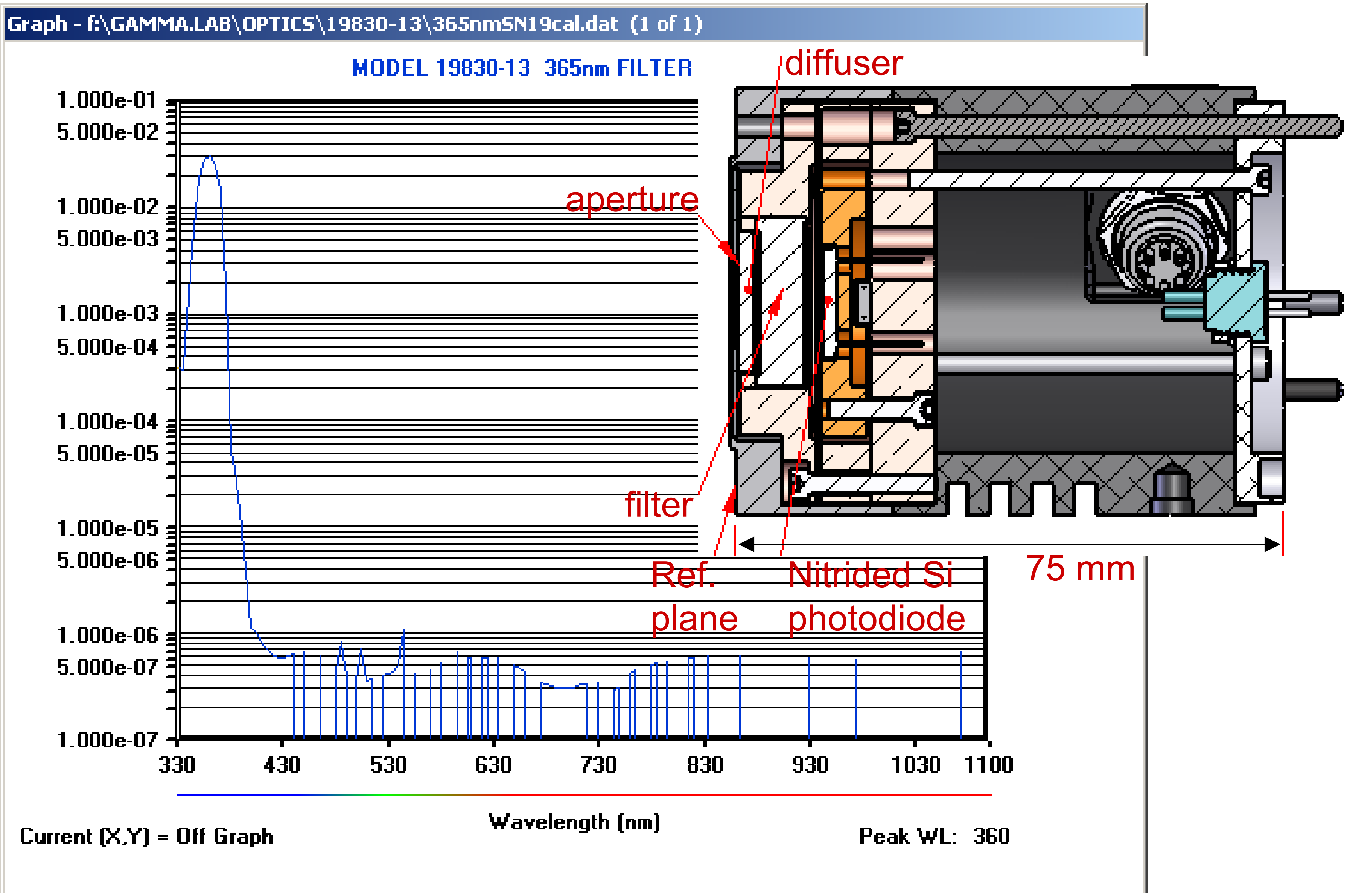


# Diffuser input irradiance meter

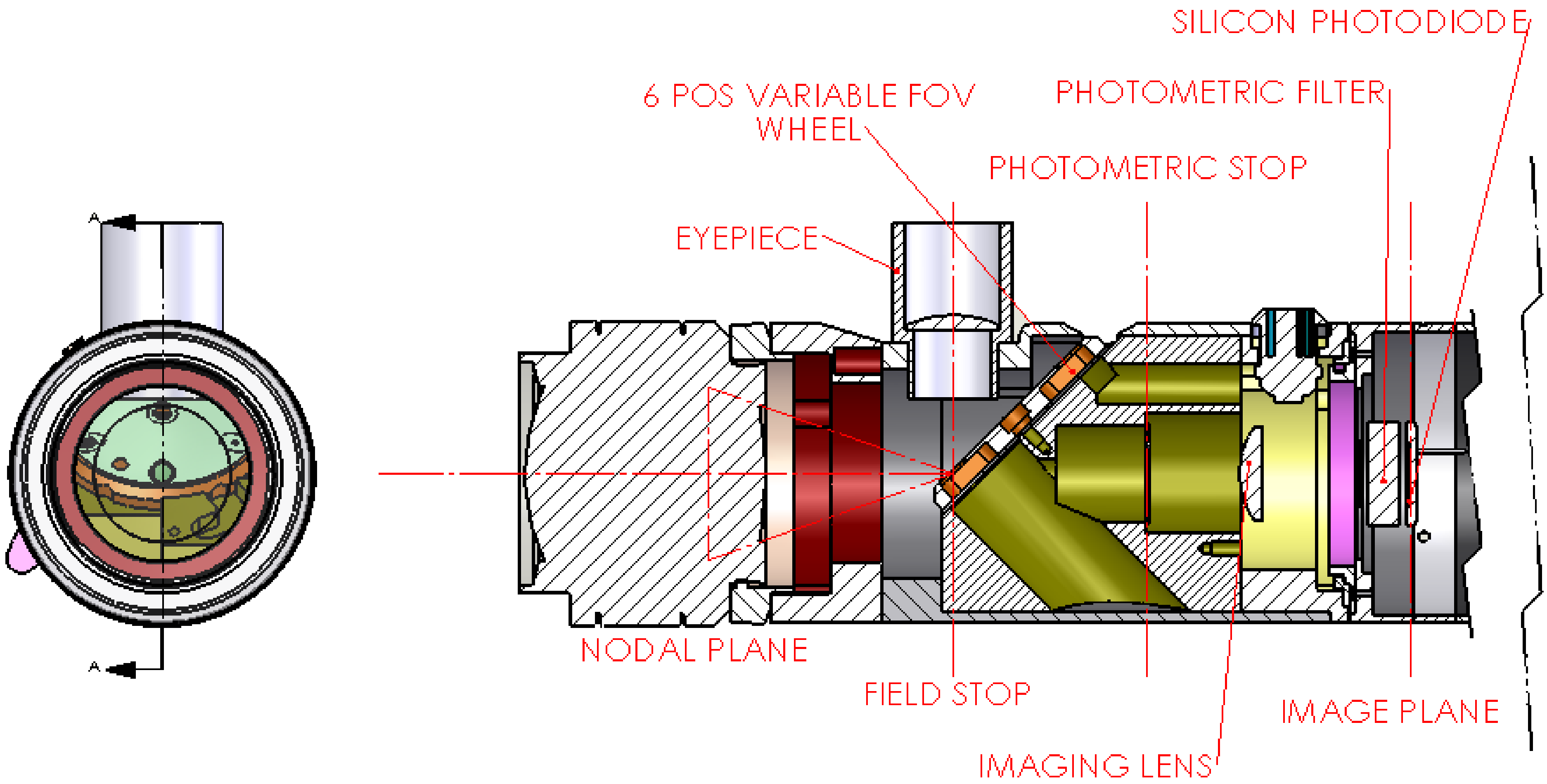


# UV filter-irradiance meter

## selective at 365 nm

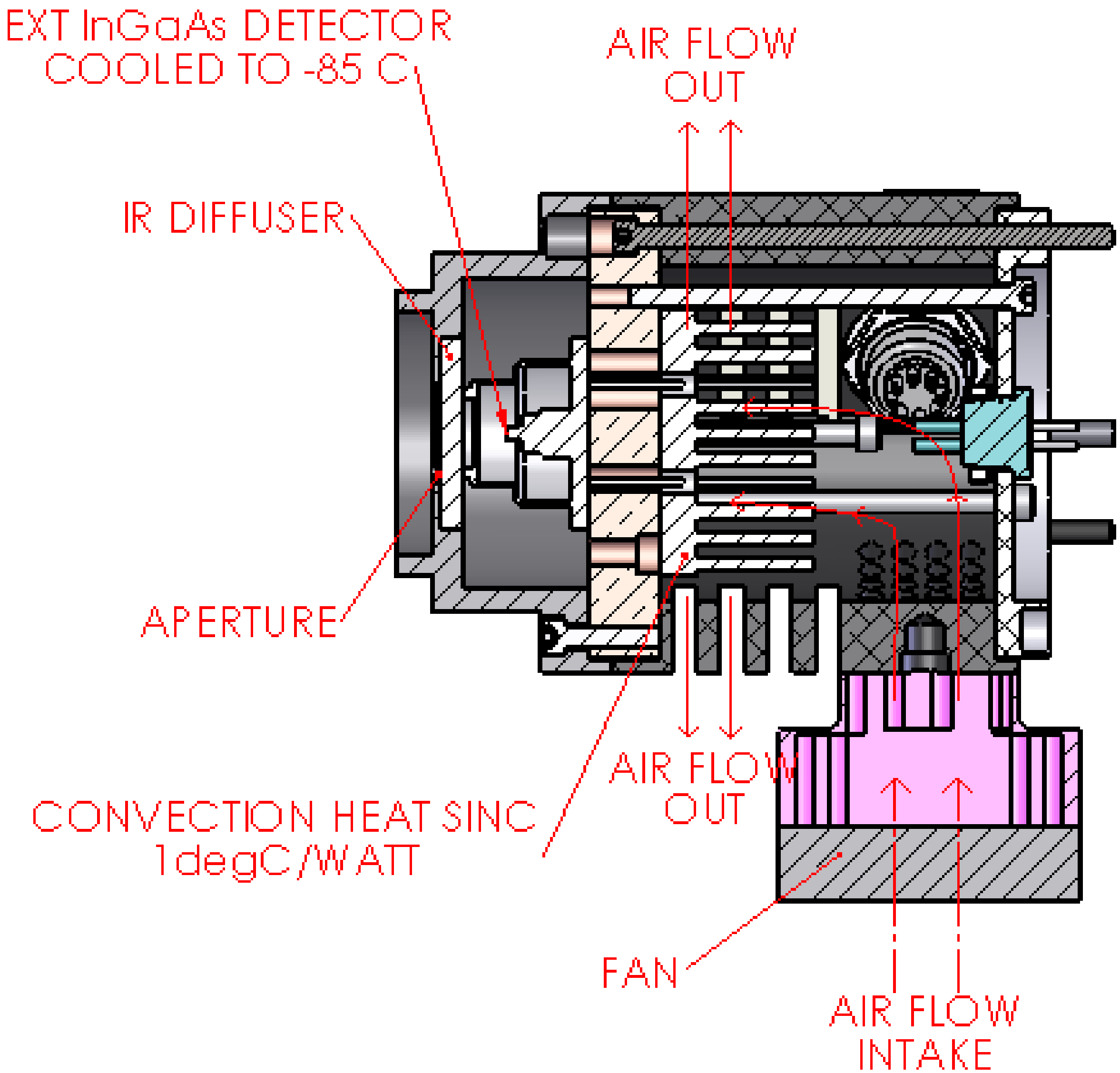


# Radiance (luminance) measuring input optics



# Design of temperature control

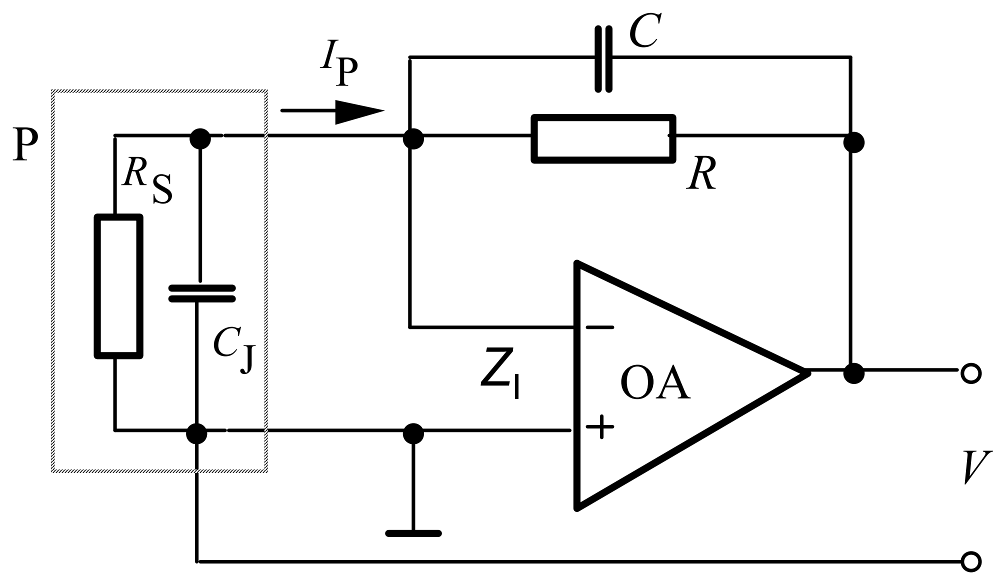
## Housing of a cooled Ext-InGaAs irradiance detector




**It is necessary to deliver the dissipated heat away from the 4-stage TE cooler**

# Electronic design

## signal-gain and loop-gain optimization, linearity




**Signal gain and its uncertainty:**

$$\frac{V}{I_P} = R\frac{1}{1+G^{-1}}$$

**R resistors have 0.01 % tolerances and 10 ppm/C**

**Input Impedance:**

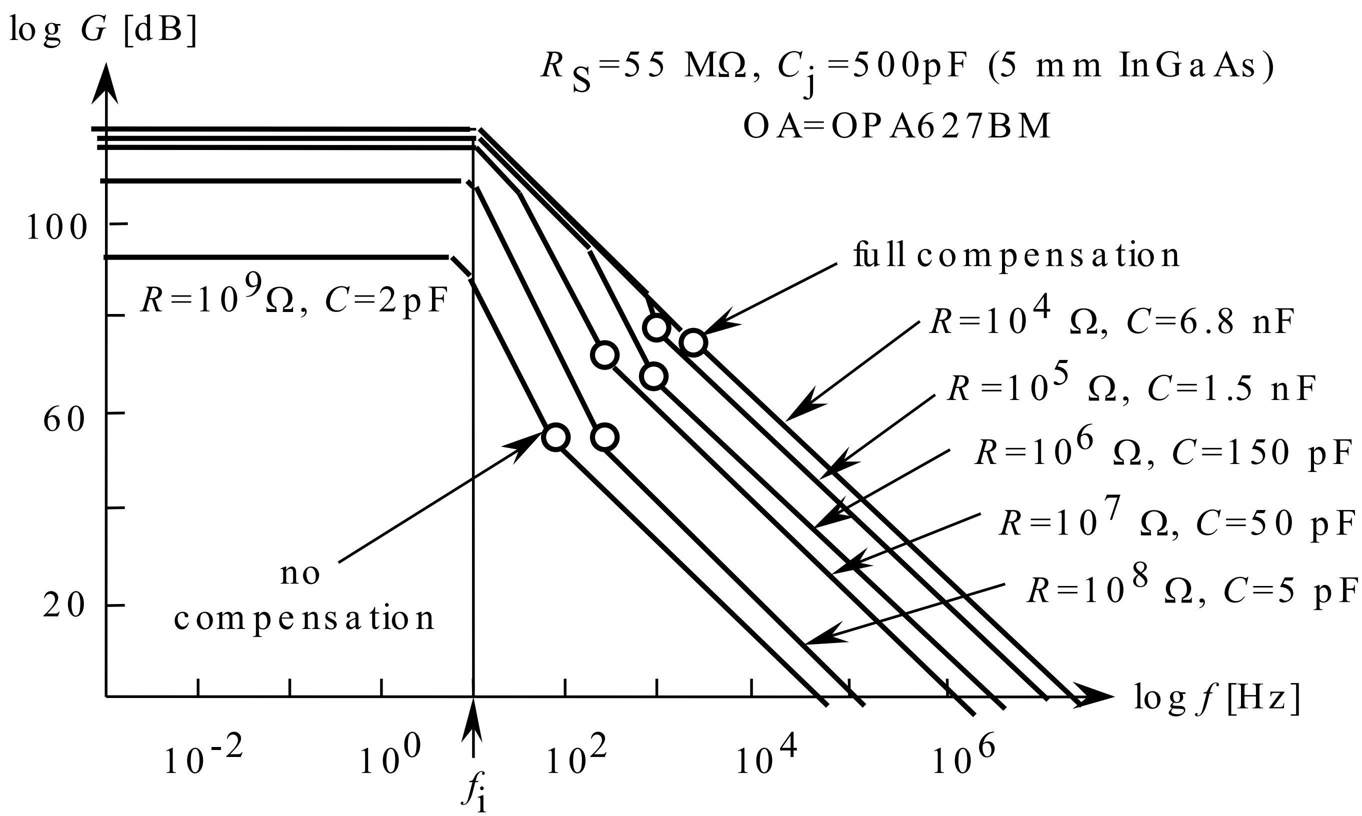
$$(Z_I)^{-1} = \left(\frac{R}{A}\right)^{-1} + \left(\frac{1}{j\omega AC}\right)^{-1}$$

**Loop gain:**

$$G = A_0\beta_0 \frac{1}{1+j\omega\tau_i}\frac{1+j\omega\tau}{1+j\omega\tau_2}$$

**To obtain linearity:** $Z_I << Z_P$

# Calculated loop-gain curves and signal roll-off frequencies
## of an InGaAs radiometer




$G_{min}$= 1000 = 60 dB (at f<100 Hz chopping)

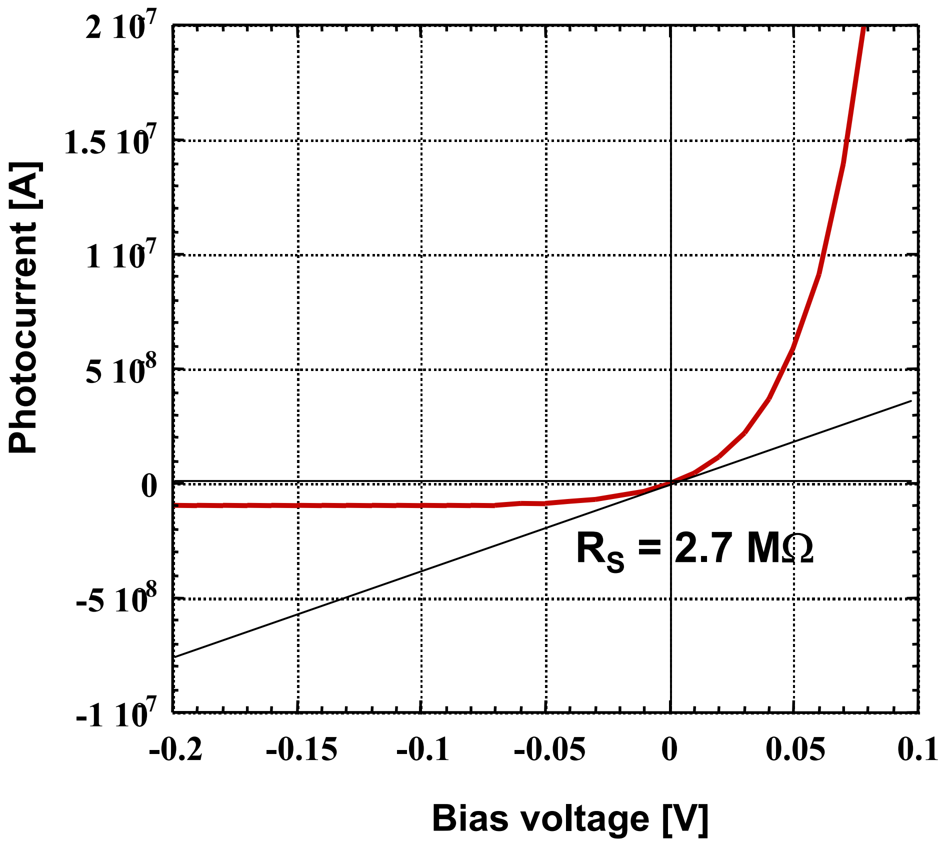
**O** = signal-gain 3 dB roll-off points

# Quality tests

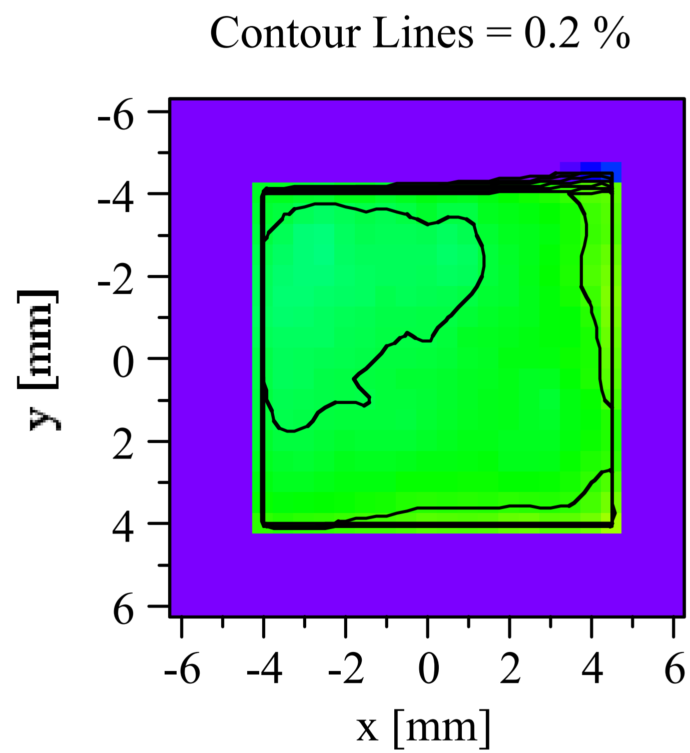
1. Detector tests (for selection)
   - Shunt resistance (versus temperature)
   - Spatial non-uniformity of responsivity
2. Radiometer dark-tests
   - Output offset voltage versus signal gains
   - Noise test (NEC and NEP)
3. Temperature control (cooling-heating) tests
4. Radiometric tests
   - DC tests:
     - Spectral responsivity (power, irradiance, or radiance)
   - AC tests:
     - Upper roll-off frequency of responsivity
     - AC-to-DC responsivity conversion factor (lock-in calibration)

# Shunt resistance $R_S$ and spatial non-uniformity of responsivity of photodiodes

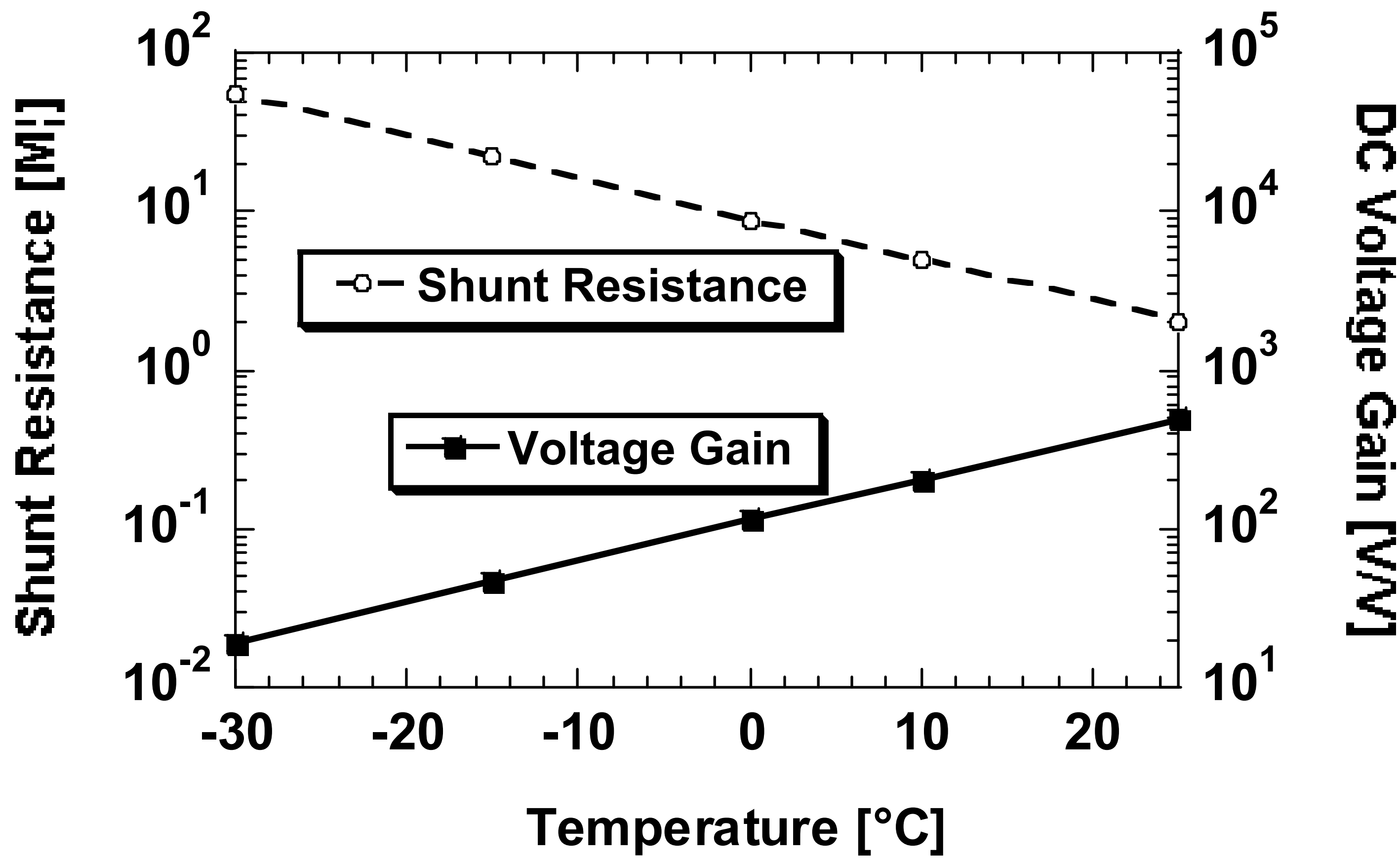
**Computed example for InGaAs:**




**Measured silicon S1337 @ 500nm:**

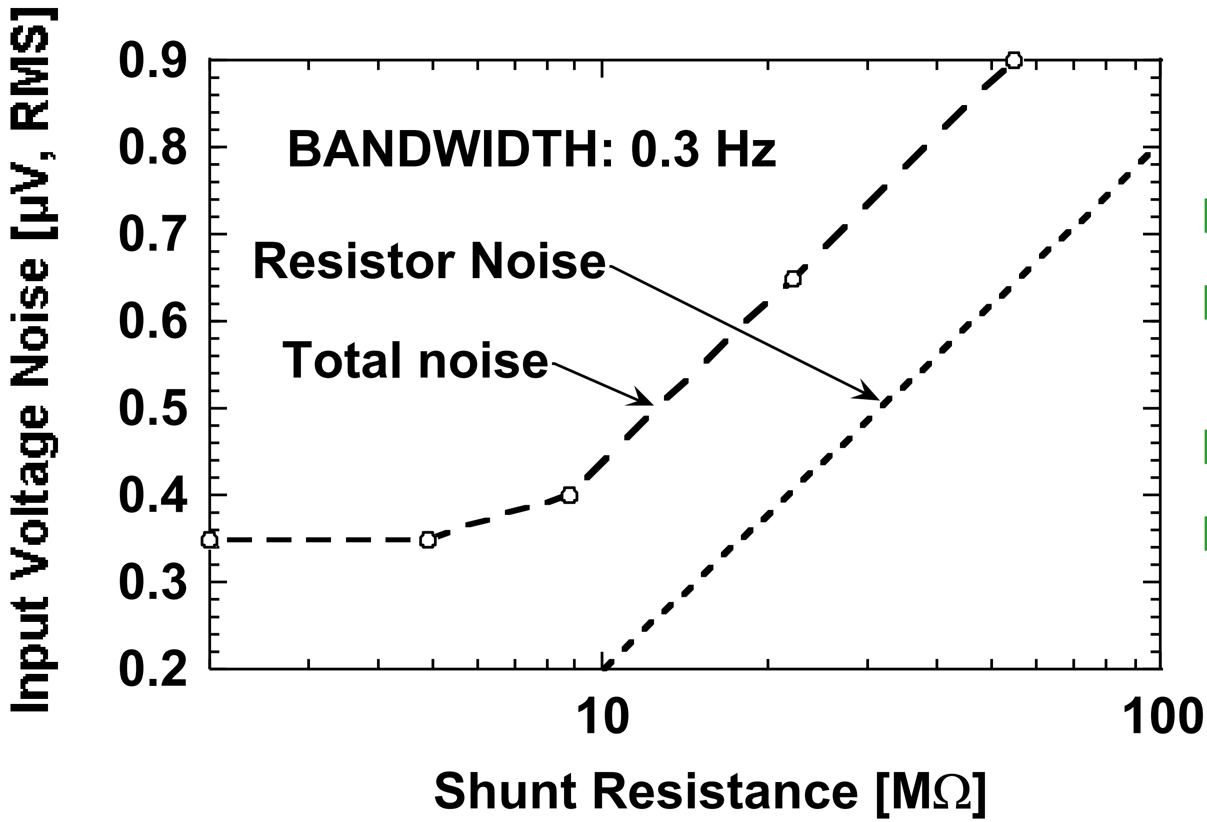


# Shunt resistance and DC voltage gain versus temperature
## of an InGaAs radiometer



# Noise test in dark

## $R_S$ dependent noise of an InGaAs radiometer




**Noise Equivalent Current:**

**NEC = $V_{out}$(STD) / R(feedb)**

**Noise Equivalent Power:**

**NEP = NEC / responsivity**

# NEC in dark as measured by the same preamplifier for two photodiodes at gain $10^{10}$ V/A

| Hamamatsu photodiodes | 23°C | | 4°C | |
|---|---|---|---|---|
| | $R_S$ | NEC ($\Delta f$=0.3 Hz) | $R_S$ | NEC ($\Delta f$=0.3 Hz) |
| Si S1226 | 20 GΩ | 3 fA | - | - |
| InGaAs G5832-25 | 6 MΩ | 180 fA | 42 MΩ | 25 fA |

Cooling by 19 $^0$C resulted in:

**- a factor of 7 increase in shunt resistance**

**- a factor of 7 decrease in the noise floor**

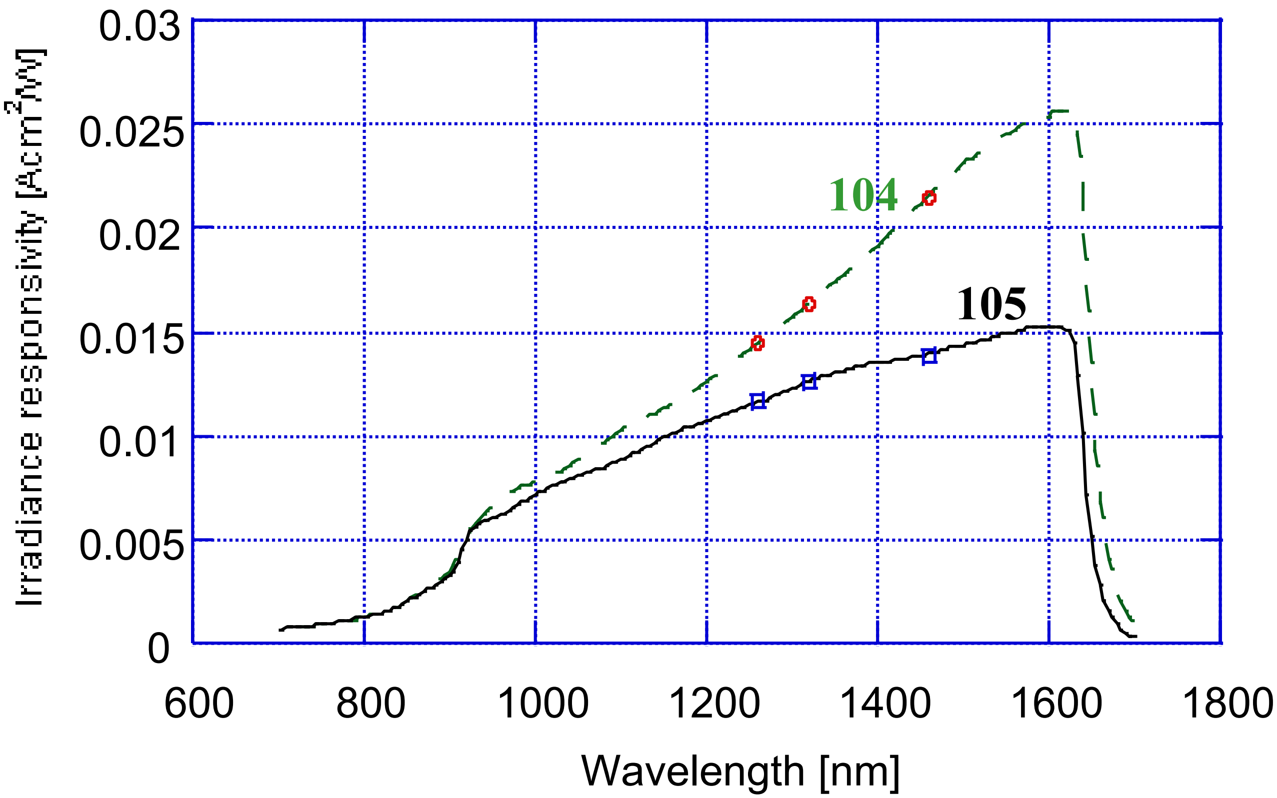
# Temperature control (cooling) tests

- **Checking the voltage drop on the thermistor sensor**
  1. Select the thermistor bias current to obtain a large enough voltage drop on the thermistor for its cold (highest) resistance
  2. Measure the voltage drop at room temperature (the control loop is in DISABLE) and then at cold (the loop is in ENABLE)
- **The cold voltage drop must be larger than the room temperature voltage drop. Otherwise, the control loop will heat.** Compare this voltage ratio with the thermistor resistance ratio (in the temperature dependent characteristics). **The two ratios should agree.**
- **The voltage reading on the thermistor and the SET (reference) voltage should be equal within a few mV (loop standstill error) and this *difference should be constant when the cooling is on for hours.***

# Radiometric tests

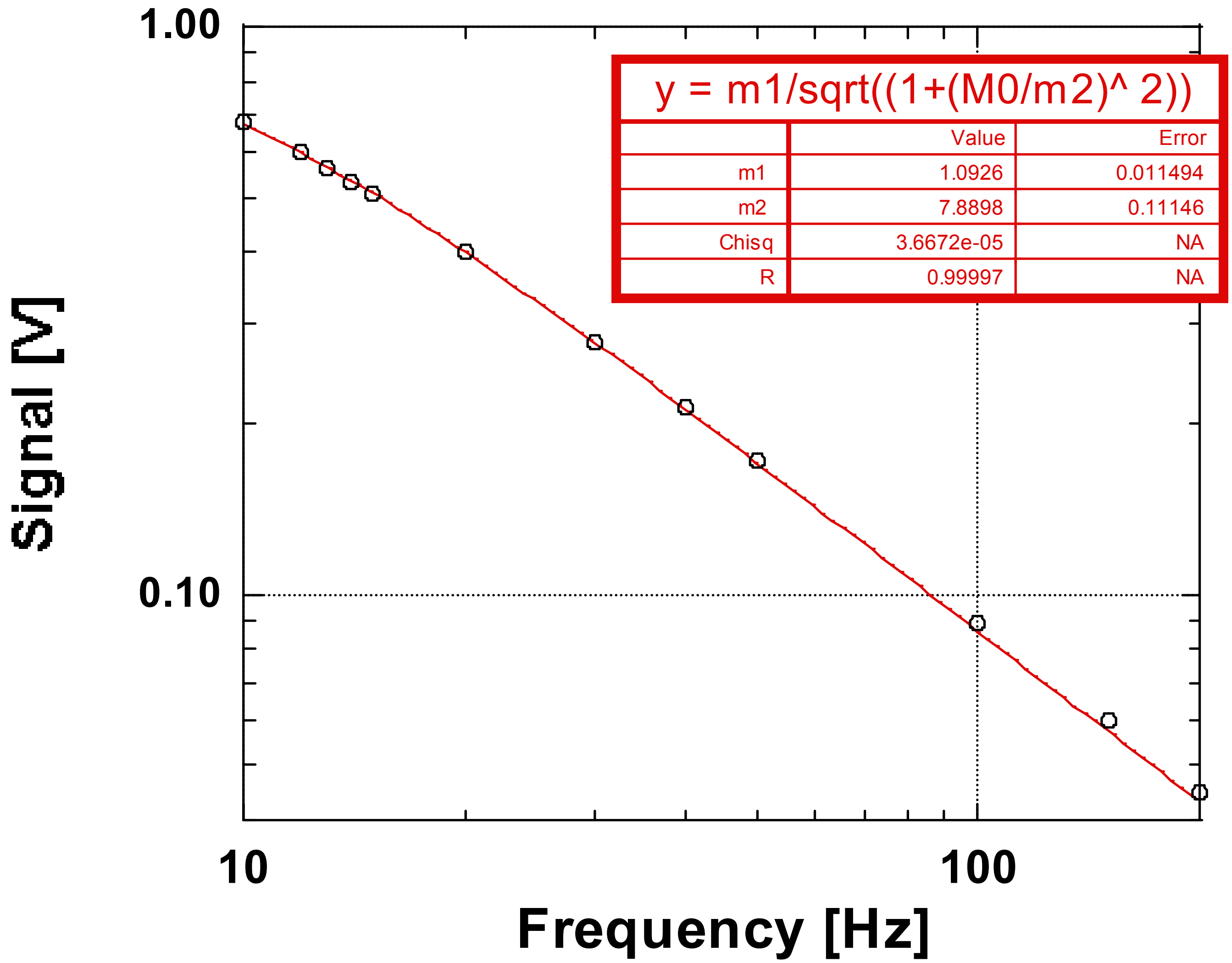
## Spectral responsivity test

of InGaAs irradiance meters



# Upper roll-off frequency test

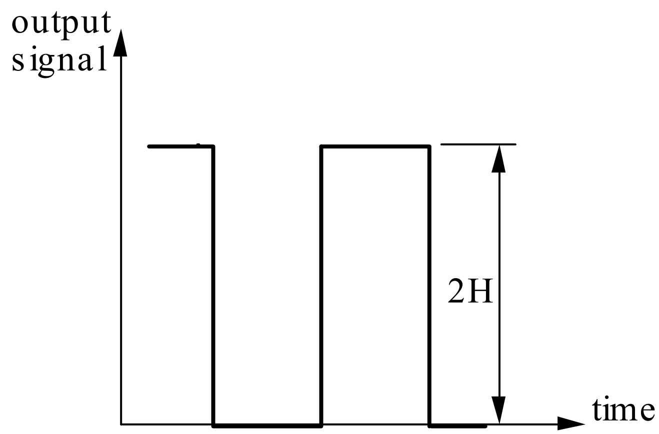
## Responsivity versus frequency at $10^{10}$ V/A signal-gain



# DC-to-AC conversion factor

## when a sine wave measuring lock-in measures square wave

- **Signal to be measured:**




- **Theoretical reading of a sine-wave lockin:** $$S_1 = \frac{H}{\sqrt{2}} \frac{4}{\pi} = 0.9003H$$

- **The theoretical DC-to-AC conversion factor is:** $S_2/S_1$ = 2H / 0.9003 H = **2.221**
  $S_2$ can be measured by a DVM when the chopper is stopped. $S_1$ should be the real lock-in reading to correct for errors obtained using the theoretical conversion factor.

- **Even if signal is chopped, the DC responsivity can be reported. The gain versus frequency curve can be utilized here.**

# Conclusions

- A modular radiometer-photometer system has been developed that can measure the most important quantities from UV to mid-IR with low measurement uncertainty and high sensitivity.
- Mechanical, optical, thermal, and electronic design considerations have been discussed to achieve the uncertainty and sensitivity requirements.
- Quality-tests have been introduced to improve the performance and reliability.