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# Multiphysics Simulation of Polymer-Based Filters for Sub-Millimetre Space Optics

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# INTRODUCTION



- Heating of polymer-based filters [1],[2] for space missions working in sub-mm and FIR bands was analysed.
- Simulation was performed with heritage from Herschel and Planck-HFI.
- Design from large format array instrument for next generation CMB probe. [3],[4],[5]

- In past missions this aspect was not considered since no appreciable variation in the signal was detected [6]
- Future concepts include larger apertures, increasing the risk of heating (due to absorption of MIR radiation)
- Potential issues that could arise:
  - DC effect – rise in the average temperature of the portion of optical element seen by the detectors
  - Modulated effect – due to temporary absorption of power when pointing at bright near-IR sources


Credit: ESA


Credit: B-POL [4]


Credit: PRISM [5]

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# OPTICAL DESIGN CASE STUDY

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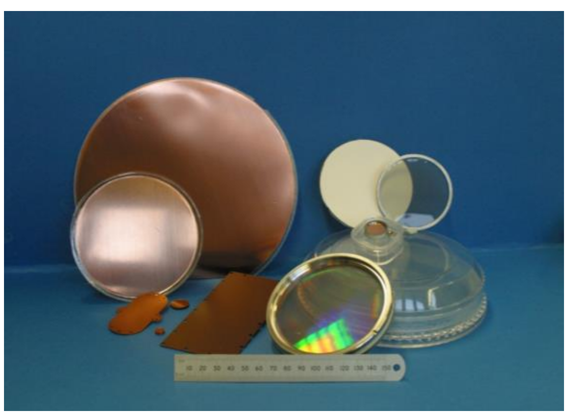
- Missions considered include a filter/window/lens between the incoming radiation and the first transmissive cryogenic optical element.

- Lack of window/thermal filters:
  - ↑ Space vacuum is better than induced vacuum in the lab;
  - ↑ In most cases (especially L2), radiative loading is lower than lab conditions (no thermal filters required)
  - ↓ Does this still hold true as the diameter of optical elements increases?

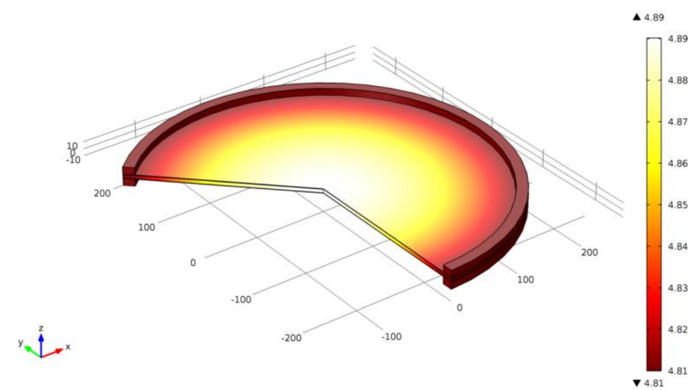
- Instrument concept chosen that of a CMB probe spinning on its axis (similarly to Planck).

❖ Two types of polypropylene filters analysed, one of which is coated with pPTFE.  Designed to have 100GHz and 143GHz as central frequencies.

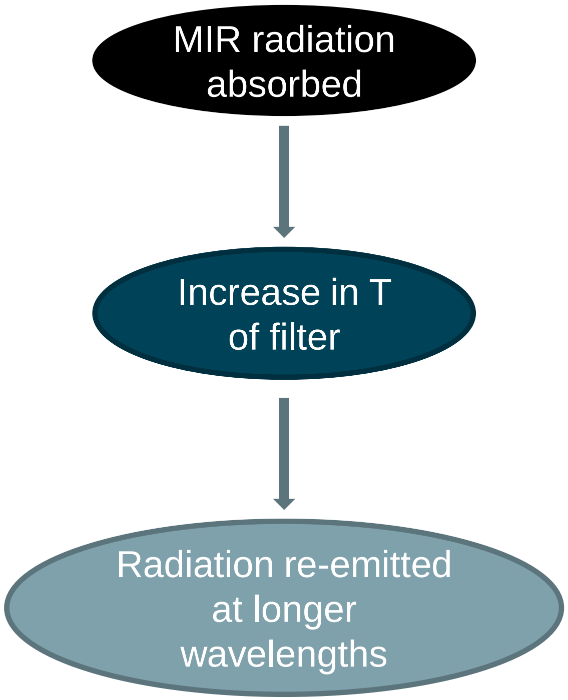
❖ Diameter of 250mm with 4.9mm thickness. Coating 625um thick.

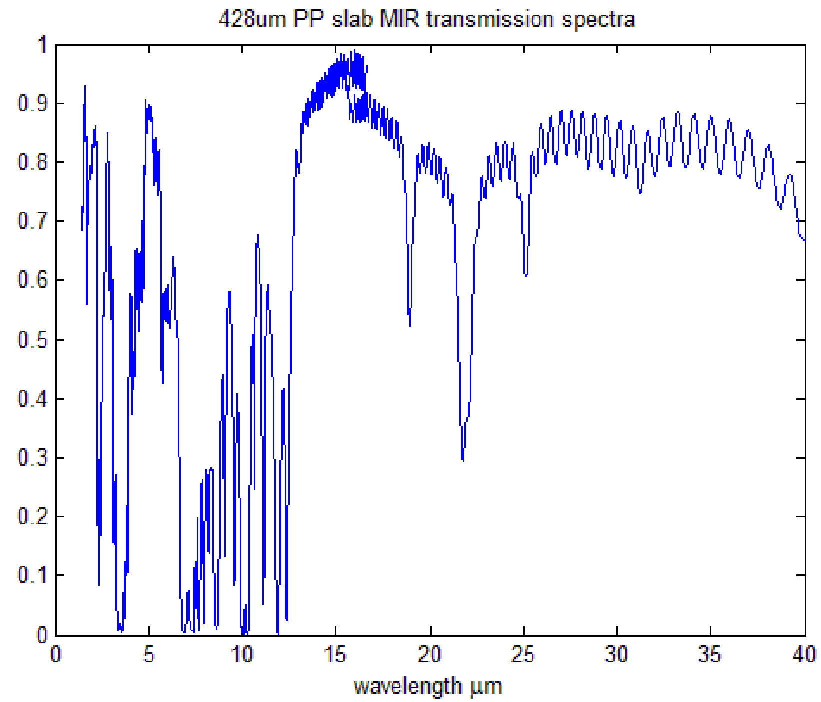


Large diameter hot-pressed and air-gap filters produced at Cardiff University.[1,2]



- Polymer filters highly transparent in the FIR but absorptive in the MIR
- Effective transducers in these wavelength ranges
- Crucial is to quantify the amount of radiation emitted from the filter's heating



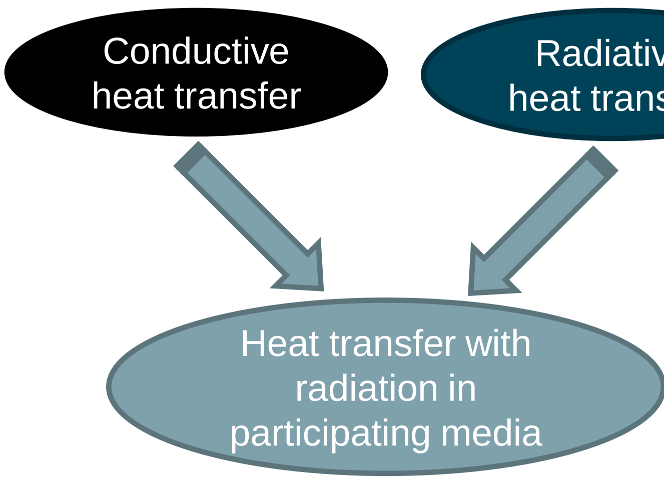



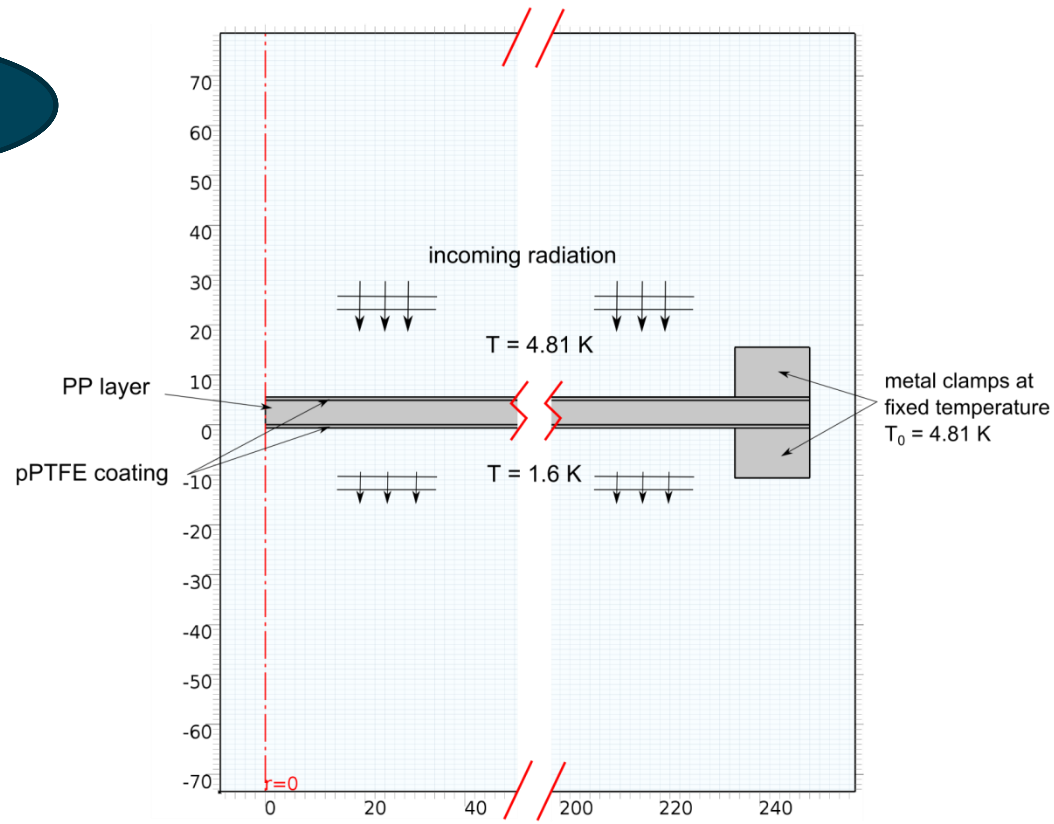

**Although small, this effect is not negligible**

# MULTIPHYSICS SIMULATION



- Polymer filters highly transparent in the FIR but absorptive in the MIR
- Effective transducers in these wavelength ranges
- Crucial is to quantify the amount of radiation emitted from the filter's heating



# THERMAL MODEL: radiative input

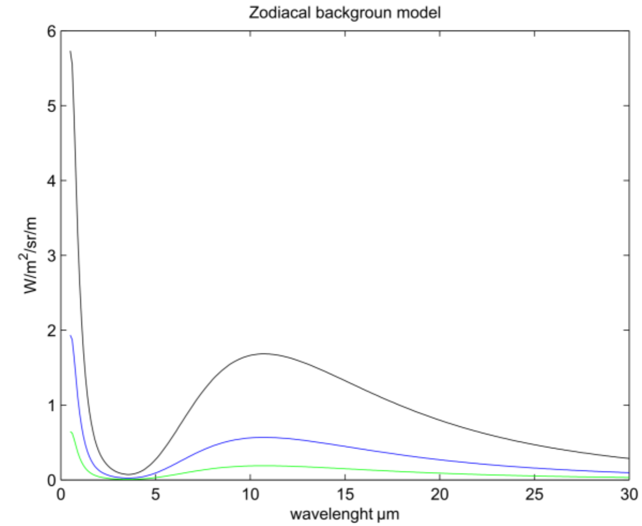


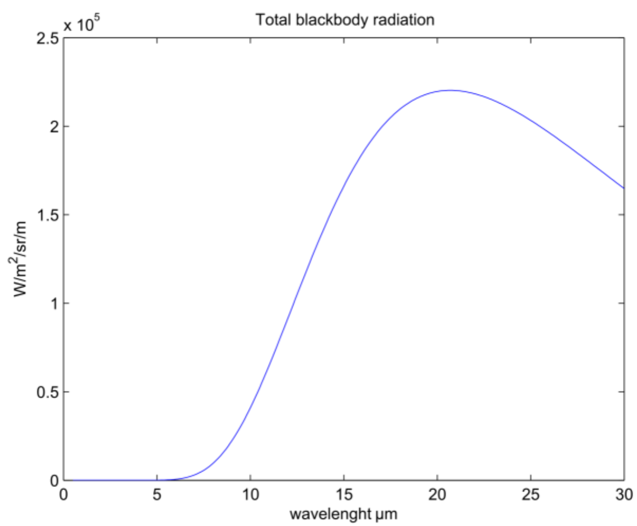
- Dominant emissions in the NIR-MIR region ($0.5 - 30\ \mu m$):
  - Zodiacal light
  - Jupiter's thermal emission

- Total incident power as function of satellite's throughput ($A\Omega$)

- $A\Omega$ values obtained from proposed concepts of future CMB missions [14,15]

| Incident power [W] | $A\Omega$ [$\mathrm{cm}^2$ sr] |
|---|---|
| $P_A = 1.0757 \cdot 10^{-4}$ | 0.3006 |
| $P_B = 13 \cdot 10^{-4}$ | 3.6829 |
| $P_{crs\_drg} = 0.2147$ | 600 |
| $P_{epicIM} = 0.3220$ | 900 |
| Satellite rotation period | 60 s |



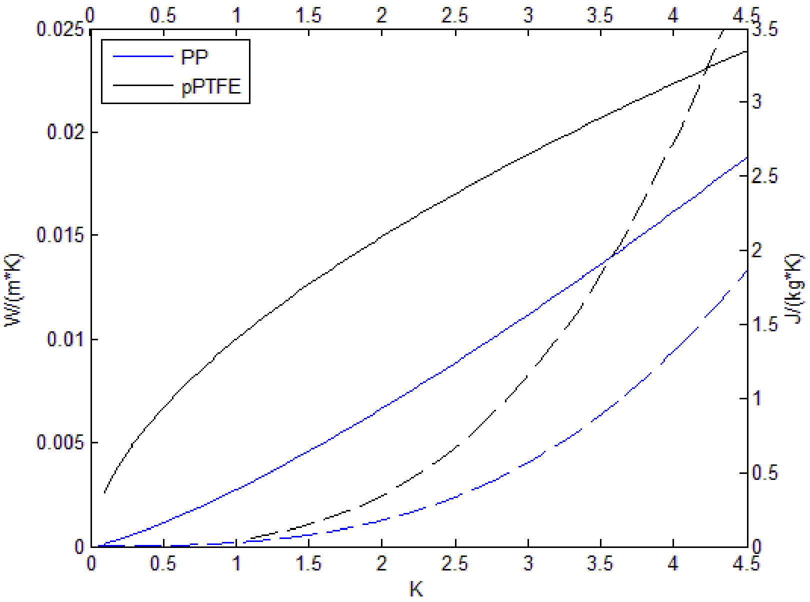



# THERMAL MODEL: material properties

Simulation enhanced with detailed thermal model of both PP and pPTFE

Equations were obtained from literature [7,8,9] for both Heat Capacity ($C_p$) and Thermal Conductivity ($K$)

Values of their optical constants obtained from spectral measurements of a previous experiment completed with data from literature [9,10,11,12].




| Polymers simulation constants | Value |
|---|---|
| PP emissivity (in band) | 0.01 |
| pPTFE emissivity (in band) | 0.01 |
| PP refraction index at 4 K (in band) | 1.5042 |
| pPTFE refraction index at 4 K (in band) | 1.2000 |
| PP density | 900 kg/m^3 |
| pPTFE density | 700 kg/m^3 |

# DATA ANALYSIS



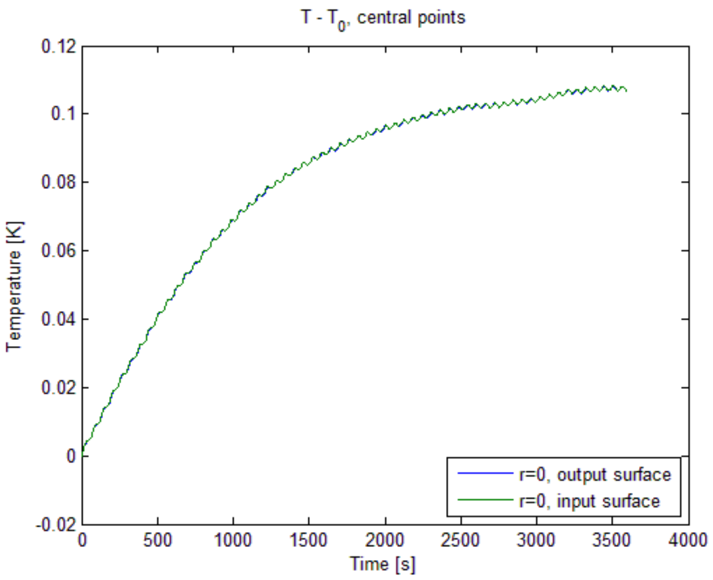
The change of temperature within time was analysed by fitting a lumped-temperature model to the data.

$$T(t) = T_\infty + (T_0 - T_\infty)e^{-t/\tau} - A\sin(\omega t + \phi)$$

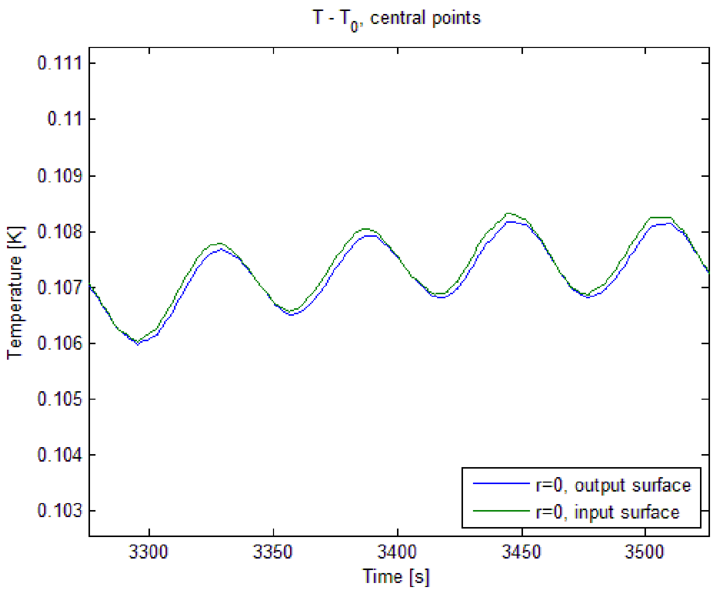
The total transmitted energy was calculated applying Planck's law in the 30% bandwidth frequency interval of the filter

$$I = A\Omega \int_{0.85\nu_0}^{1.15\nu_0} \frac{2h}{c^2} \frac{\nu^3}{e^{\frac{h\nu}{KT}} - 1}$$

**143GHz filter, $10^{-4}$W incident power**

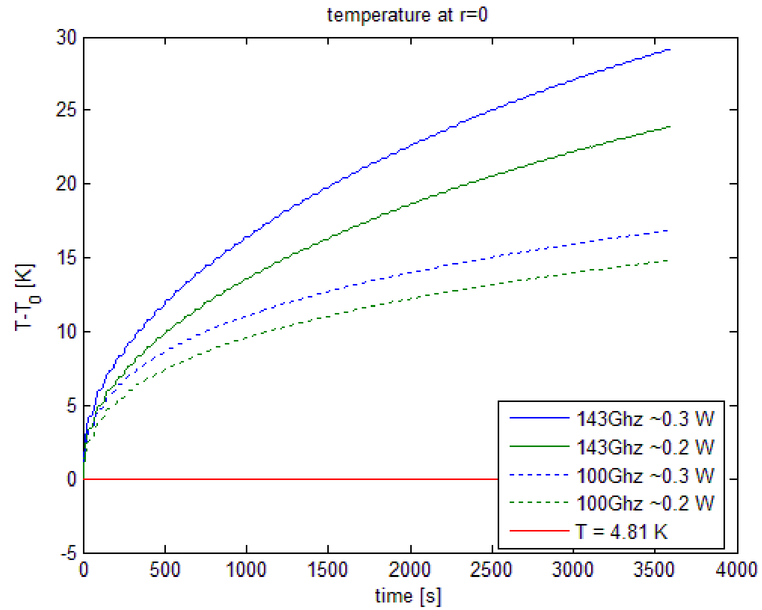


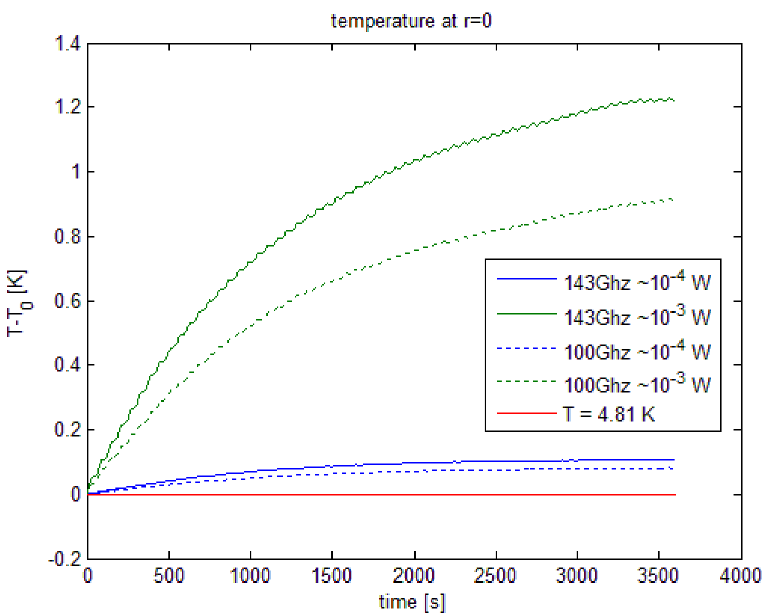

Full scale temperature increase




Small scale fluctuations

# DATA ANALYSIS




| **Incident power ~$10^{-4}$ W** | **100 GHz** | | **143 GHz** | |
|---|---|---|---|---|
| | Input surface | Output surface | Input surface | Output surface |
| $\tau$ | 1168 s | 1171 s | 1061 s | 1062 s |
| $T_\infty$ | 4.89510 K | 4.89510 K | 4.92210 K | 4.92210 K |
| $A$ | 0.00055 K | 0.00050 K | 0.00070 K | 0.00067 K |
| $\phi$ | 2.06 | 1.86 | 1.93 | 1.80 |
| $I(T_\infty)$ | 8.0 nW | 8.0 nW | 18.3 nW | 18.3 nW |

| **Incident power ~$10^{-3}$ W** | **100 GHz** | | **143 GHz** | |
|---|---|---|---|---|
| | Input surface | Output surface | Input surface | Output surface |
| $\tau$ | 1297 s | 1301 s | 1232 s | 1234 s |
| $T_\infty$ | 5.77540 K | 5.77490 K | 6.10180 K | 6.10140 K |
| $A$ | 0.00479 K | 0.00421 K | 0.00581 K | 0.00543 K |
| $\phi$ | 2.09 | 1.83 | 1.99 | 1.80 |
| $I(T_\infty)$ | 125.9 nW | 125.9 nW | 327.2 nW | 327.2 nW |

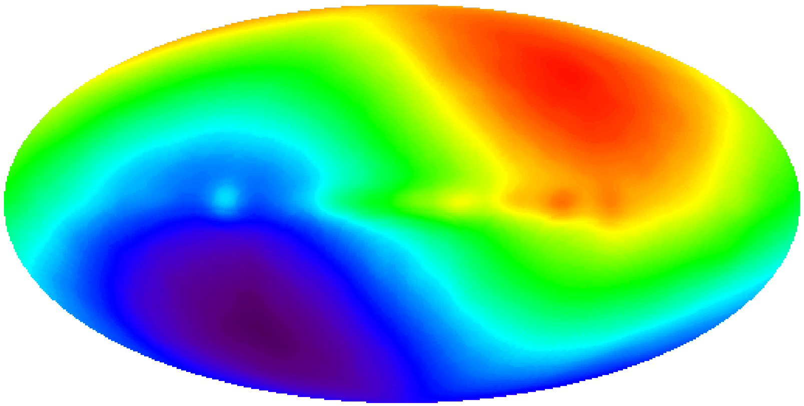
# DATA ANALYSIS



The radiation source considered presents a dipole-like fluctuation, therefore it could cause an error in the estimation of the dipole value

Used simulation results to find the equivalent CMB dipole amplitude that this effect would mimic (albeit with a different phase and orientation in the sky).

$$I(T_{\infty}) = \int_{0.85\nu_0}^{1.15\nu_0} BB(T_{meas}, \nu) - BB(T_{cmb}, \nu) d\nu$$



| Temperature differences of $T_{cmb}$ values | MIR incident power $10^{-4}$W | MIR incident power $10^{-3}$W |
|---|---|---|
| 100 GHz | 0.11 mK | 1.76 mK |
| 143 GHz | 0.11 mK | 2.02 mK |

With this numbers a high-precision dipole calibration in both amplitude and alignment would be compromised

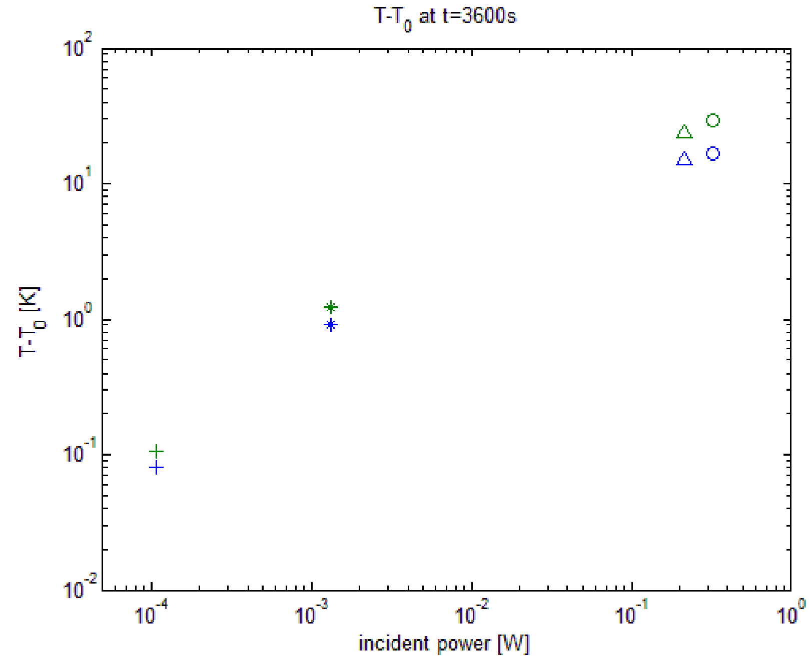
# CONCLUSIONS



- Increase in temperature directly dependent on the amount of incoming radiation was observed

- Low power cases - thermalization
  - DC component: ~0.1K ($10^{-4}$W case) and ~1.2K ($10^{-3}$W case).
  - AC component (dipole like component): between $10^{-4}$ and $10^{-3}$ K.

- High power cases ($> 0.1$ W) – small scale fluctuation without thermalization




- Similar effects already noticed during Herschel mission[13].

- With increasing the size of the optics and filters this effect would be sufficiently enhanced to affect the measurements that require a sensitivity of few Jy in the FIR-sub-mm band.

- These results highlight the need for space instruments with large focal plane arrays to employ some elements of thermal filters prior to thick polymer optical elements in the optical filter chain.

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