PYRGEOMETER CALIBRATION UNCERTAINTY

Ian Dollery

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Challenge

- An uncertainty to meet the BSRN Longwave Target:
  - 5% or 10 W.m^{-2} (1997)

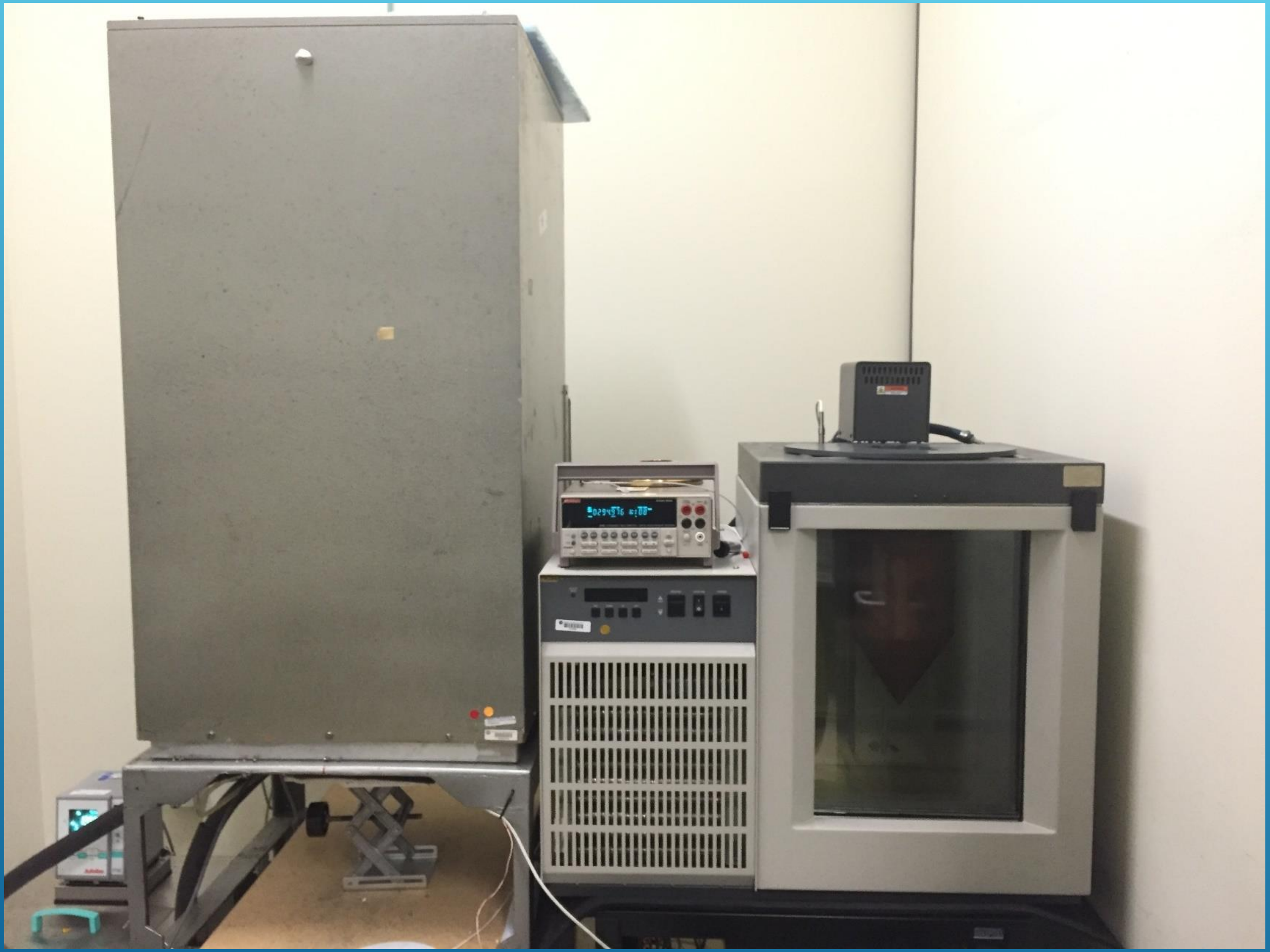
Action

- Used Guide to the Expression of Uncertainty in Measurement (GUM) methods to develop the uncertainty

Result

- Uncertainty < target
- Highlighted major contributors (focused developments)

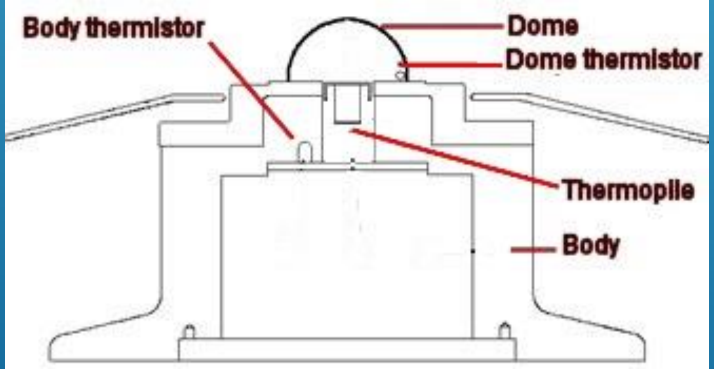
CALIBRATION METHODS



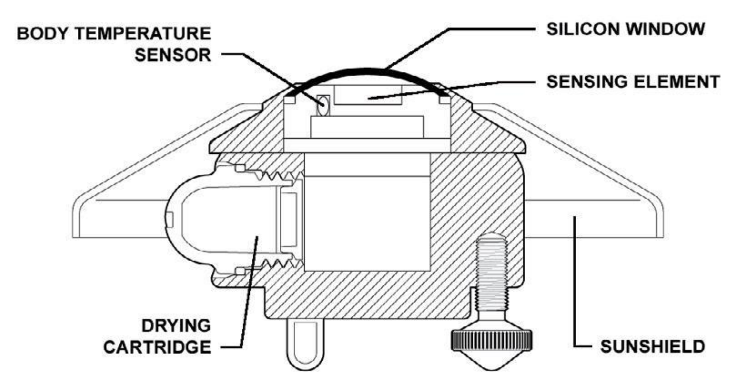
Black Body

Comparison

PYRGEOMETERS



Eppley PIR



Kipp & Zonen CGR4

UNCERTAINTY DEVELOPMENT

Adapted from the GUM (Section 8)

1. Model (measureand) $f(x_1, x_2, \ldots x_n)$
2. List inputs $x_1, x_2, \ldots X_n$
3. input uncertainties $u(X_n)$;
4. sensitivity coefficients $\frac{\delta f}{\delta X_n}$ or $\frac{\Delta f}{\Delta X_n}$
5. Convert into measurand uncertainties; $u(f(Xn)) = (\delta f / \delta X_n) * u(X_n)$
6. Combine uncertainties $u(f)^2 = \Sigma(f(Xn))^2$
7. Express as 95% uncertainty **U(f).**

MATHEMATICAL MODEL

$$C = \frac{V}{E_{L,REF} + K_S(E_D - E_B) - E_B}$$

Calibration Equation

$$E_L = \frac{V}{C} + E_B - K.(E_D - E_B)$$

$$E_D = \sigma.T_D^4$$

Field Equation

$$E_{L,REF} = \frac{V_{REF}}{C_{REF}}\left(1 + K_{1,REF}.\sigma.\frac{T_{B,REF}^4}{T_{B,REF}}\right) + K_{2,REF}.E_{B,REF} - K_{3,REF}.(E_{D,REF} - E_{B,REF})$$

PMOD Equation

ADDITIONAL INPUTS

$$E=\sigma.T^4$$

$$T = \frac{1}{\alpha+\beta.Ln(R)+\gamma.(Ln(R))^3}.$$

SENSITIVITY COEFFICIENTS

1. Unit conversion factor
2. The sensitivity of the measureand to changes in the input

Determined by either:

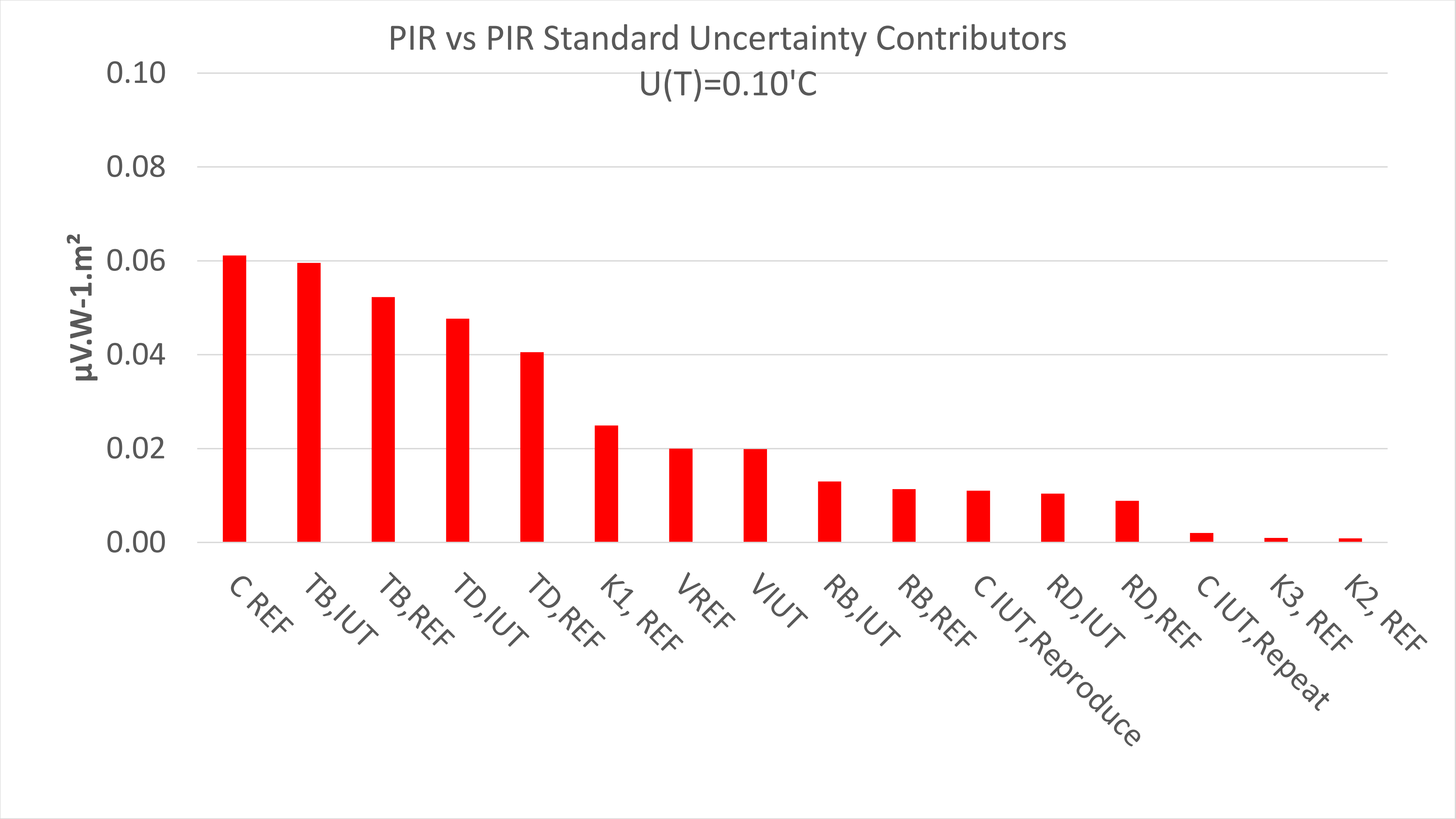
- Partial derivative of the model w.r.t. inputs; or
- Calculating the impact of small changes by inputs.

$$\frac{\delta f}{\delta X_n} \approx \frac{\Delta f}{\Delta X_n}$$

$$u(f) = \sqrt{\sum_i \left(\frac{\partial C_{IUT}}{\partial X_i} . u(X_i) \right)^2}$$

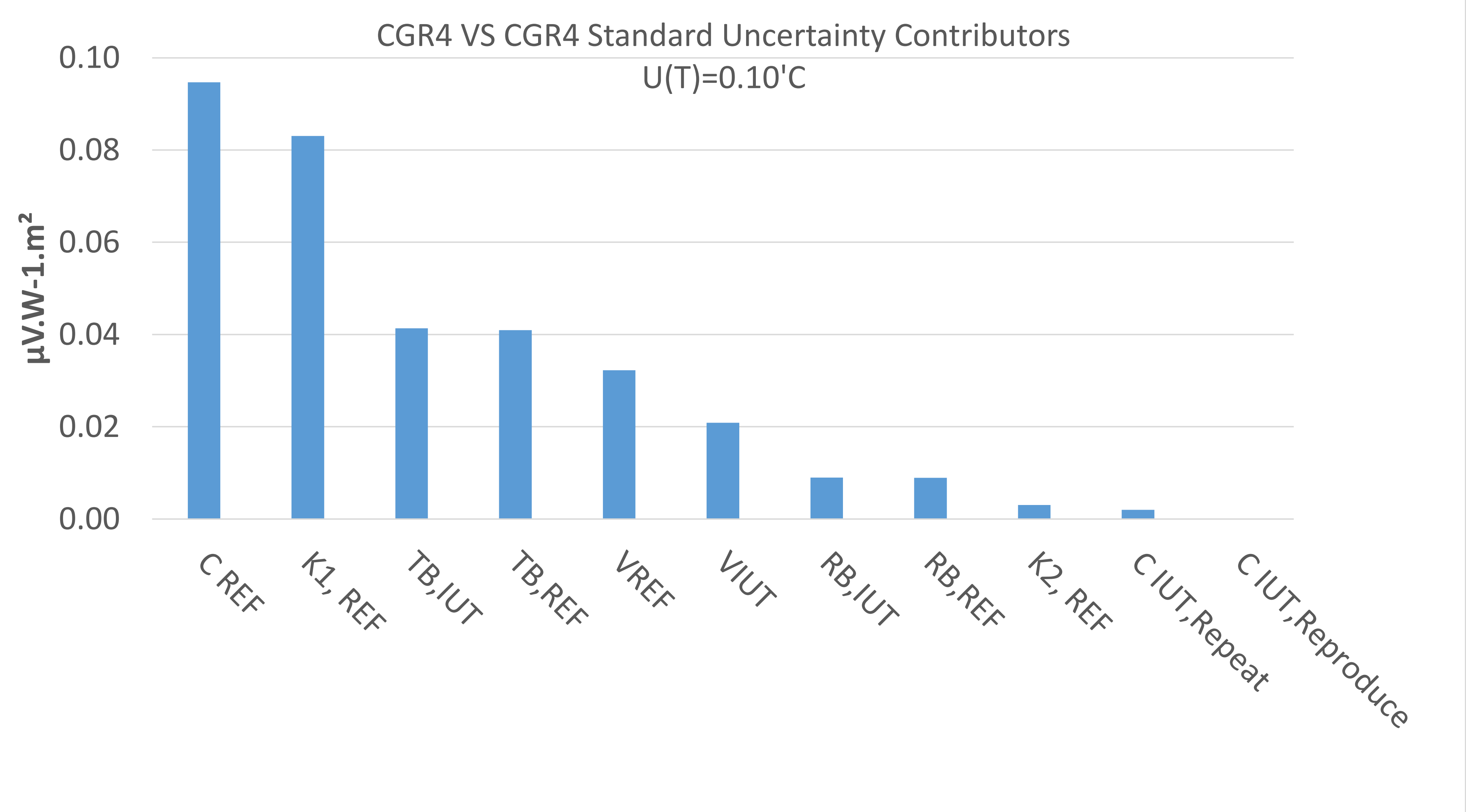
RELATIVE MAGNITUDE OF THE INPUTS

For a coefficient of 3.73 $\mu V.W^{-1}.m^2$ the uncertainty is 0.25 $\mu V.W^{-1}.m^2$ at a 95%



RELATIVE MAGNITUDE OF THE INPUTS

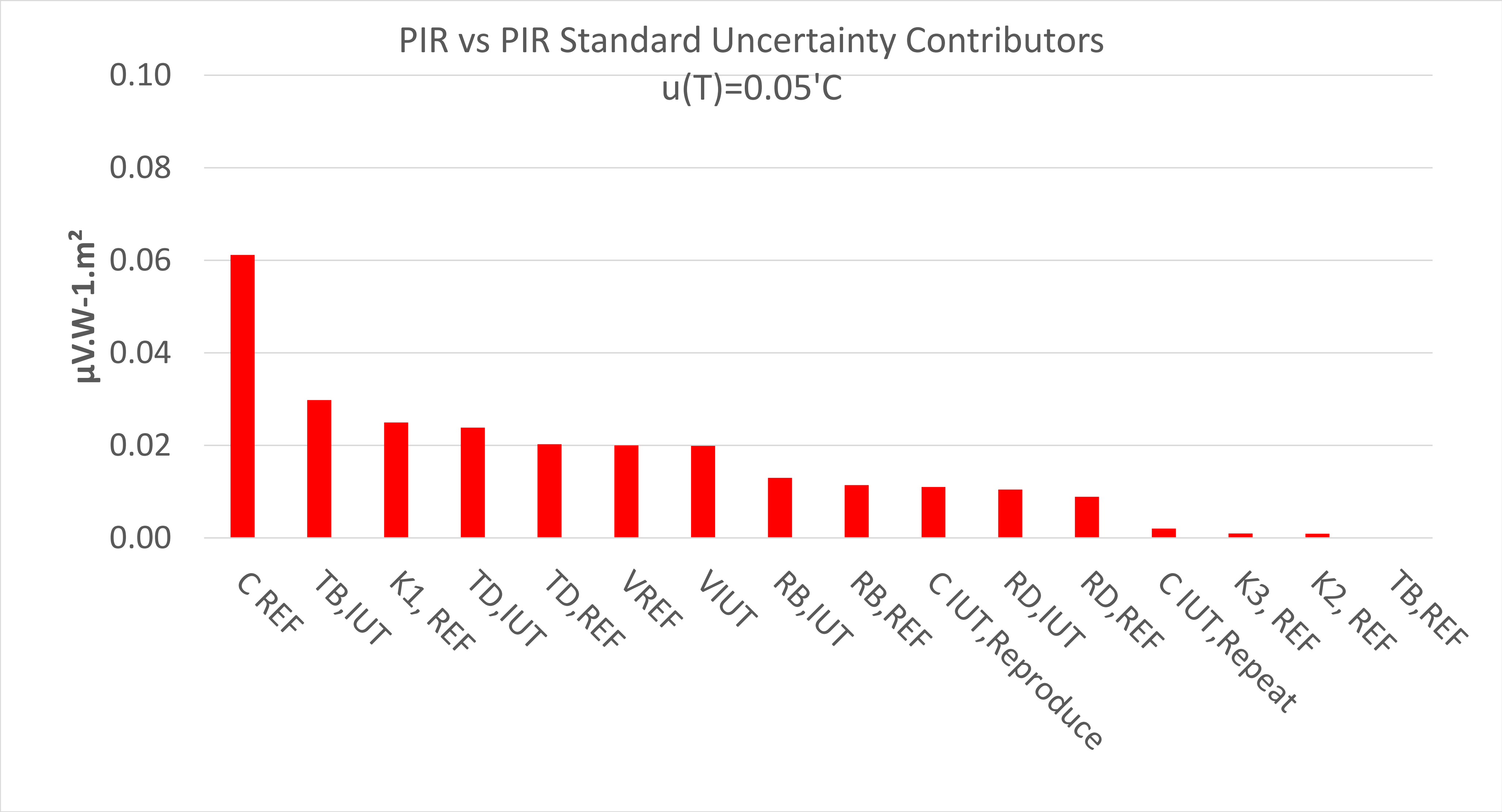
For a coefficient of 12. 3 $\mu V.W^{-1}.m^2$ the uncertainty is 0.28 $\mu V.W^{-1}.m^2$ at a 95%



RETURN ON EFFORT UNCERTAINTY IMPROVEMENTS

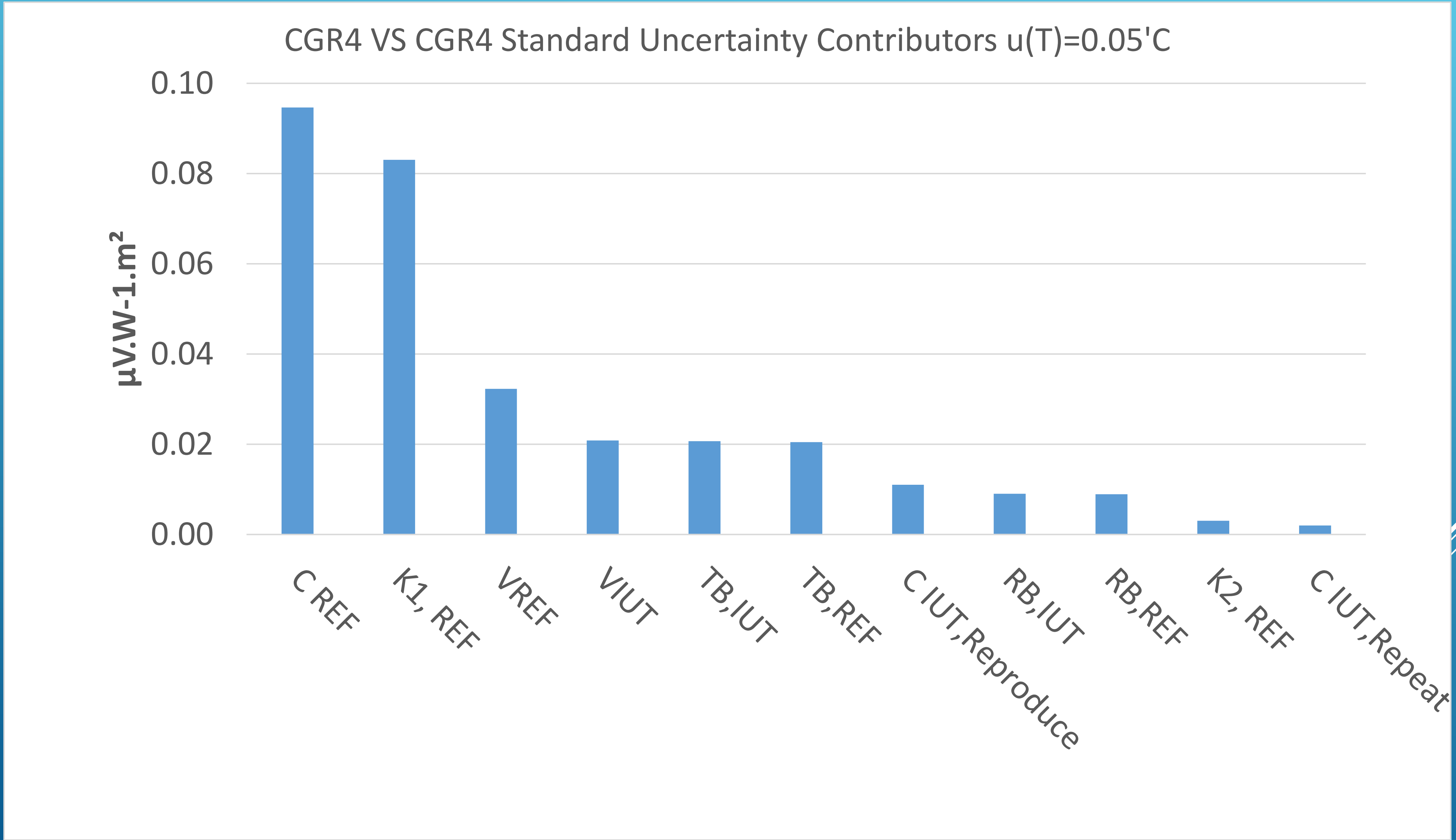
RELATIVE MAGNITUDE OF THE INPUTS

For a coefficient of 3.73 $\mu V.W^{-1}.m^2$ the uncertainty is 0.18 $\mu V.W^{-1}.m^2$ at a 95%

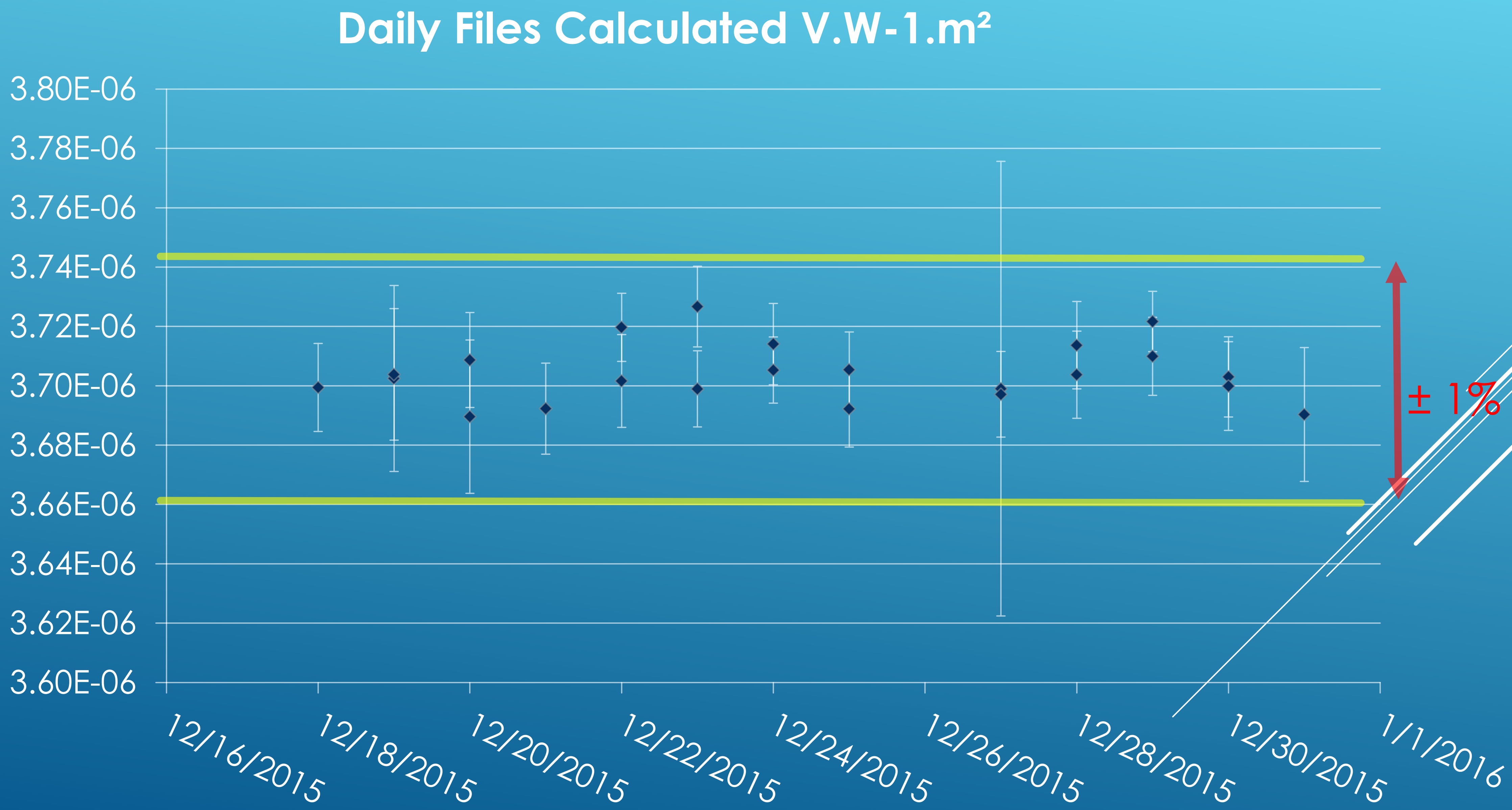


RELATIVE MAGNITUDE OF THE INPUTS

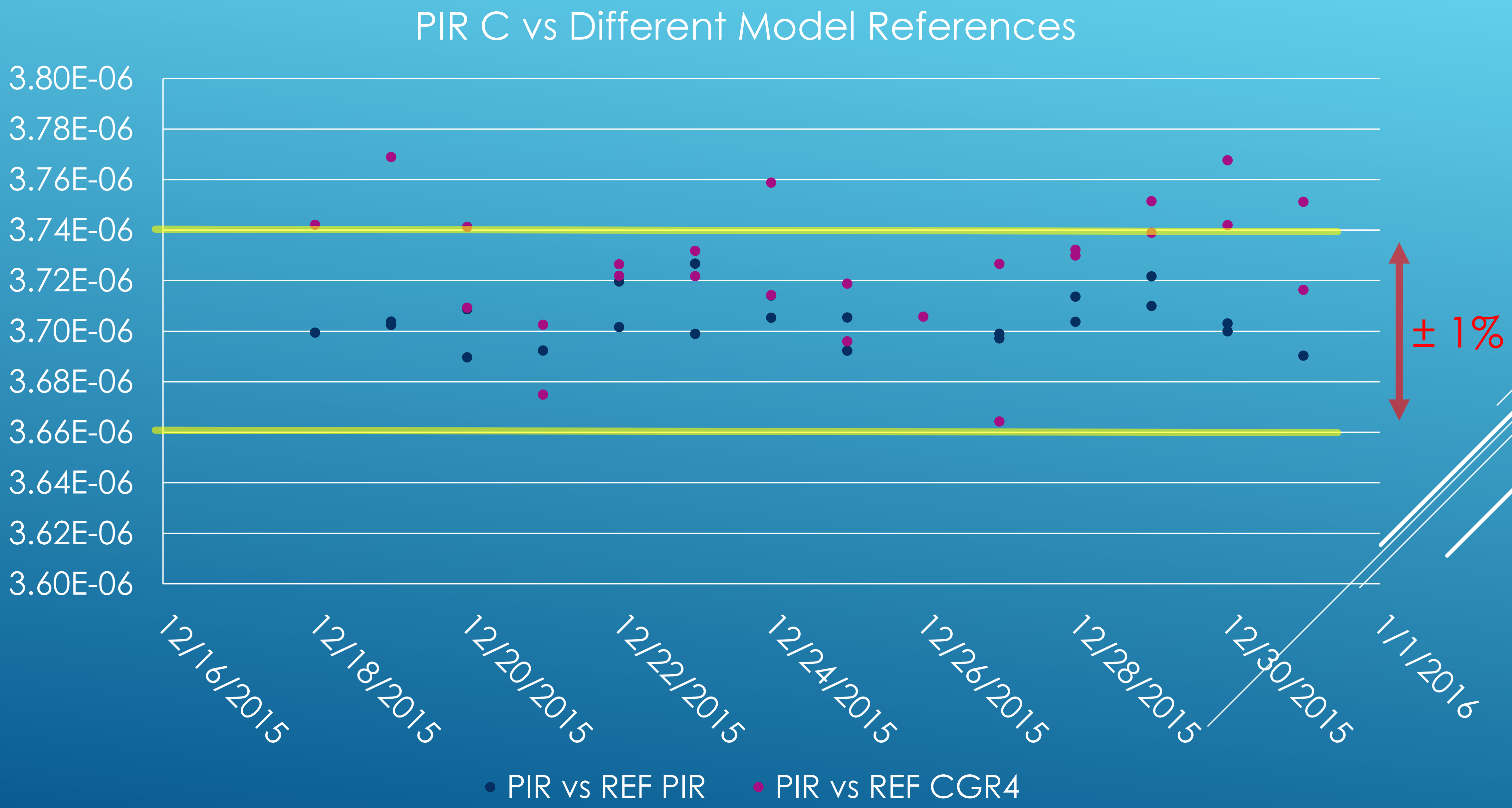
For a coefficient of 12. 3 µV.W^{-1}.m^2 the uncertainty is 0.26 µV.W^{-1}.m^2 at a 95%



TEST DATA EXAMPLE (PIR VS PIR)



TEST DATA EXAMPLE (PIR VS CGR4)



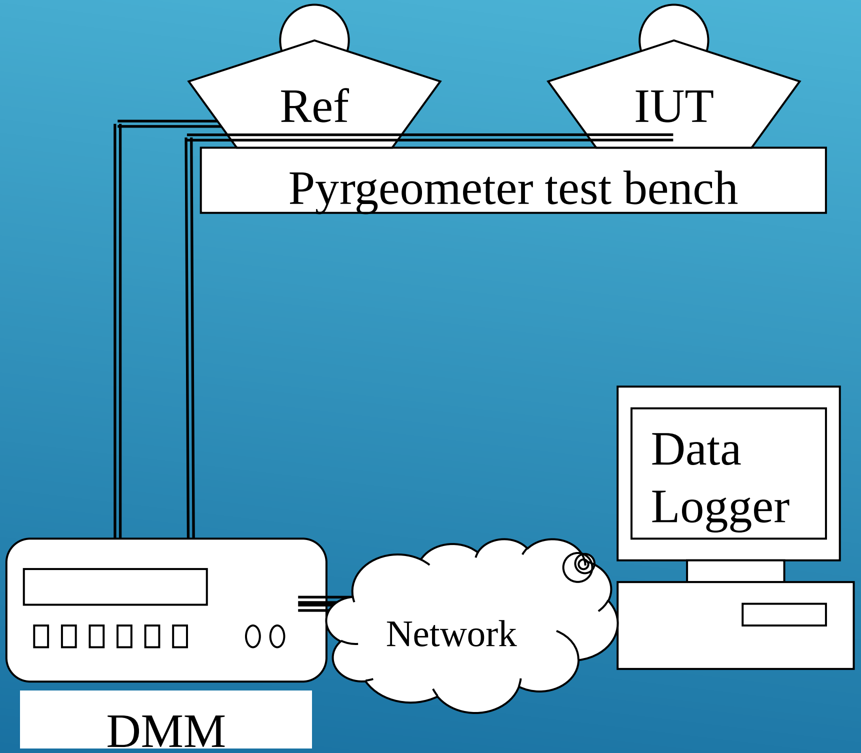
Parameter	Value	Units	Standard Uncertainty (u)	Sensitivity Coefficient (W.m^{-2})	Degrees of Freedom (Dof)	u.s (W.m^{-2})
V_{REF}	-3.34E-04	V	1.78E-06	2.68E+05	12.5	0.48
$R_{B,REF}$	1.22E+04	Ω	5.5	-5.66E-02	12.5	-0.31
$T_{B,REF}$	293.27	K	0.050	-2.29E+01	26	-1.15
$R_{D,REF}$	1.22E+04	Ω	5.5	4.55E-02	12.5	0.25
$T_{D,REF}$	293.35	K	0.050	-2.29E+01	26	-1.15
C_{REF}	3.73E-06	$V.W^{-1}.m^{-2}$	1.26E-07	2.41E+07	92.77	3.04
$K_{1,\ REF}$	0	K^{-1}				
$K_{2,\ REF}$	1	_				
$K_{3,\ REF}$	4	_				
						(W.m-^{2})
$E_{L,REF,CAL}$	328.03	W.m^{-2}	_		141.85	3.50

WHAT HAVE WE ACHIEVED?

- Measurement uncertainty less than (5% or 10 W.m^{-2})
  - 3.50 W.m-^{2} in 328.03 W.m-^{2} (~1%)
- Major contributors
  - Thermistors temperature measurement
- Uncertainty Incomplete
  - Small but insignificant difference between CGR4 and PIR

QUESTIONS

BUREAUS SKY COMPARISON TEST SYSTEM



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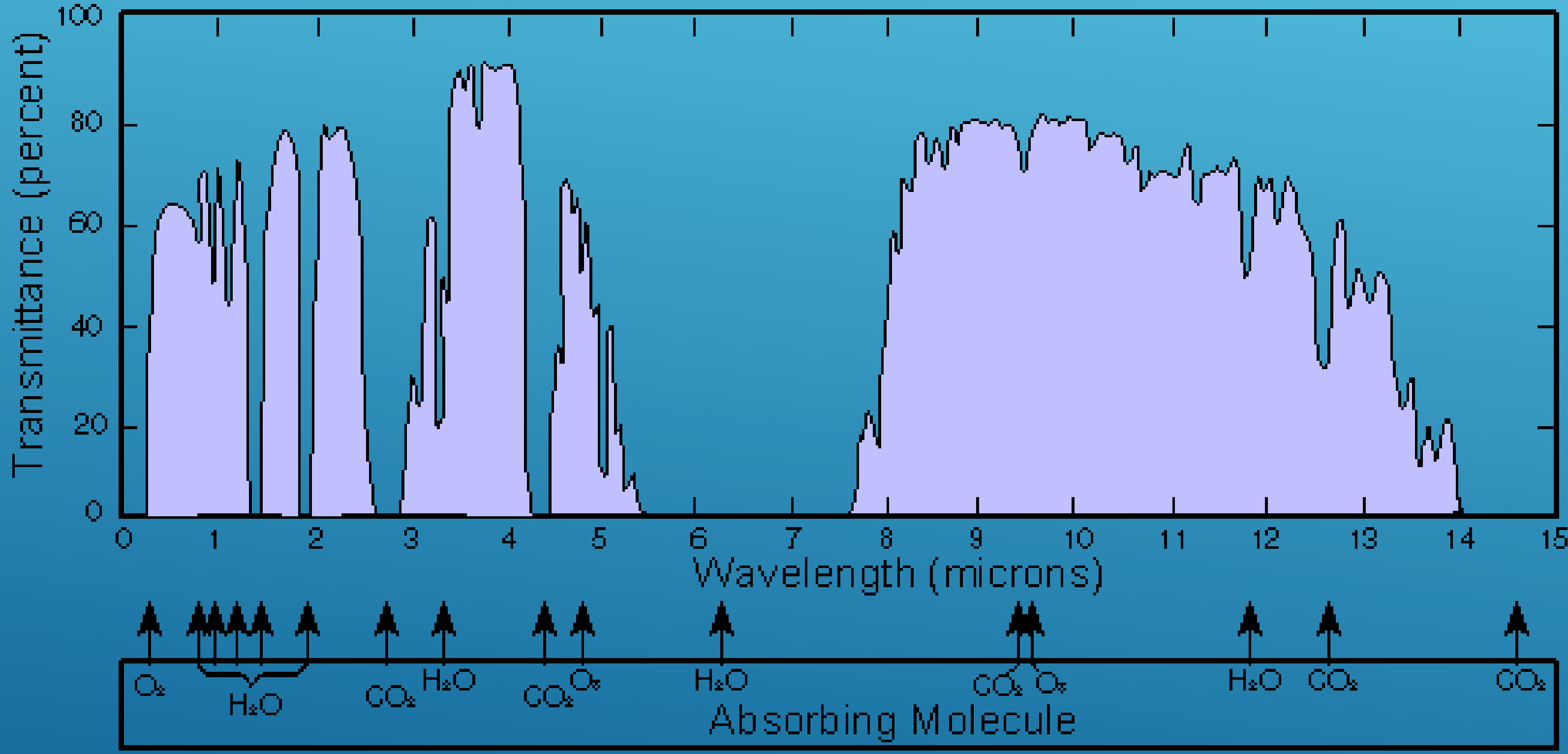
ATMOSPHERIC WINDOW



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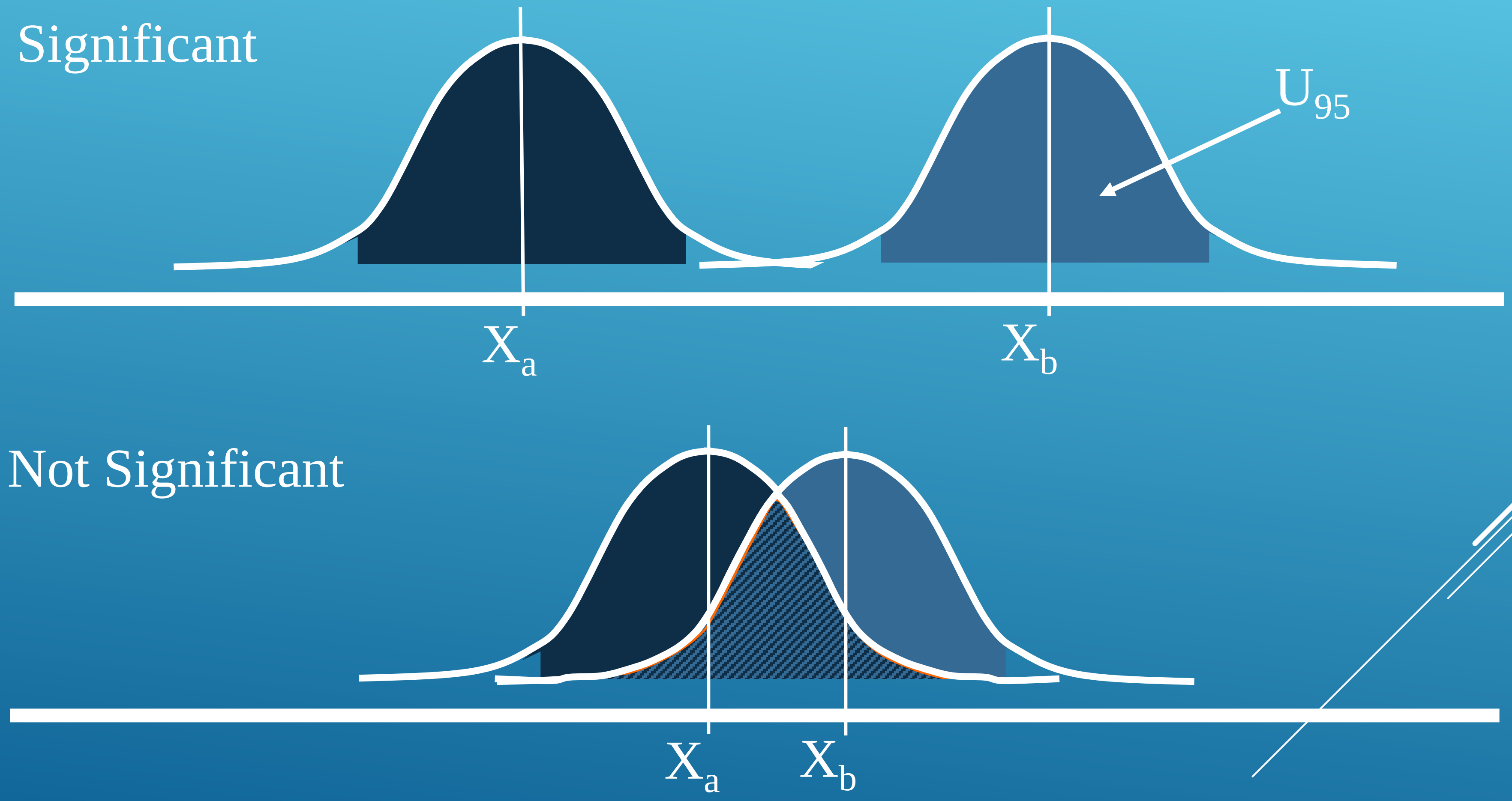
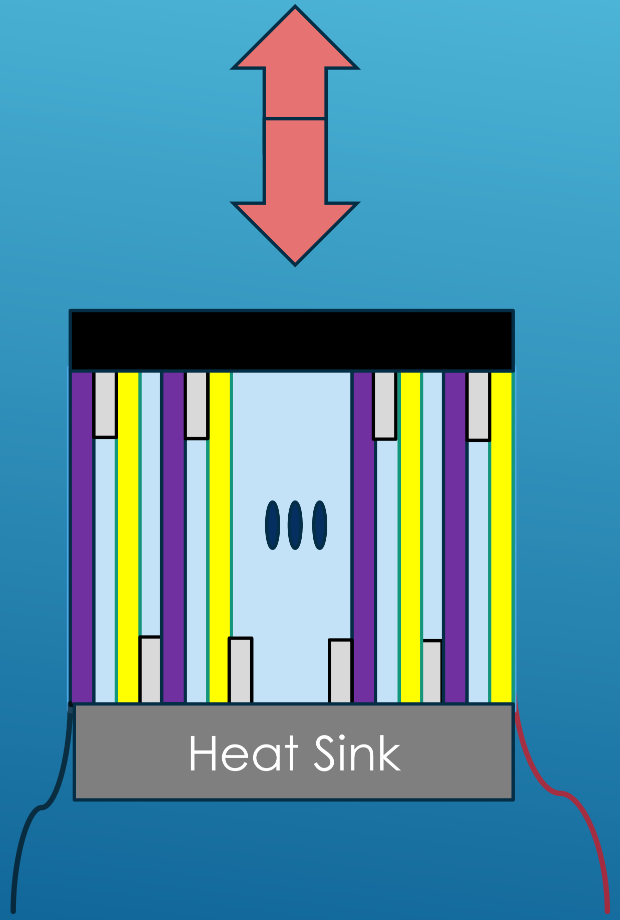
SIGNIFICANCE OF DIFFERENCES



THERMOPILE



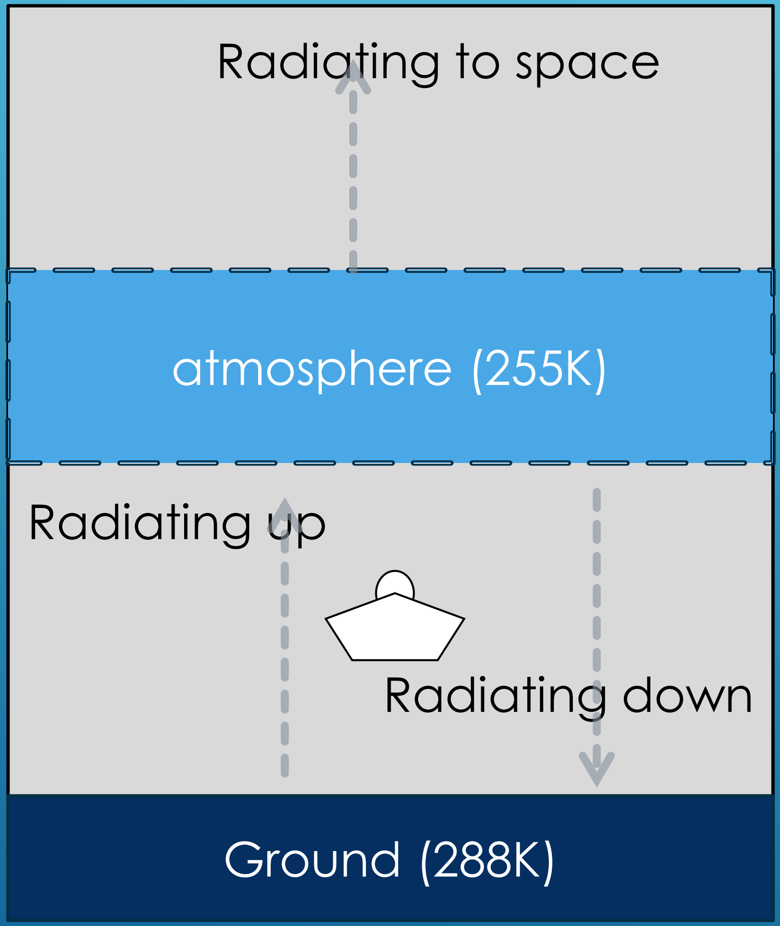
Irradiance W/m²

High Emissivity Surface T_1

Thermopile
Signal Volt = $S \times (T_1 - T_2)$

Body T_2

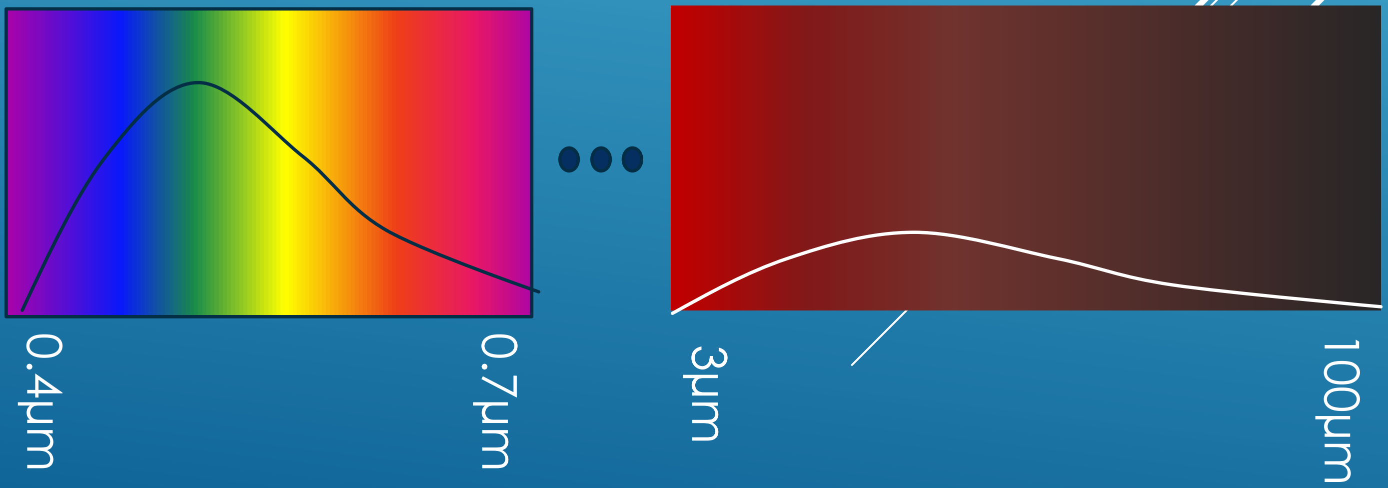
OVERVIEW LONGWAVE MEASUREMENT



Night

Source	**Effective BB Temperature**	**Wavelength maximum**
Day (in)	5780 K (5507°C)	0.5 µm
Night (in)	255K (-18°C)	11µm
Terrestrial (out)	288K (15°C)	10µm

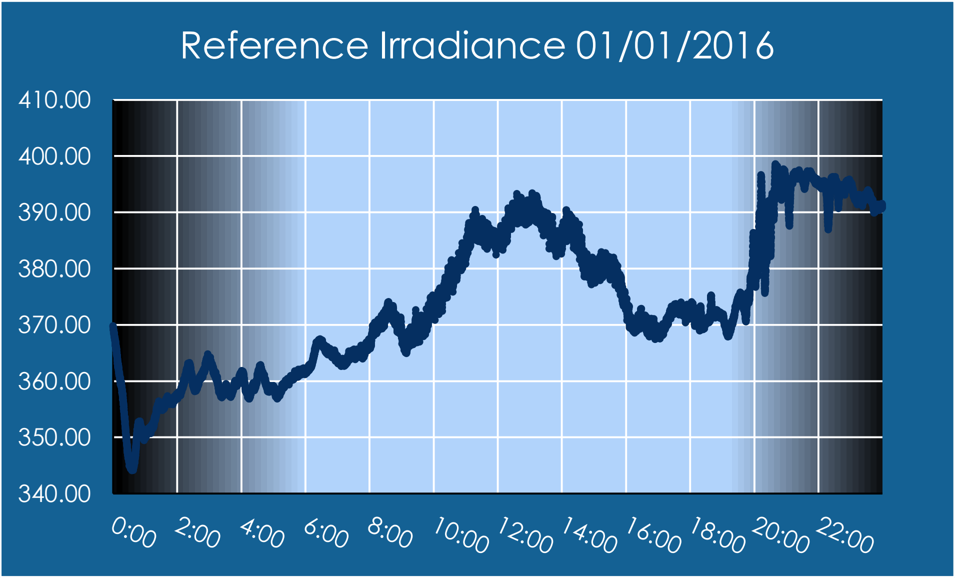
Recommended longwave uncertainty is:
5% or 10 $W.m^{-2}$ whichever is greater

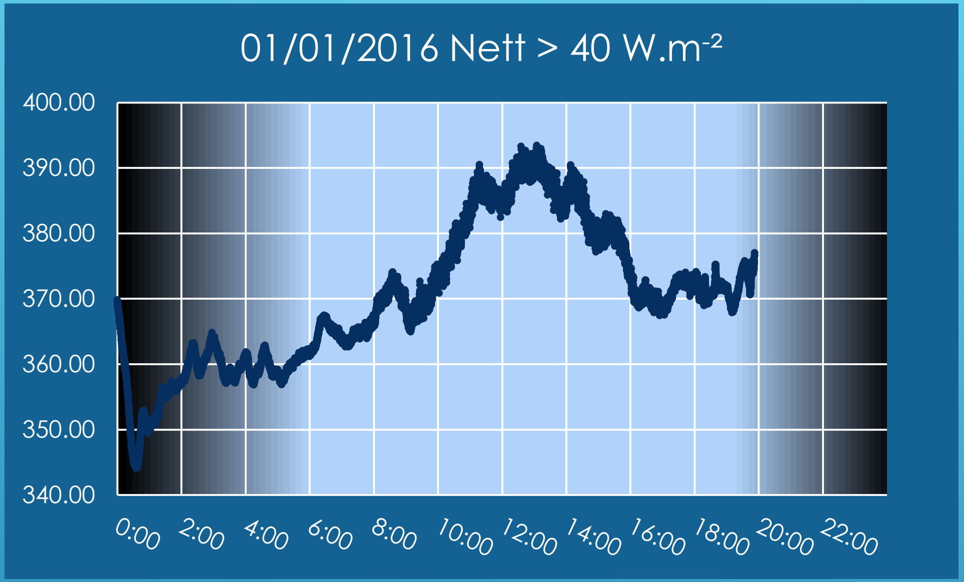


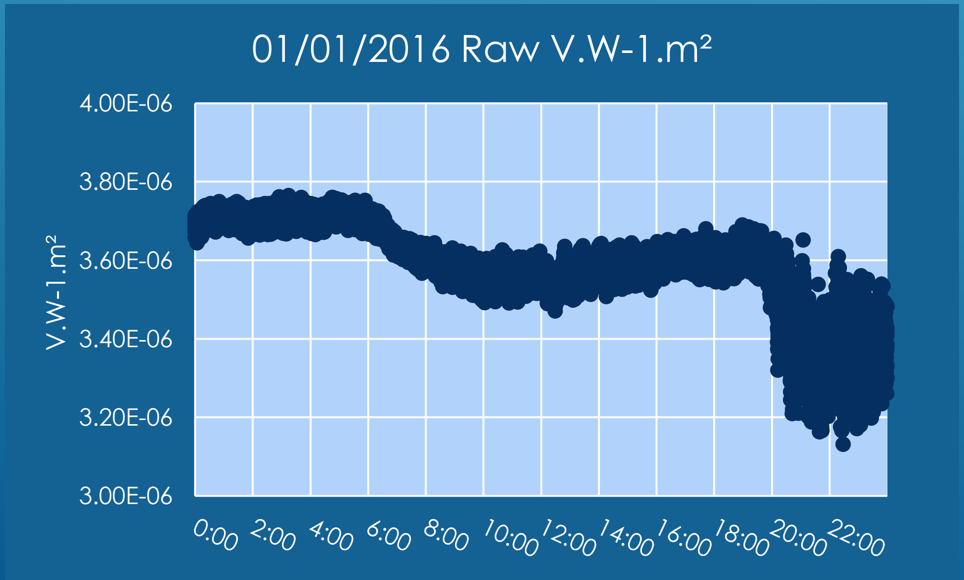
TEST METHOD

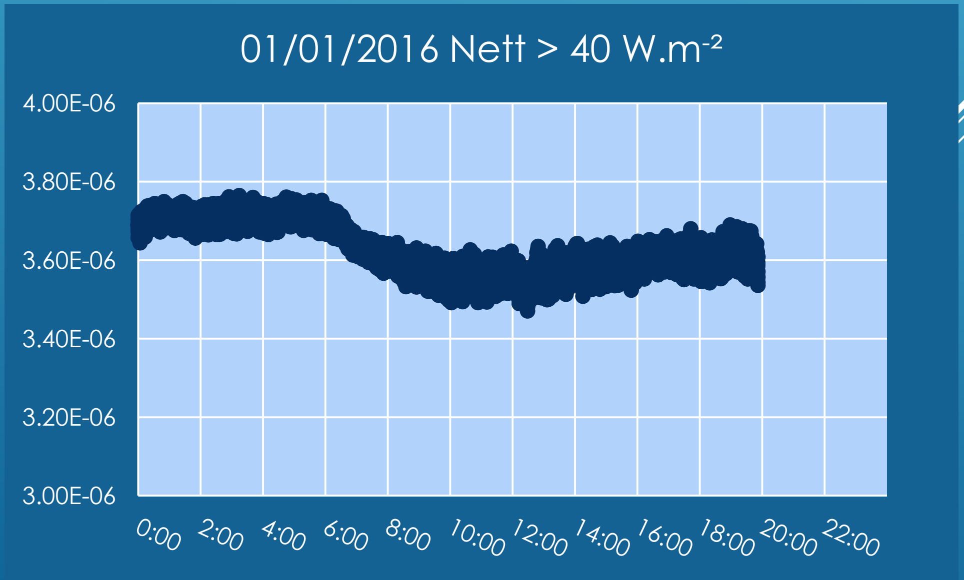
1. Mount the test and the reference pyrgeometer (same model);
2. Select data from astronomically (-18°) dark skies;
3. Calculate reference irradiance (PMOD calibration equation);
4. Filter for significant nett irradiance data (>40 $W.m^{-2}$);
5. Filter for stable irradiance data (<20 $W.m^{-2}.h^{-1}$);
6. Calculate pyrgeometer sensitivity coefficient (Field Equation);
7. Select nights (>4) with sensitivity coefficients with $\sigma < 2\%$.
8. Calculate the uncertainty;

TEST DATA EXAMPLE

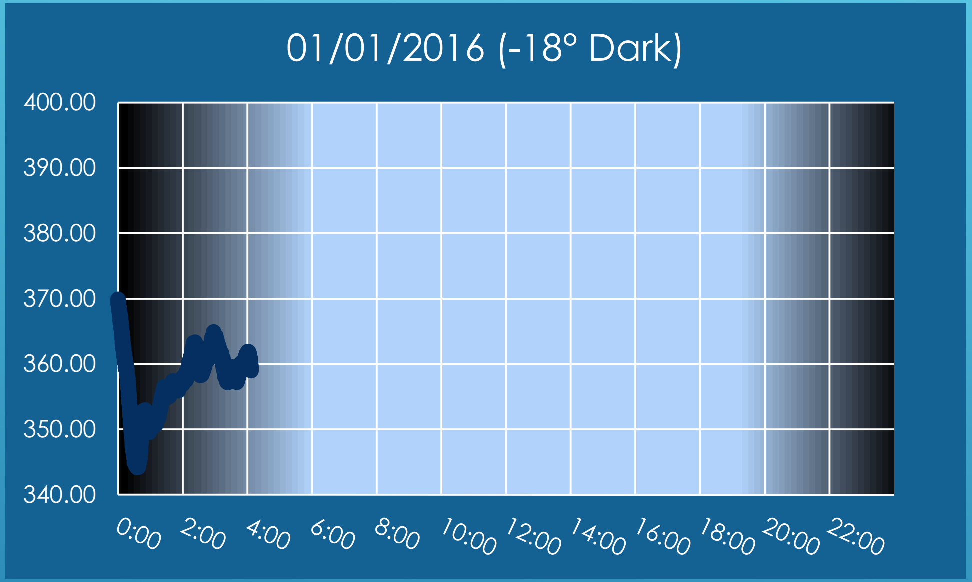

Reference Irradiance 01/01/2016

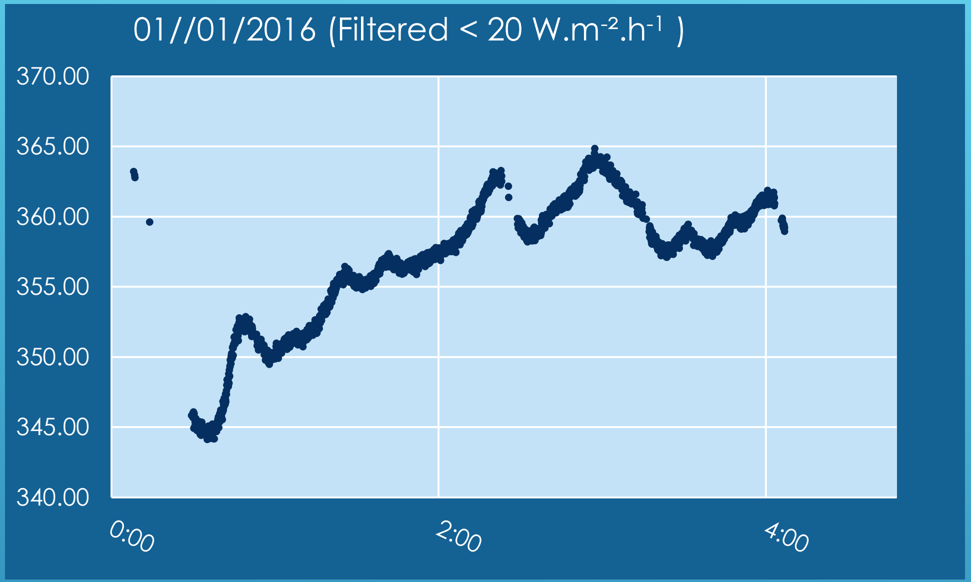

01/01/2016 Nett > 40 $W.m^{-2}$

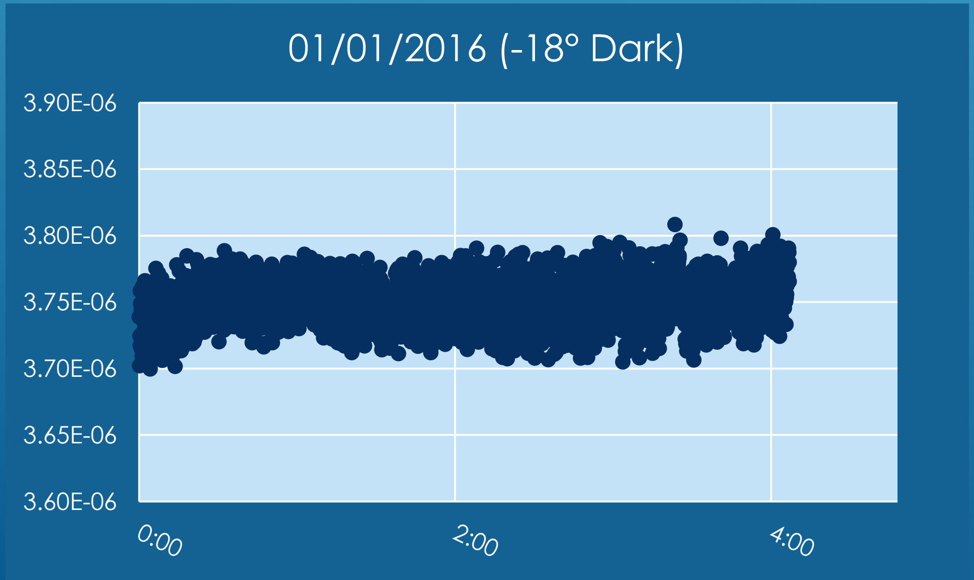

01/01/2016 Raw $V.W-1.m^2$

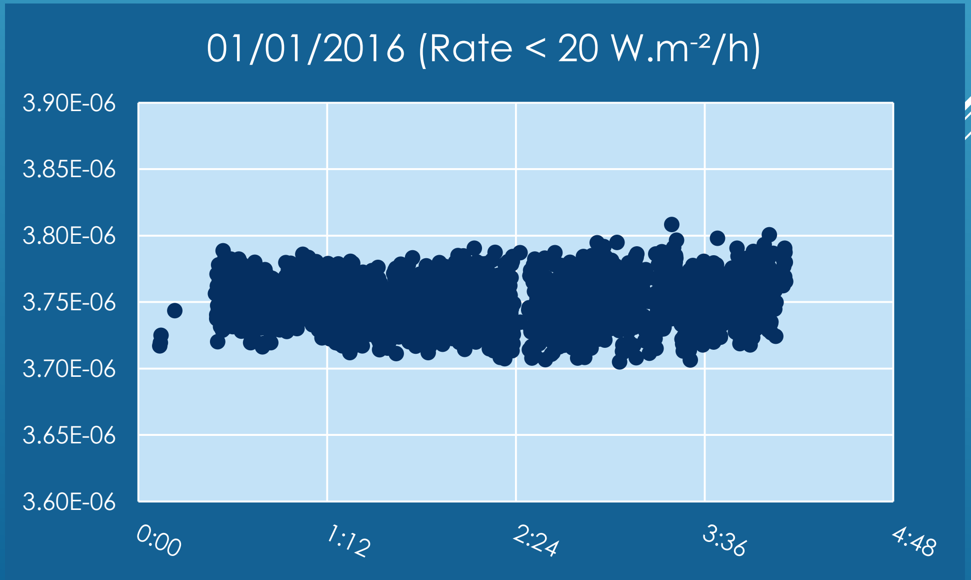

01/01/2016 Nett > 40 $W.m^{-2}$

TEST DATA EXAMPLE (PART 2)


01/01/2016 (-18° Dark)


01//01/2016 (Filtered < 20 $W.m^{-2}.h^{-1}$)


01/01/2016 (-18° Dark)


01/01/2016 (Rate < 20 $W.m^{-2}/h$)

SENSITIVITY COEFFICIENTS (REFERENCE E_L)

$$\frac{\partial E_{L,REF}}{\partial C_{REF}} = -\frac{V}{C_{REF}^2}\left(1+K_1.\sigma.T_{B,REF}^3\right)$$

$$\frac{\partial E_{L,REF}}{\partial K_{1,REF}} = \frac{V}{C_{REF}}\sigma.T_{B,REF}^3$$

$$\frac{\partial E_{L,REF}}{\partial K_{2,REF}} = -\sigma.T_{B,REF}^4$$

$$\frac{\partial E_{L,REF}}{\partial K_{3,REF}} = \sigma.(T_{B,REF}^4 - T_{D,REF}^4)$$

$$\frac{\partial E_{L,REF}}{\partial V_{REF}} = \frac{(1+K_{1,REF}.\sigma.T_{B,REF}^3)}{C_{REF}}$$

$$\frac{\partial E_{L,REF}}{\partial T_{D,REF}} = -4.K_{3,REF}.\sigma.T_{D,REF}^3$$

$$\frac{\partial E_{L,REF}}{\partial T_{B,REF}} = 3.\frac{V_{REF}}{C_{REF}}.K_{1,REF}.\sigma.T_{B,REF}^2 + 4.\sigma.T_{B,REF}^3.\left(K_{2,REF} + K_{3,REF}\right)$$

$$\frac{\partial E_{L,REF}}{\partial R_{B,REF}} = \frac{\partial E_{L,REF}}{\partial T_{B,REF}} \cdot \frac{\partial T_{B,REF}}{\partial R_{B,REF}}$$

$$\frac{\partial T_{B,REF}}{\partial R_{B,REF}} = \frac{-\beta - 3.\gamma.Ln(R_{B,REF})^2}{R_{B,REF}.\left(\alpha + \beta.Ln(R_{B,REF}) + \gamma.Ln(R_{B,REF})^3\right)^2}$$

$$\frac{\partial E_{L,REF}}{\partial R_{D,REF}} = \frac{\partial E_{L,REF}}{\partial T_{D,REF}} \cdot \frac{\partial T_{D,REF}}{R_{D,REF}}$$

$$\frac{\partial T_{D,REF}}{\partial R_{D,REF}} = \frac{-\beta - 3.\gamma.Ln(R_{D,REF})^2}{R_{D,REF}.\left(\alpha + \beta.Ln(R_{D,REF}) + \gamma.Ln(R_{D,REF})^3\right)^2}$$

REFERENCE IRRADIANCE UNCERTAINTY

$$
\begin{aligned}
u(E_{L,REF})^2 = {} & \left(\frac{\partial E_{L,REF}}{\partial C_{REF}}.u(C_{REF})\right)^2 + \left(\frac{\partial E_{L,REF}}{\partial K_{1,REF}}.u(K_{1,REF})\right)^2 \\
& + \left(\frac{\partial E_{L,REF}}{\partial K_{2,REF}}.u(K_{2,REF})\right)^2 + \left(\frac{\partial E_{L,REF}}{\partial K_{3,REF}}.u(K_{3,REF})\right)^2 \\
& + \left(\frac{\partial E_{L,REF}}{\partial V_{REF}}.u(V_{REF})\right)^2 + \left(\frac{\partial E_{L,REF}}{\partial T_{B,REF}}.u(T_{B,REF})\right)^2 + \left(\frac{\partial E_{L,REF}}{\partial R_{B,REF}}.u(R_{B,REF})\right)^2 \\
& + \left(\frac{\partial E_{L,REF}}{\partial T_{D,REF}}.u(T_{D,REF})\right)^2 + \left(\frac{\partial E_{L,REF}}{\partial R_{D,REF}}.u(R_{D,REF})\right)^2
\end{aligned}
$$

SENSITIVITY COEFFICIENTS (IUT)

$$\frac{\partial C_{IUT}}{\partial E_{L,REF}} = \frac{-V}{E_{nett}^2}$$

$$E_{nett} = E_{L,REF} + K_s.\sigma.(T_{D,IUT}^4 - T_{B,IUT}^4) - \sigma.T_{B,IUT}^4$$

$$\frac{\partial C_{IUT}}{\partial V_{IUT}} = \frac{1}{E_{nett}}$$

$$\frac{\partial C_{IUT}}{\partial R_{B,IUT}} = \frac{\partial C_{IUT}}{\partial T_{B,IUT}} \cdot \frac{\partial T_{B,IUT}}{\partial R_{B,IUT}}$$

$$\frac{\partial C_{IUT}}{\partial T_{B,IUT}} = \frac{V.4.\sigma.T_{B,IUT}^3 (K_s + 1)}{E_{nett}^2}$$

$$\frac{\partial T_{B,IUT}}{\partial R_{B,IUT}} = \frac{-\beta - 3.\gamma.Ln(R_{B,IUT})^2}{R_{B,IUT}.\left(\alpha + \beta.Ln(R_{B,IUT}) + \gamma.Ln(R_{B,IUT})^3\right)^2}$$

$$\frac{\partial C_{UIT}}{\partial T_{B,IUT}} = \frac{V_{IUT}.4.\sigma.T_{B,IUT}^3.\left(1 + K_{s,IUT}\right)}{E_{nett}^2}$$

$$\frac{\partial C_{IUT}}{\partial R_{D,IUT}} = \frac{\partial C_{IUT}}{\partial T_{D,IUT}} \cdot \frac{\partial T_{D,IUT}}{\partial R_{D,IUT}}$$

$$\frac{\partial C_{IUT}}{\partial T_{D,IUT}} = \frac{V_{IUT}.K_{s,IUT}.4.\sigma.T_{D,IUT}^3}{E_{nett}^2}$$

$$\frac{\partial T_{D,IUT}}{\partial R_{D,IUT}} = \frac{-\beta - 3.\gamma.Ln(R_{D,IUT})^2}{R_{D,IUT}.\left(\alpha + \beta.Ln(R_{D,IUT}) + \gamma.Ln(R_{D,IUT})^3\right)^2}$$

$$\frac{\partial C_{IUT}}{\partial T_{D,IUT}} = \frac{V_{IUT}.K_{s,IUT}\, 4.\sigma.T_{D,IUT}^3}{E_{nett}^2}$$

$$\frac{\partial C_{IUT}}{\partial C_{IUT}} = 1$$

$$\frac{\partial C_{IUT}}{\partial C_{IUT}} = 1$$

STEP 4. ATTRIBUTING STANDARD UNCERTAINTIES

- The two major evaluation categories are:
  - Type A - by statistical methods
  - Type B - by other means:

Purpose: to quantify a standard uncertainty

EXAMPLE: U(R_B) UNCERTAINTY IN DMM MEASUREMENT OF BASE THERMISTOR RESISTANCE

YSI 44031 (-10°C to +55 °C) 50 kΩ to 5 kΩ

Type A: laboratory testing over a year

- Measure standard resistors with DMM in likely ambient conditions (climate chamber)
- From scatter of residuals determine
  - Standard uncertainty (SD) and DOF

EXAMPLE: U(R_B) UNCERTAINTY IN DMM MEASUREMENT OF BASE THERMISTOR

- YSI 44031 (-10°C to +55 °C) 50 kΩ to 5 kΩ

- Type B: Manufacture Specifications
  - The DMM specification
    - 100 ppm of reading + 10 ppm of range (95%)

      (over a 1 year calibration interval)
  - Expanded U=11Ω for the range 50 kΩ to 5 kΩ (95%)
  - Std u = 5.5 Ω

    (assuming cf 2.0 for a normal distribution)

INPUTS UNCERTAINTIES

u(EL,REF)	Reference Irradiance, (C, K1, K2, K3 and PMOD Equation).
u(VREF)	Ref thermopile voltage by the DMM.
u(TB,REF)	Ref base temperature (manufacturing tolerance).
u(TD,REF)	Ref dome temperature (manufacturing tolerance).
u(RB,REF)	Ref base temperature (DMM resistance measurement).
u(RD,REF)	Ref dome temperature (DMM resistance measurement).
u(VIUT)	IUT thermopile voltage by the DMM.
u(TB,IUT)	IUT base temperature (manufacturing tolerance).
u(TD,IUT)	IUT dome temperature (manufacturing tolerances).
u(RB,IUT)	IUT base temperature (DMM resistance measurement).
u(RD,IUT)	IUT dome temperature (DMM resistance measurement)
u(CRepeat, IUT)	Maximum ESDOM in C from a single night.
u(CRepro, IUT)	ESDOM for combined nightly average.

STEP 2. INPUTS

Reference

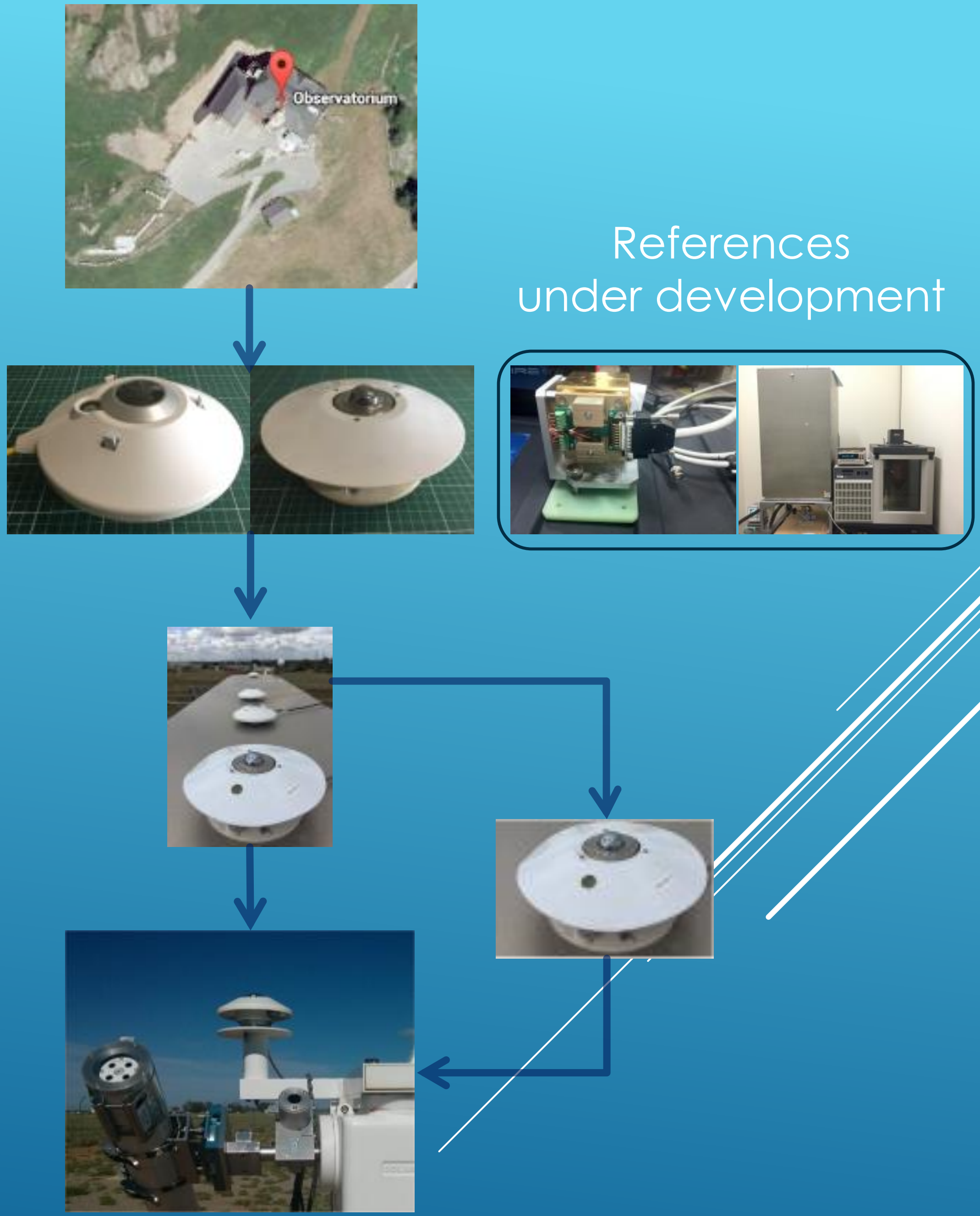
1. Reference Irradiance EL_{ref}
2. Reference calibration Coefficients (C_{ref}, $K1_{ref}$, $K2_{ref}$, $K3_{ref}$)
3. Temperatures base and dome (Tb_{ref}, Td_{ref})
4. Performance of the temperature sensors
5. Measurement of the sensors resistance
6. Measurement of differential sky to earth (V_{ref})

Instrument under test

1. Temperatures base and dome (Tb_{IUT}, Td_{IUT})
2. Performance of the temperature sensors
3. Measurement of the sensors resistance
4. Measurement of differential sky to earth (V_{IUT})
5. Stability of the comparison sky
6. Reproducibility of the comparison

TRACEABILITY

- PMOD to
  - Bureau reference PIR and CGR4
- Bureau reference to
  - Transfer Standards and
  - new network instruments
- Transfer Standards to
  - Network instruments



References
under development