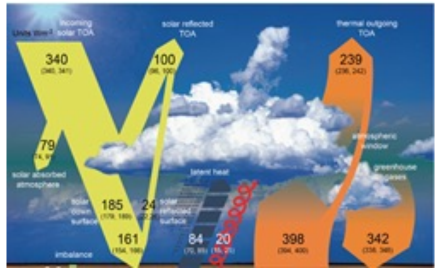
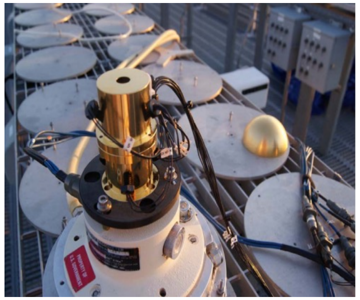
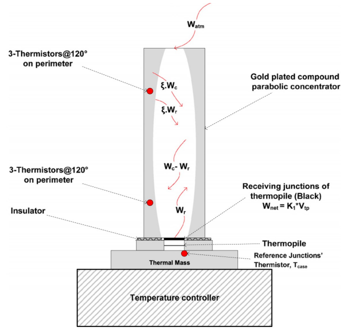


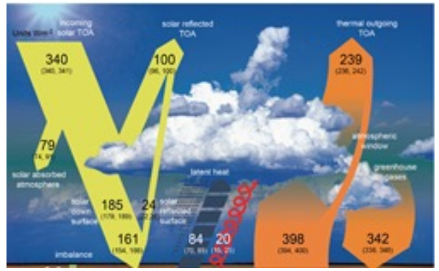
A new equation for ACPs

Bruce Forgan (Australia)
Julian Groebner (PMOD)
Ibrahim Reda (NREL)

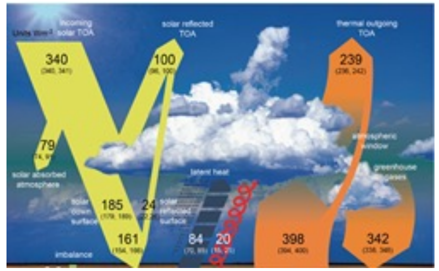
IPC/IPgC/FRV Seminar Series 13 Oct 2021







- Reda et. al. (2012) introduced the Active Cavity Pyrgeometer including an absolute calibration methodology based on linear least squares regression
- ACPs attended IPgC II (2015)
- Special Session of CIMO TT Rad Ref on IR in November 2017 (Teddington, UK) recommended
  - *Examine alternate ACP equations* and alternate temperature monitoring within the body
  - Examine any change of gold emissivity in the concentrator vs temperature and wavelength
  - Encourage other agencies to acquire and use an ACP
  - Develop finite element model of the ACP
  - Ask NREL to develop a report on the early work of the ACP gold cavity emissivity
  - *Examine the temperature field in the body of a PIR during the transient cooling process*
- ACP96 loaned to PMOD in 2019
- 2020 *New equation developed that satisfies Kirchhoff's Law and adds convection*



Derivation of new ACP equation (1) *In a vacuum*

Cavity impact on Incoming Irradiance *W*

$W = W(\tau+\beta+\alpha)$

τW = transmitted

βW = reflected

αW = absorbed

Cavity

ε_c = emissivity

α_c = absorption = ε_c

W_c = BB irradiance

Thermopile

ε_r = emissivity

ρ = reflection = $(1-\varepsilon_r)$

S = Seebeck

K_1 = sensitivity $Wm^{-2}/\mu V$

C = responsivity $\mu V/(Wm^{-2})$

= $1/K_1$

W_r = BB irradiance

$$KV = F\downarrow - F\uparrow$$

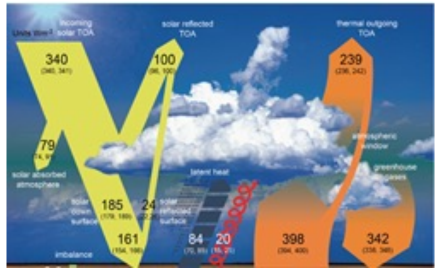
$$F\downarrow = \tau W + \varepsilon_c W_c + \beta F\uparrow$$

$$F\uparrow = W_r\varepsilon_r + \rho F\downarrow = W_r\varepsilon_r + (1-\varepsilon_r)F\downarrow$$

$$KV = F\downarrow - F\uparrow = \frac{\varepsilon_r(\tau W + \varepsilon_c W_c - (1-\beta)W_r)}{1-\beta(1-\varepsilon_r)}$$

$$W = \frac{(1-\beta(1-\varepsilon_r))K}{\varepsilon_r\tau}V + \frac{(1-\beta)}{\tau}W_r - \frac{\varepsilon_c}{\tau}W_c$$

$$T_r(t) = T_b(t) + V(t)S \qquad S = \frac{1}{S_o n\varpi} \qquad K_1 = \frac{(1-\beta(1-\varepsilon_r))}{\varepsilon_r}K = \frac{1}{C}$$



Derivation of new ACP equation (2) *In Air*

Cavity impact on Incoming Irradiance W_{atm}

$W_{atm} = W_{atm}(\tau+\beta+\alpha)$

τW_{atm} = transmitted

βW_{atm} = reflected

αW_{atm} = absorbed

Cavity

ε_c = emissivity

α_c = absorption = ε_c

W_c = BB irradiance

Thermopile

ε_r = emissivity

ρ = reflection = (1-ε_r)

S = Seebeck

K_1 = sensitivity $Wm^{-2}/\mu V$

C = responsivity $\mu V/(Wm^{-2})$

= $1/K_1$

W_r = BB irradiance

Cavity Convection

γ = convection coeff. Wm^{-2}/K

$$F_{conv} = \gamma(T_{air} - T_r)$$

$$F\downarrow = \tau W_{atm} + \varepsilon_c W_c + \beta F\uparrow + \gamma(T_{air} - T_r)$$

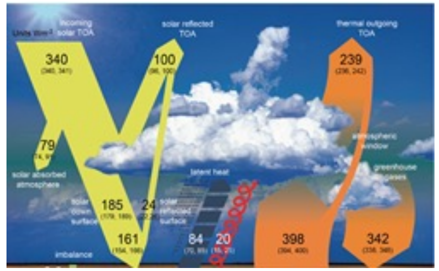
$$F\uparrow = W_r\varepsilon_r + \rho F\downarrow = W_r\varepsilon_r + (1-\varepsilon_r)F\downarrow$$

$$\tau W_{atm} = \frac{(1-\beta(1-\varepsilon_r))K}{\varepsilon_r}V + (1-\beta)W_r - \varepsilon_c W_c + \gamma(T_r - T_{air})$$

$$W_{atm} = \frac{K_1}{\tau}V + \frac{(1-\beta)}{\tau}W_r - \frac{\varepsilon_c}{\tau}W_c + \frac{\gamma}{\tau}(T_r - T_{air}) = \frac{K_1}{\tau}V + \frac{W_{net}}{\tau}$$

$$K_1 = \frac{(1-\beta(1-\varepsilon_r)}{\varepsilon_r}K = \frac{1}{C}$$

Reda et. al. (2012) vs New ACP equation *In Air*



Cavity impact on Incoming Irradiance W_{atm}

$W_{atm} = W_{atm}(\tau+\beta+\alpha)$

τW_{atm} = transmitted

βW_{atm} = reflected

αW_{atm} = absorbed

Cavity

ε_c = emissivity

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Thermopile

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S = Seebeck

K_1 = sensitivity $Wm^{-2}/\mu V$

C = responsivity $\mu V/(Wm^{-2})$

= $1/K_1$

W_r = BB irradiance

Cavity Convection

γ = convection coeff. Wm^{-2}/K

New equation

$$W_{atm} = \frac{K_1}{\tau}V + \frac{(1-\beta)}{\tau}W_r - \frac{\varepsilon_c}{\tau}W_c + \frac{\gamma}{\tau}(T_r - T_{air}) = \frac{K_1}{\tau}V + \frac{W_{net}}{\tau}$$

Reda et. al. (2012) equation (expanded)

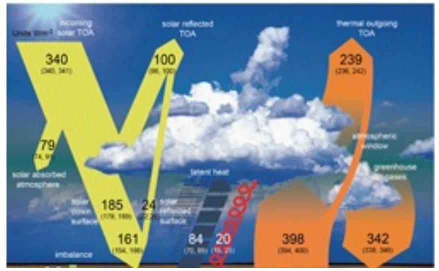
$$W_{atm} = \frac{K_1}{\tau}V + \frac{1}{\tau}W_r - \frac{\varepsilon_c}{\tau}W_c + \frac{1}{\tau}(W_r - W_c) - \frac{\varepsilon_c}{\tau}W_r$$

Reda et. al. (2012) equation

$$W_{atm} = \frac{K_1}{\tau}V + \frac{(2-\varepsilon_c)}{\tau}W_r - \frac{(\varepsilon_c + \varepsilon_{cav})}{\tau}W_c$$

Is the Reda et.al (2012) cavity emission from thermopile irradiance compatible with Kirchhoff's Law?

Jinan et. al (2010) and ACP transmission



Cavity impact on Incoming Irradiance W_{atm}

$W_{atm} = W_{atm}\,(\tau+\beta+\alpha)$

τW_{atm} = transmitted

βW_{atm} = reflected

αW_{atm} = absorbed

Cavity

ε_c = emissivity

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Thermopile

ε_r = emissivity

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S = Seebeck

K_1 = sensitivity $Wm^{-2}/\mu V$

C = responsivity $\mu V/(Wm^{-2})$

= $1/K_1$

W_r = BB irradiance

Cavity Convection

γ = convection coeff. Wm^{-2}/K

Jinan et. al. (2010) calculated the transmission using

$$\tau = \frac{(V_c K_1 + W_{rc})}{S_c} \Big/ \frac{(V_o K_1 + W_{ro})}{S_o}$$

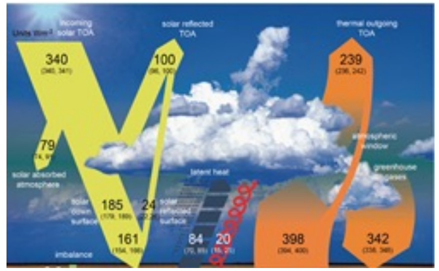
They found a value of ~0.91. Reda et. al. (2012) noted that Jinan et. al. (2010) used the wrong value for K_1 and calculated a value of ~0.992. Reda recommends generating a new value of transmission for a new value of K_1 based on the Jinan et. al. (2010) equation.

Using the new equation

$$\tau \simeq \frac{(V_c K_1 + W_{rc} - \varepsilon_c W_{cc} + \gamma(T_{rc} - T_{airc}))}{S_c} \Big/ \frac{(V_o K_1 + W_{ro} + \gamma(T_{ro} - T_{airo}))}{S_c}$$

and the raw data of Jinan et. al. (2010) a new value of the transmission was calculated ~0.977.
An alternate approximation for the transmission is to assume (1-ε_c) ~0.9775

Cavitation or Convection?



Incoming irradiance W_{atm}

$W_{atm} = W_{atm}\,(\tau+\beta+\alpha)$

τW_{atm} = transmitted

βW_{atm} = reflected

αW_{atm} = absorbed

Concentrator

ε_c = emissivity

α_c = absorption = ε_c

Thermopile

ε_r = emissivity

ρ = refection = (1-ε_r)

S = Seebeck

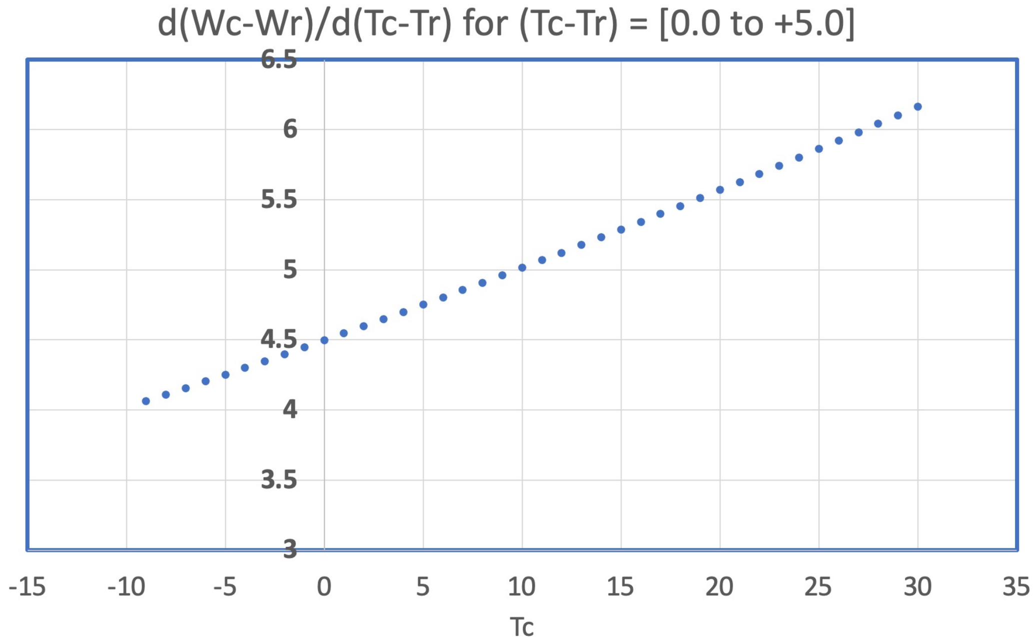
K_1 = sensitivity $Wm^{-2}/\mu V$

C = responsivity $\mu V/(Wm^{-2})$

= $1/K_1$

$$W_{atm} = \frac{K_1}{\tau}V + \frac{1}{\tau}W_r - \frac{\varepsilon_c}{\tau}W_c + \frac{1}{\tau}(W_r - W_c) - \frac{\varepsilon_c}{\tau}W_r$$

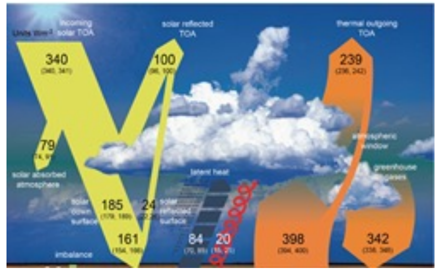
$$(W_r - W_c) \sim \psi(T_r - T_c)$$



PMOD BB calibration of ACP96 has suggested a value of 8.5 for convection coefficeint.
An additional value of 6.5 was initially chosen as a compromise between
a 4.5 Reda et. al. equivalent and 8.5 from the BB

Another method to calculate gamma is also available.

Calibration using new equation via Reference Irradiance
Results: Using 2020 Reference Irradiances: IRIS2 & IRIS4



{C and τ} were found using 2020 data in periods of passive monitoring by finding the pair of values that gave a mean of within +/- 0.2 Wm^{-2} of zero and also minimized the standard deviation of the mean. Over 14000 reference irradiance were available for each IRIS.

Constants used:
ε_c= 0.0225
γ = 8.4 and 6.5

Reminder:
NIST (Jinan/Forgan) τ =0.977
NIST (1-ε_c) = τ =0.9775

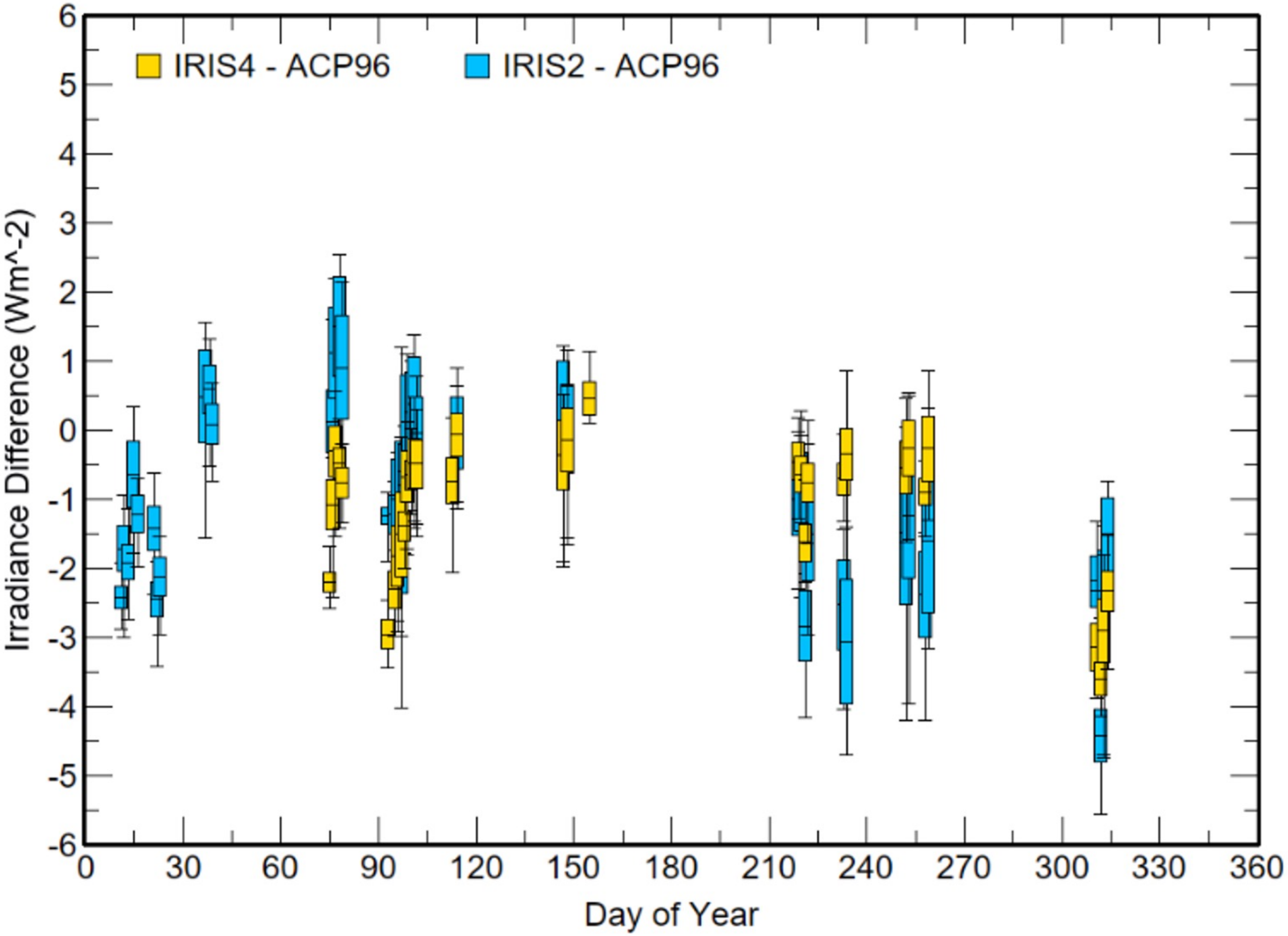
γ=8.5, ε_c= 0.0225

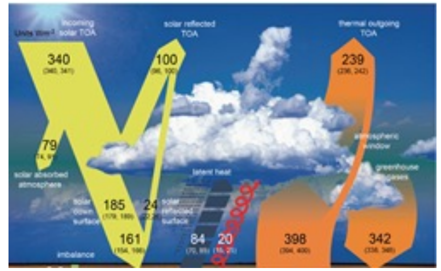
	No	*ACP96 C*	*ACP96 τ*	W_{IRIS}-W_{ACP96} Average	W_{IRIS}-W_{ACP96} Std Dev	W_{IRIS}-W_{ACP96} Max	W_{IRIS}-W_{ACP96} Min
W_{IRIS2}-W_{ACP96}	18802	10.72	0.9820	0.04	1.08	3.90	-4.24
W_{IRIS4}-W_{ACP96}	14085	10.28	0.9707	-0.03	0.96	2.30	-3.37
W_{IRIS2}-W_{ACP96}	18802	*10.50*	*0.9764*	-1.19	1.44	2.42	-5.68
W_{IRIS4}-W_{ACP96}	14085	*10.50*	*0.9764*	-1.39	1.07	1.00	-4.84

γ=6.5, ε_c= 0.0225

	No	*ACP96 C*	*ACP96 τ*	W_{IRIS}-W_{ACP96} Average	W_{IRIS}-W_{ACP96} Std Dev	W_{IRIS}-W_{ACP96} Max	W_{IRIS}-W_{ACP96} Min
W_{IRIS2}-W_{ACP96}	18802	10.51	0.9819	0.08	1.41	3.67	-4.39
W_{IRIS4}-W_{ACP96}	14085	10.06	0.9692	-0.04	0.99	2.23	-3.28
W_{IRIS2}-W_{ACP96}	18802	*10.28*	*0.9756*	0.19	1.43	3.71	-4.06
W_{IRIS4}-W_{ACP96}	14085	*10.28*	*0.9756*	-0.03	1.04	2.32	-3.38

Calibration using new equation via Reference Irradiance
Results: Using 2020 Reference Irradiances: IRIS2 & IRIS4



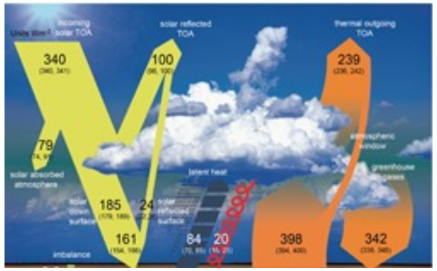


C=10.50
τ= 0.976
ε_c=0.0225
γ=6.5

Measurements

IRIS2-ACP96 18802
IRIS4-ACP96 14085

Alternate Modified linear LSQ Calibration (1)



Cavity impact on Incoming Irradiance W_{atm}

$W_{atm} = W_{atm}\,(\tau+\beta+\alpha)$

τW_{atm} = transmitted

βW_{atm} = reflected

αW_{atm} = absorbed

Cavity

ε_c = emissivity

α_c = absorption = ε_c

W_c = BB irradiance

Thermopile

ε_r = emissivity

ρ = reflection = (1-ε_r)

S = Seebeck

K_1 = sensitivity $Wm^{-2}/\mu V$

C = responsivity $\mu V/(Wm^{-2})$

= $1/K_1$

W_r = BB irradiance

Cavity Convection

γ = convection coeff. Wm^{-2}/K

$$W_{atm} = \frac{K_1}{\tau}V + \frac{(1-\beta)}{\tau}W_r - \frac{\varepsilon_c}{\tau}W_c + \frac{\gamma}{\tau}(T_r - T_{air}) = \frac{K_1}{\tau}V + \frac{W_{net}}{\tau}$$

Assume β ~ 0 as in Reda et. al. (2012). Then the predictand of linear least squares regression (LSQ) is $y(t) = W_{net}(t)$ and a predictor $V(t)$. Given

$$y(W_r, W_c, T_r, T_c, t) = W_{net}(t) = W_r(t) - \varepsilon_c W_c(t) + \gamma(T_r(t) - T_c(t))$$

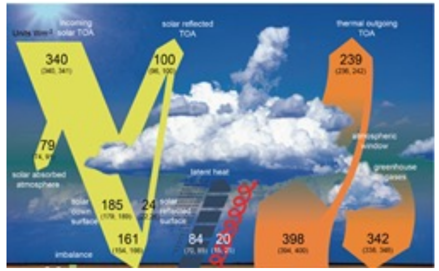
Then the linear equation to solve by LSQ is

$$y(W_r, W_c, T_r, T_c, t) = W_{net}(t) = \langle K_1 \rangle V(t) + \langle \tau W_{atm} \rangle$$

Hence can solve for $\langle K_1 \rangle$ and $\langle \tau W_{atm} \rangle$

As in Reda et. al. (2012) to achieve a continuous variation in the irradiance components, the base of the ACP is cooled for ~300 s so that the range of $V(t)$ is about ~500 μV.

Alternate Modified linear LSQ Calibration (2)



Cavity impact on Incoming Irradiance W_{atm}

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βW_{atm} = reflected

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K_1 = sensitivity $Wm^{-2}/\mu V$

C = responsivity $\mu V/(Wm^{-2})$ = $1/K_1$

W_r = BB irradiance

Cavity Convection

γ = convection coeff. Wm^{-2}/K

As it is a linear LSQ in ONE predictor variable *V*(*t*) each component of $W_{net}(t)$ can be regressed against *V*(*t*) separately, hence for

$$y(W_r, W_c, T_r, T_c, t) = W_{net}(t) = W_r(t) - \varepsilon_c W_c(t) + \gamma(T_r(t) - T_c(t))$$

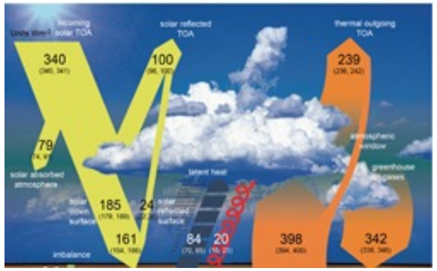
We have

$$W_r(t) = y_r(W_r, t) = < A_r > V(t) + < B_r >$$

$$W_c(t) = y_c(W_c, t) = < A_c > V(t) + < B_c >$$

$$dT(t) = (T_r(t) - T_c(t)) = y_{dT}(dT, t) = < A_{dT} > V(t) + < B_{dT} >$$

Alternate Modified linear LSQ Calibration (3)



Cavity impact on Incoming Irradiance W_{atm}

$W_{atm} = W_{atm}(\tau+\beta+\alpha)$

τW_{atm} = transmitted

βW_{atm} = reflected

αW_{atm} = absorbed

Cavity

ε_c = emissivity

α_c = absorption = ε_c

W_c = BB irradiance

Thermopile

ε_r = emissivity

ρ = reflection = (1-ε_r)

S = Seebeck

K_1 = sensitivity $Wm^{-2}/\mu V$

C = responsivity $\mu V/(Wm^{-2})$

= $1/K_1$

W_r = BB irradiance

Cavity Convection

γ = convection coeff. Wm^{-2}/K

To calculate the linear LSQ results just apply the constant terms as in the full LSQ equation, that is

$$< K_1 >=< \frac{1}{C} >= \varepsilon_c < A_c > - < A_r > -\gamma < A_{dT} >$$

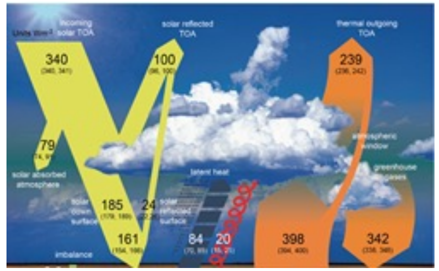
$$< \tau W_{atm} >=< B_r > -\varepsilon_c < B_c > +\gamma < B_{dT} >$$

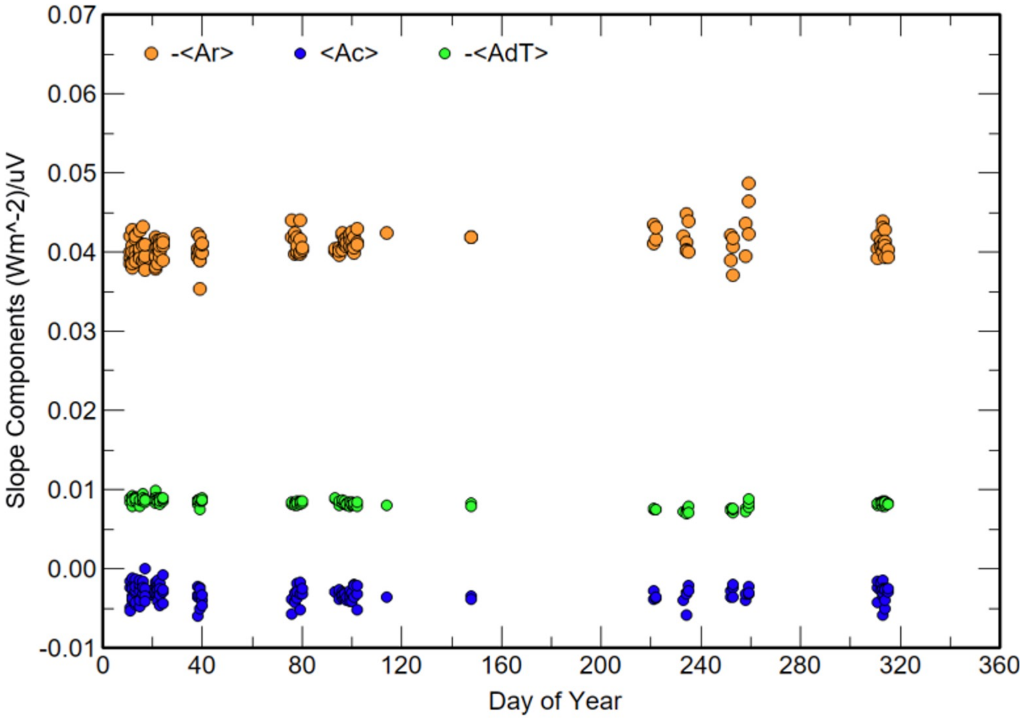
Note:

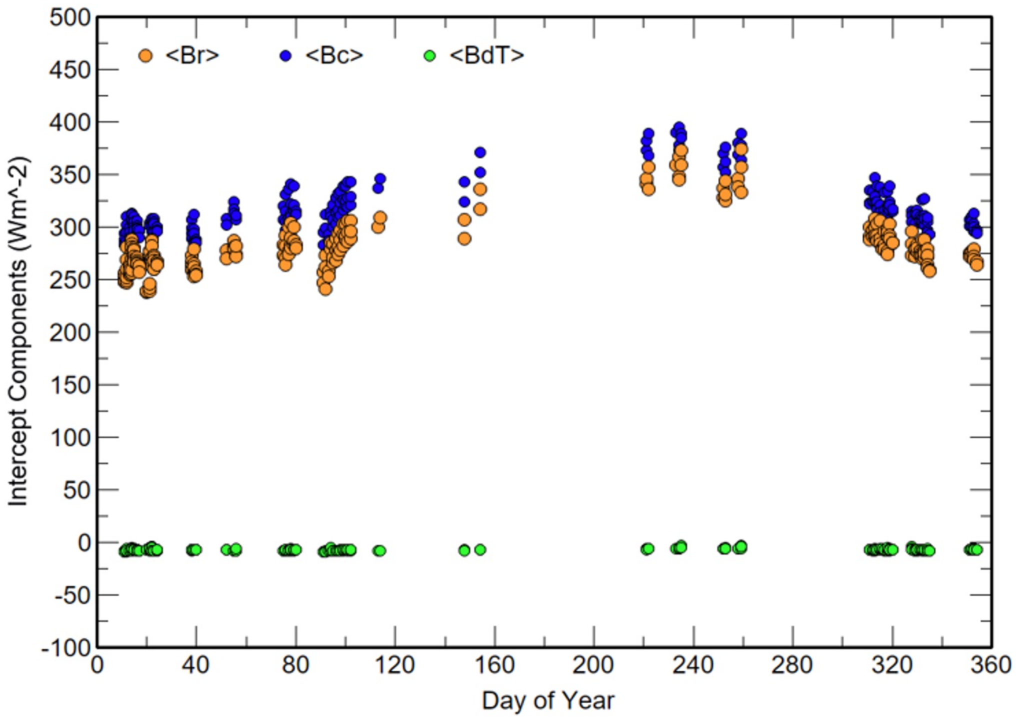
The original Reda et. al. (2012) equation only has two predictand quantities W_r and W_c. Hence once $<A_r>$ and $<A_c>$ are derived, they can be used in to calculate the Reda et. al. (2012) values of $<K_1>$ and $<\tau W_{atm}>$ without any further LSQ calculations using scalers (2-emissivity) and (1-emissivity).

Alternate Modified linear LSQ Calibration Results (1)
Results: ACP96 2020

Linear LSQ Predictand Components – can be used for the new and Reda et. al. (2020) equations

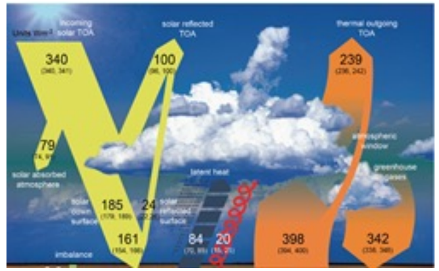






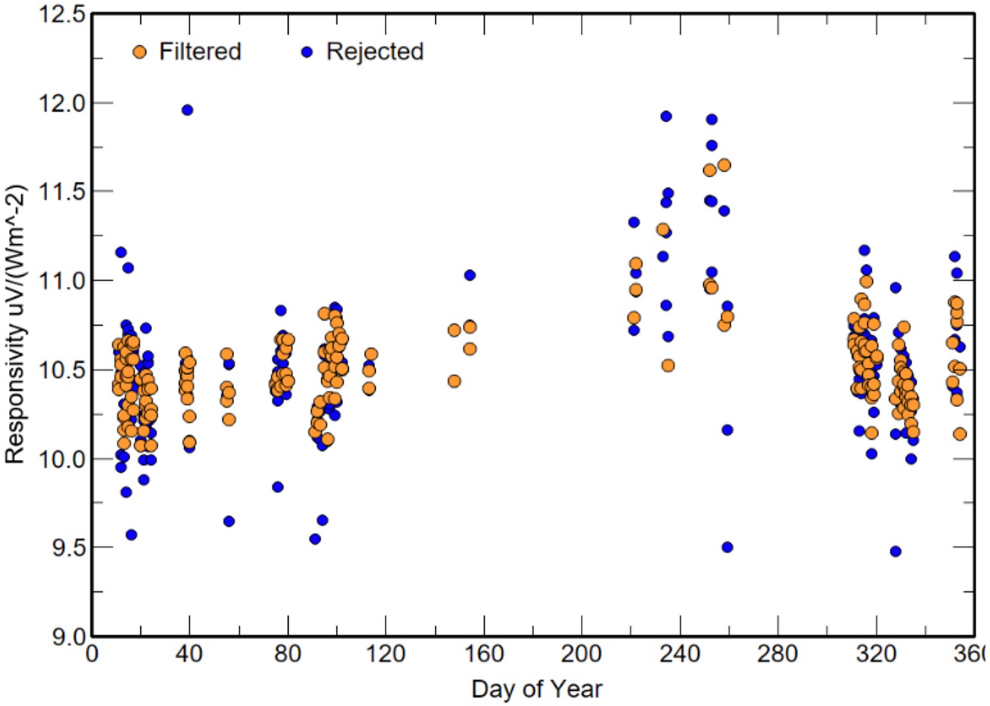
Alternate Modified linear LSQ Calibration Results (2)

Results: ACP96 PMOD 2019 to 2021

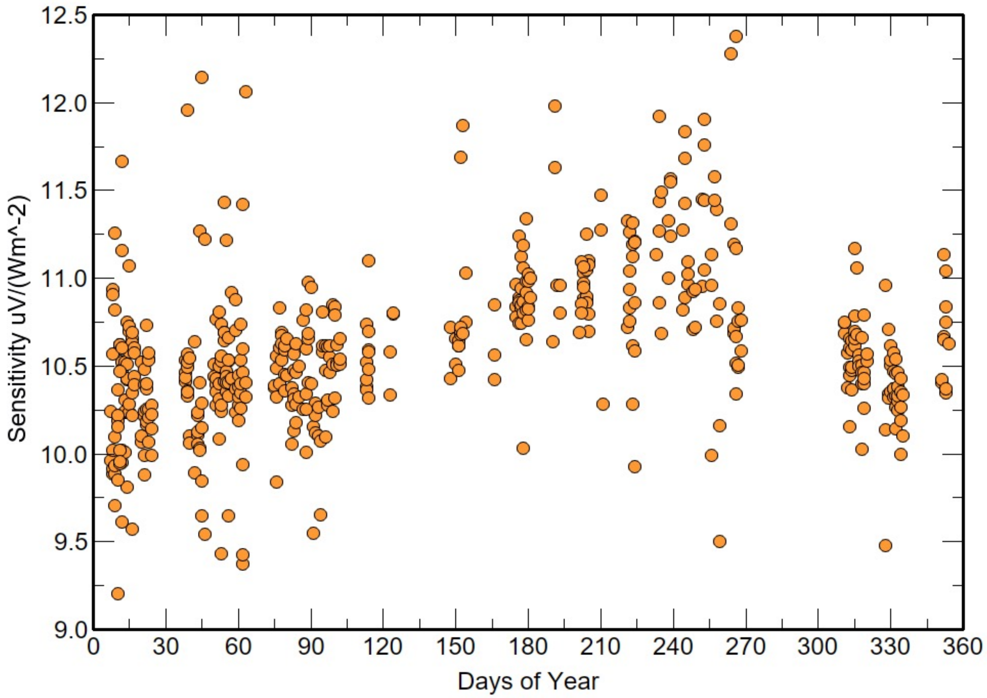


Using ε_c=0.0225 and γ=6.5. Points rejected based on confidence interval of solution and dew point depression < 4 K. Period for day 210 to 280 anomalous but a period of low dew point depression.

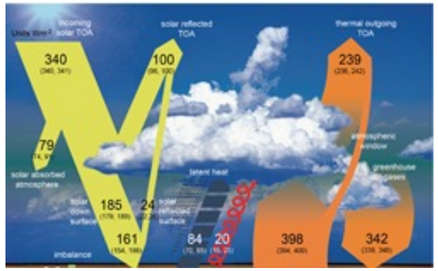
Mean *C=10.49 for 2020*



ACP96 2019 through 2021

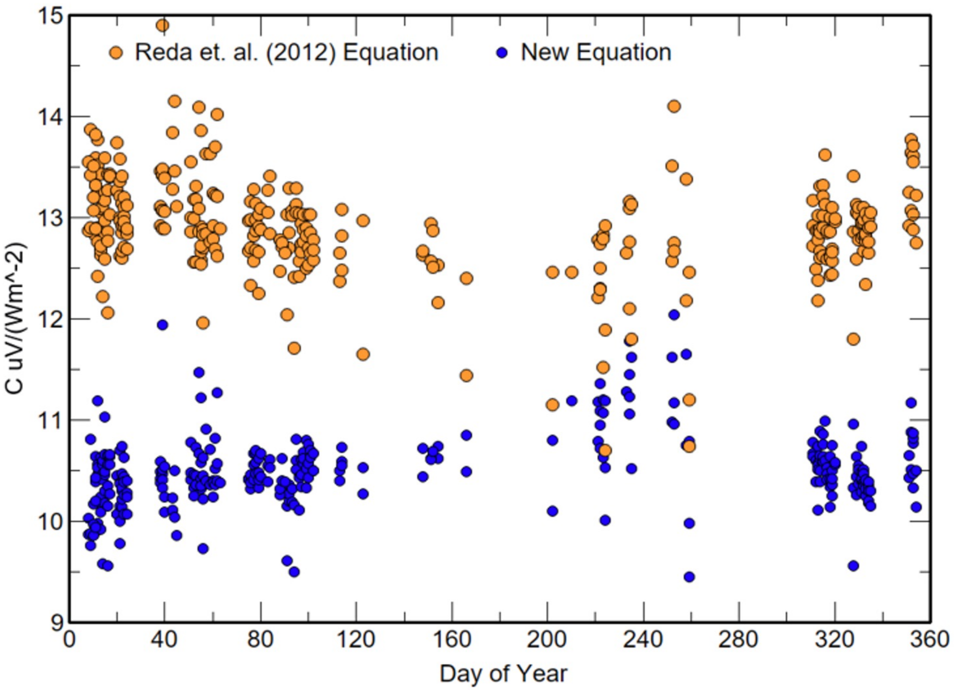


Alternate Modified linear LSQ Calibration Results (3)
Results: ACP96 - comparison with Reda et. al (2012) Eqn

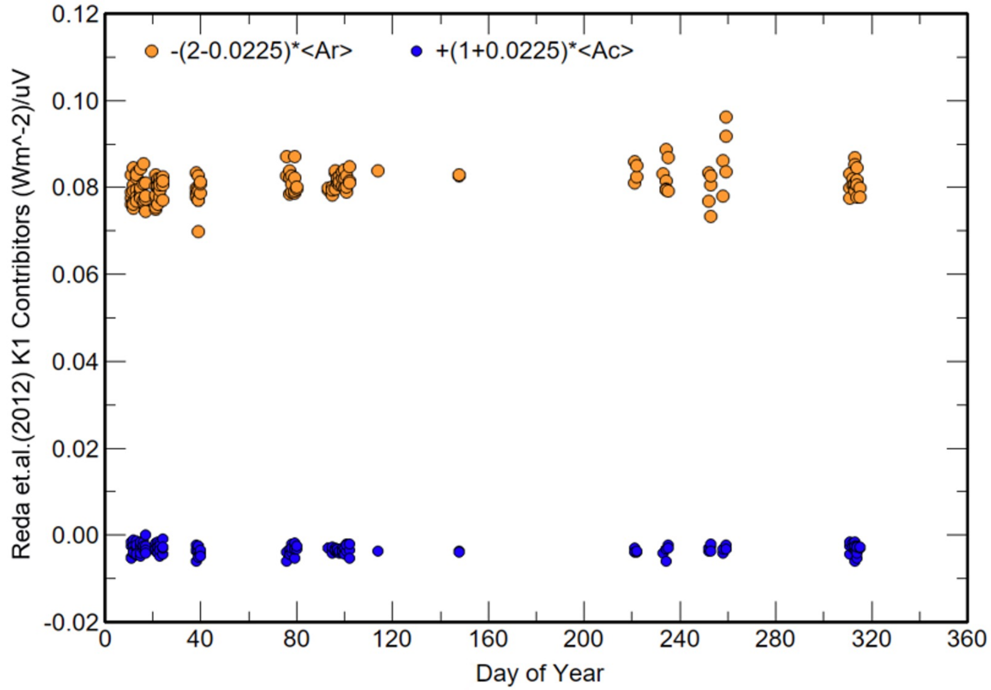


Using ε_c=0.0225 for both equations and also γ=6.5 for new equation. The $\langle A_r \rangle$ component dominates the K1 contributors with a minor contribution from the cavity.

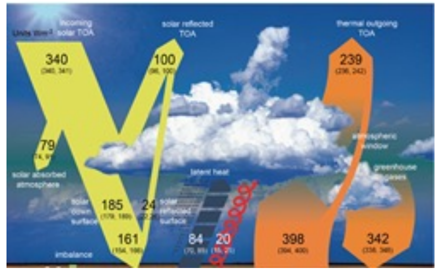
All LSQ in 2020



Reda et. al. (2012) K_1 Contributors

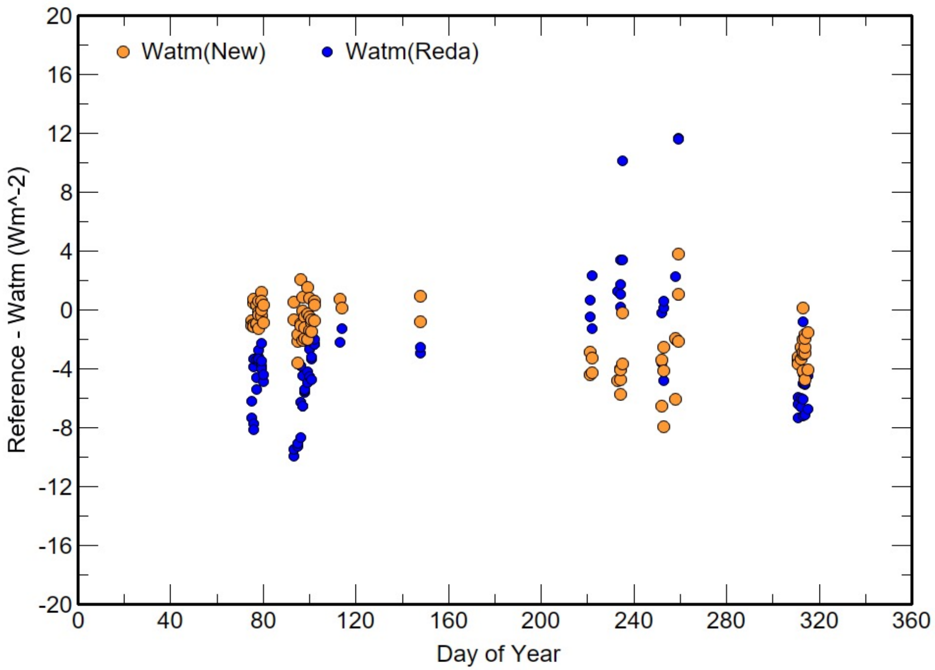


Alternate Modified linear LSQ Calibration Results (4)
Results: ACP96 - comparison with Reda et. al (2012) Eqn

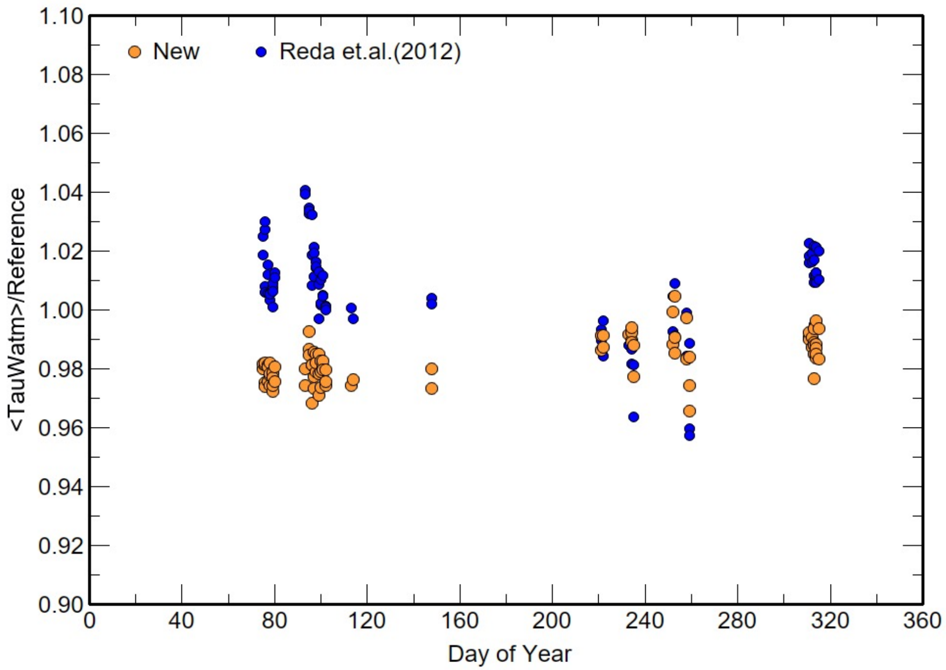


1. Calculation of W_{ref} - $\langle W_{atm} \rangle$ with IRIS4 as reference (Transmission New =.977, Reda=.992)
2. Calculation of cavity transmission by $\langle \tau W_{atm} \rangle / W_{ref}$ with IRIS4 as reference

W_{ref} - $\langle W_{atm} \rangle$

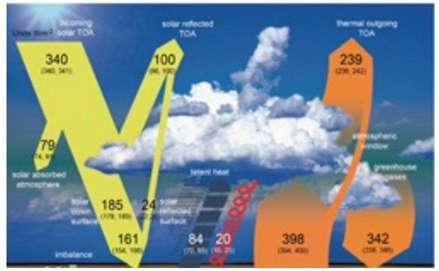


$\langle \tau W_{atm} \rangle / W_{ref}$



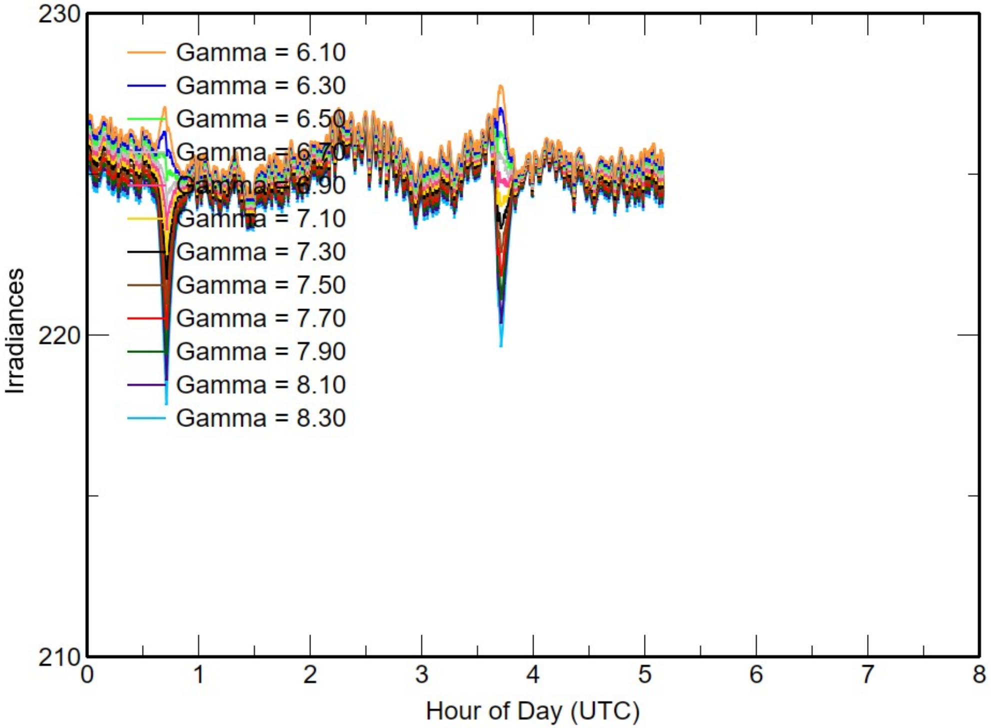
Issue: Water Vapour content impacts on ACP LSQ Calibrations

Issue: Convection coefficient γ varies with Water Vapour?



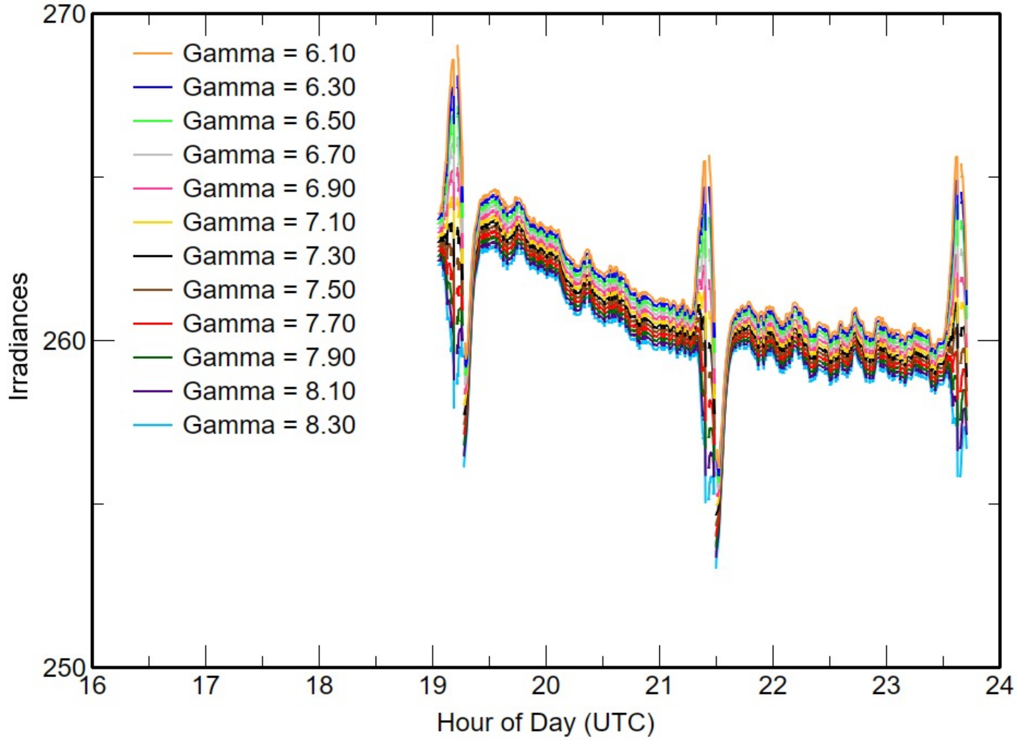
26 Feb 2021 RH < 60%

ACP96 2021-02-26 C 10.50 ec 0.0225 tau 0.9770

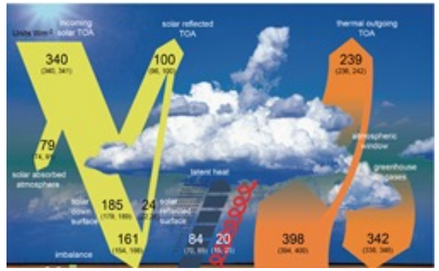


30 Sep 2021 RH > 85%

ACP96 2021-09-30 C 10.50 ec 0.0225 tau 0.9770



Some ACP Issues still to Resolve – with both equations



- Can the transmission and emissivity apply to all ACPs, or can they be derived without the need of a reference irradiance? Tentative answer: present data says Yes

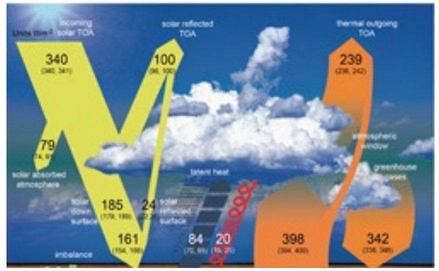
$$C = \frac{\varepsilon_r}{\varepsilon_{rsolar}} \frac{C_s}{\tau_{dome}^2}$$

- Can an initial guess for C be achieved through solar irradiance?
  Tentative answer: for a F3 thermopile not aged by solar exposure Yes

- Both ACP equations *MUST* be able to derive an accurate W_{atm} *DURING* a cooling-heating calibration phase otherwise the LSQ calibration method isn't valid. Do they?
  Answer: Most times for new equation through γ variation; not so for Reda et. al. (2012).
  Questions that need answers:
  (1) Is γ a function of dew point depression?
  (2) What is the maximum cooling and heating rate for a valid LSQ?
  (3) Is C's variation with base temperature required?

- Can a valid LSQ calibration be achieved via heating rather than cooling?
  Answer: Most likely yes given the new equation derives a valid W_{atm} during heating as well as cooling, and it would be useful during periods of low dew point depression.

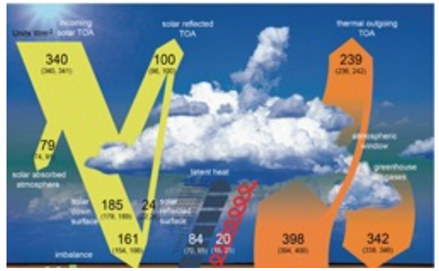
Conclusions



The new equation provides good agreement with W_{atm} in both passive and LSQ calibration conditions.

Using the new equation…..

- An ACP can be characterized as a radiometer directly traceable to SI without comparison to a reference irradiance using the new equation.
- As in other device calibrations by LSQ methods no single LSQ calibration result is sufficient, and a statistical average over a number of nights is required.
- Using a reference W_{ref} it is possible to derive representative thermopile responsivity (C) and transmission (τ) for passive monitoring.
- The F3 thermopile responsivity, and the cavity transmission and emissivity in ACPs are stable with the same values for ACP96 shown to be valid from 2019 through to the present for passive monitoring.
- More investigations are required to
  - determine the influence of water vapour content on the convection term;
  - the limitations on the rate of change in base temperature during LSQ calibrations;
  - determine if periodic solar calibrations can independently check thermopile responsivity (and its temperature coefficient).



Thank You for Your Attention

and

Apologies for too many equations!