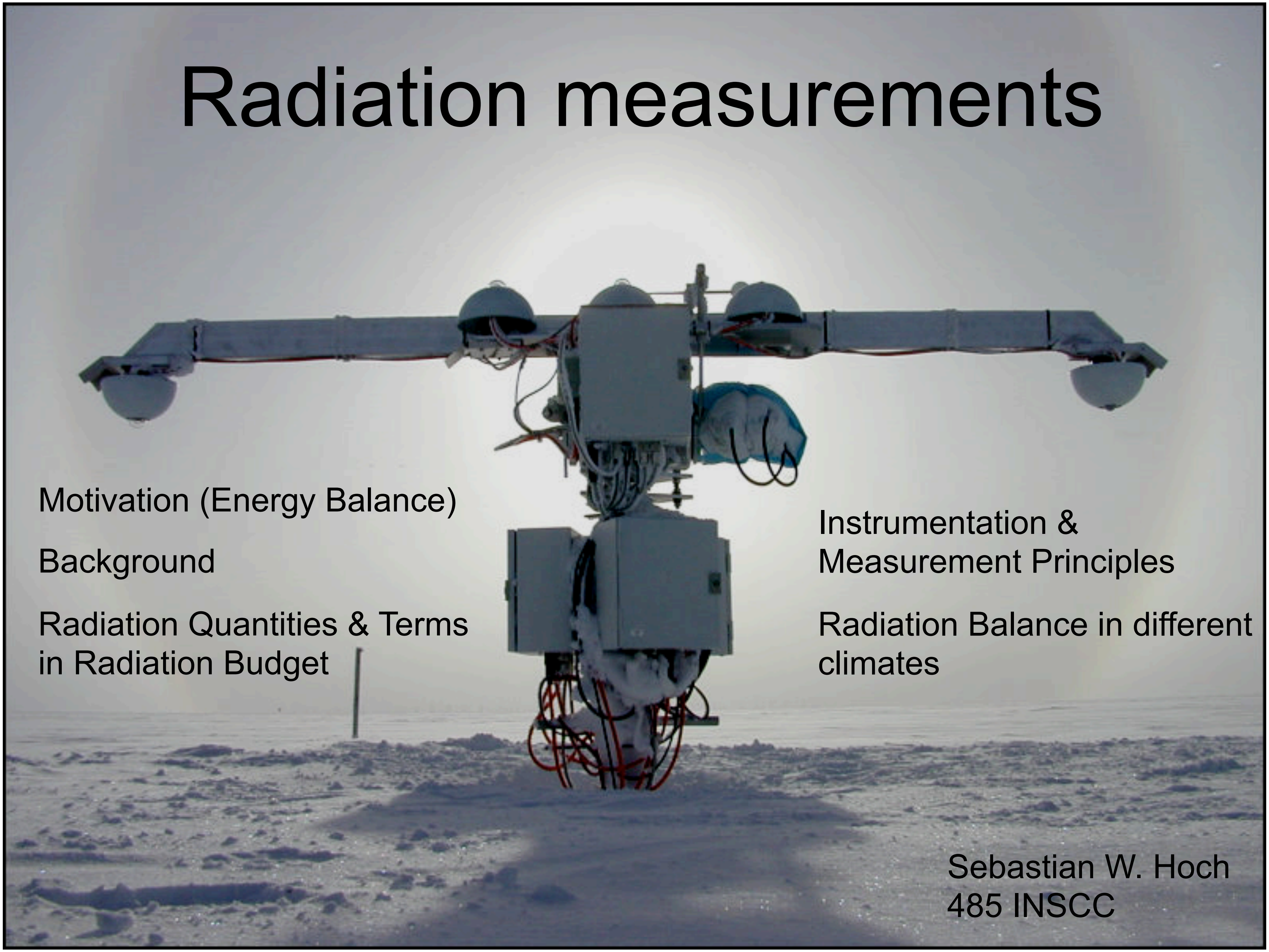
Radiation measurements



Motivation (Energy Balance)

Background

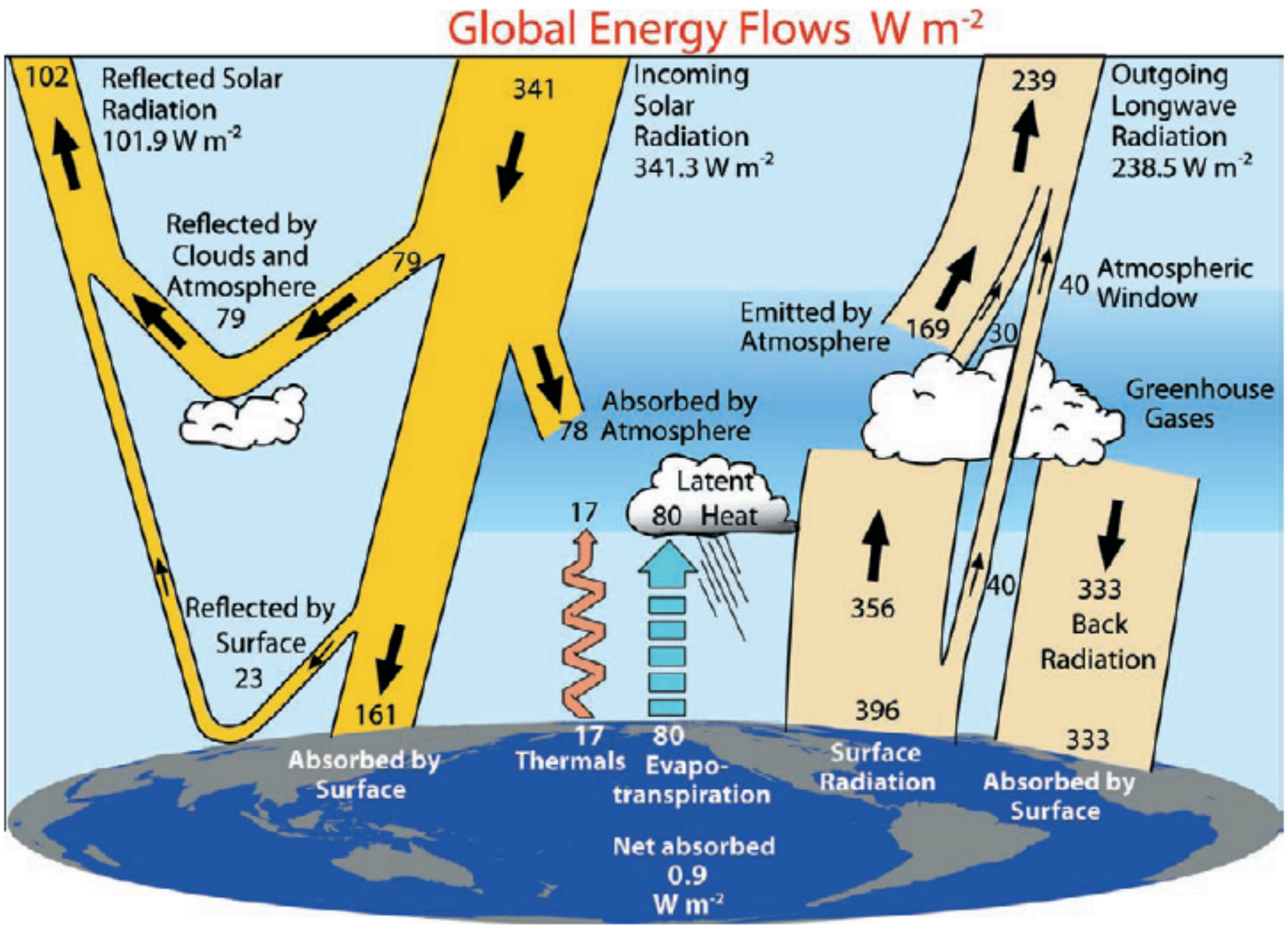
Radiation Quantities & Terms in Radiation Budget

Instrumentation & Measurement Principles

Radiation Balance in different climates

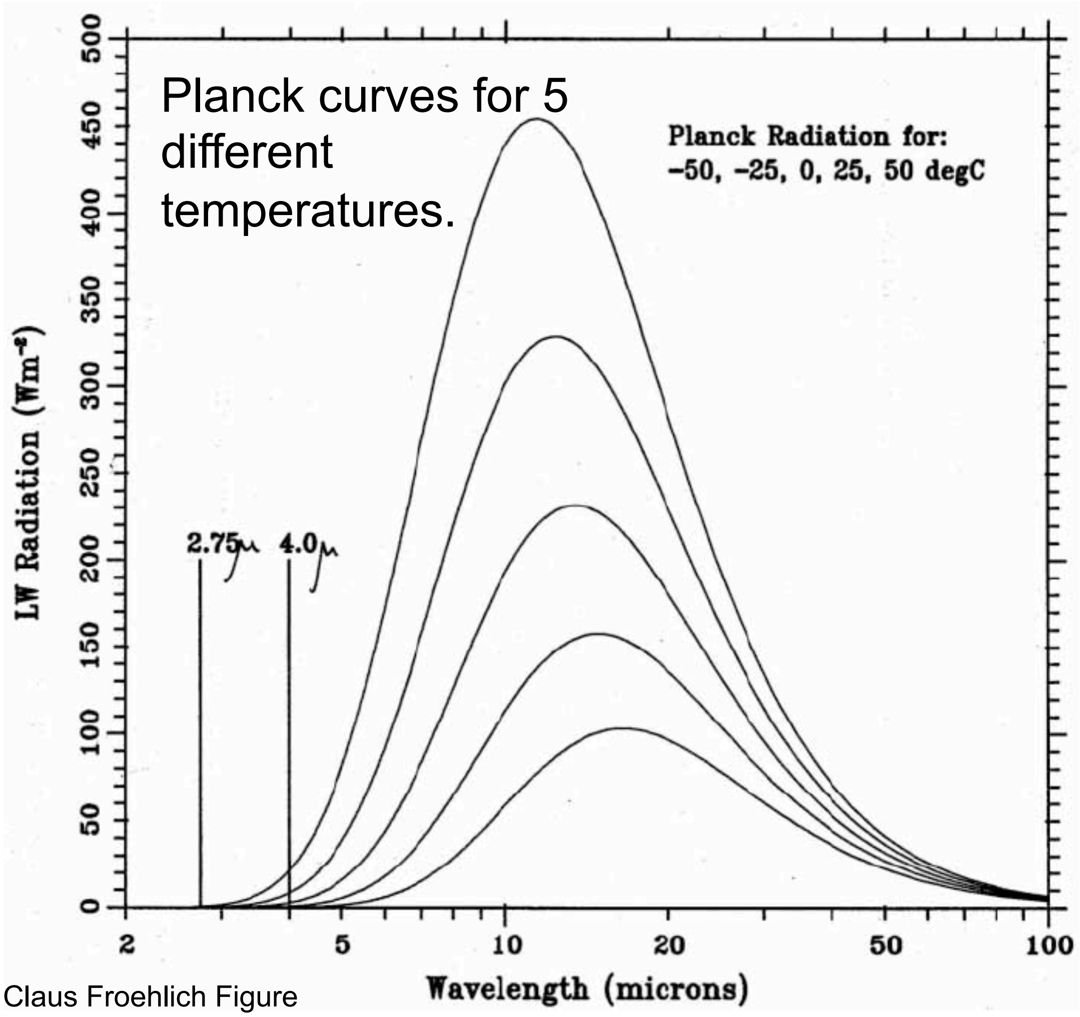
Sebastian W. Hoch
485 INSCC

Radiation and the Energy Budget



Trenberth et al. 2009 BAMS

Why Shortwave Radiation and Longwave Radiation?



Planck curves for 5 different temperatures.

Claus Froehlich Figure

Planck Function

$$B_\lambda\ (T) = \frac{2hc^2}{\lambda^5\,(e^{hc\,/\,k\lambda T} - 1)}$$

$h = 6.626\ 068\ 96(33) \times 10^{-34}\ \mathrm{J\ s}$

c: *speed of light*

λ : *wavelength*

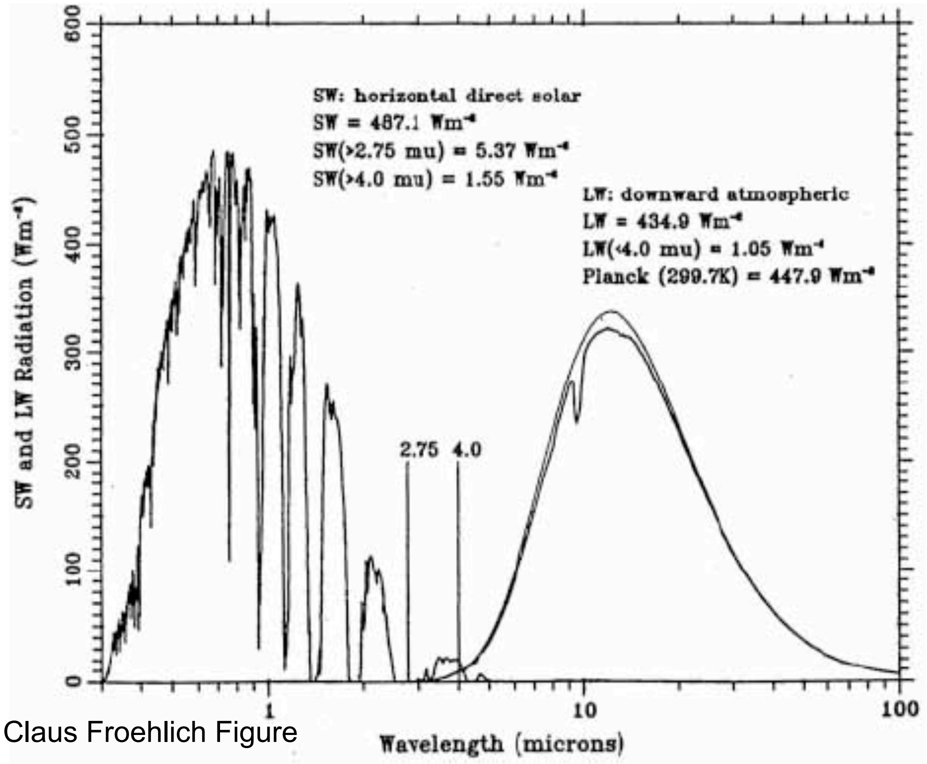
Everything emits radiation – depending on the temperature!

Wien's Displacement Law

$$\lambda_{\mathrm{max}} = \frac{a}{T} \text{ mit } a = 2.89776 \times 10^{-3}\ \mathrm{m\,K}$$

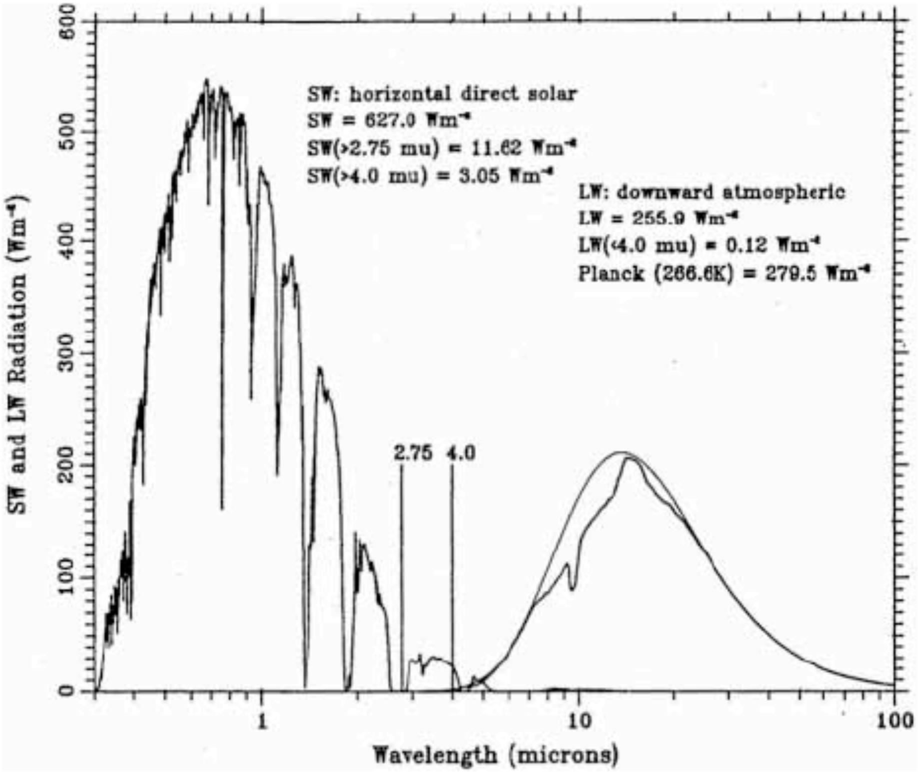
Longwave or ***Terrestrial*** or ***Infrared*** Radiation and

Shortwave or ***Solar*** Radiation



Claus Froehlich Figure

Tropical atmosphere



Midlatitude Summer, 1600 m (ASL)

Other quantities defined by spectral range:

- UV Radiation (A, B, C)
- PAR: Photosynthetically Active Radiation; 400 - 700 nm

There's an overlap at times ...

Radiation Quantities

Quantity	Symbol	SI unit	Abbr.	Notes
Radiant energy	Q	joule	J	energy
Radiant flux	Φ	watt	W	radiant energy per unit time, also called *radiant power*
Radiant intensity	I	watt per steradian	W·sr^{-1}	power per unit solid angle
Radiance	L	watt per steradian per square metre	W·sr^{-1}·m^{-2}	power per unit solid angle per unit *projected* source area. called *intensity* in some other fields of study.
Irradiance	E, I	watt per square metre	W·m^{-2}	power incident on a surface. sometimes confusingly called "intensity".
Radiant exitance / Radiant emittance	M	watt per square metre	W·m^{-2}	power emitted from a surface.
Radiosity	J or J_λ	watt per square metre	W·m^{-2}	emitted plus reflected power leaving a surface
Spectral radiance	L_λ or L_ν	watt per steradian per metre^3 *or* watt per steradian per square metre per hertz	W·sr^{-1}·m^{-3} *or* W·sr^{-1}·m^{-2}·Hz^{-1}	commonly measured in W·sr^{-1}·m^{-2}·nm^{-1}
Spectral irradiance	E_λ or E_ν	watt per metre^3 *or* watt per square metre per hertz	W·m^{-3} *or* W·m^{-2}·Hz^{-1}	commonly measured in W·m^{-2}·nm^{-1}

Source: Wikipedia

The Radiation Balance – the terms (Irradiances W m^{-2})

Direct Solar Radiation S↓

Diffuse (Solar) Radiation D↓

Global Radiation (K↓, Gl) = S↓+ D↓

Shortwave Reflected Radiation K↑

Shortwave Net Radiation K*

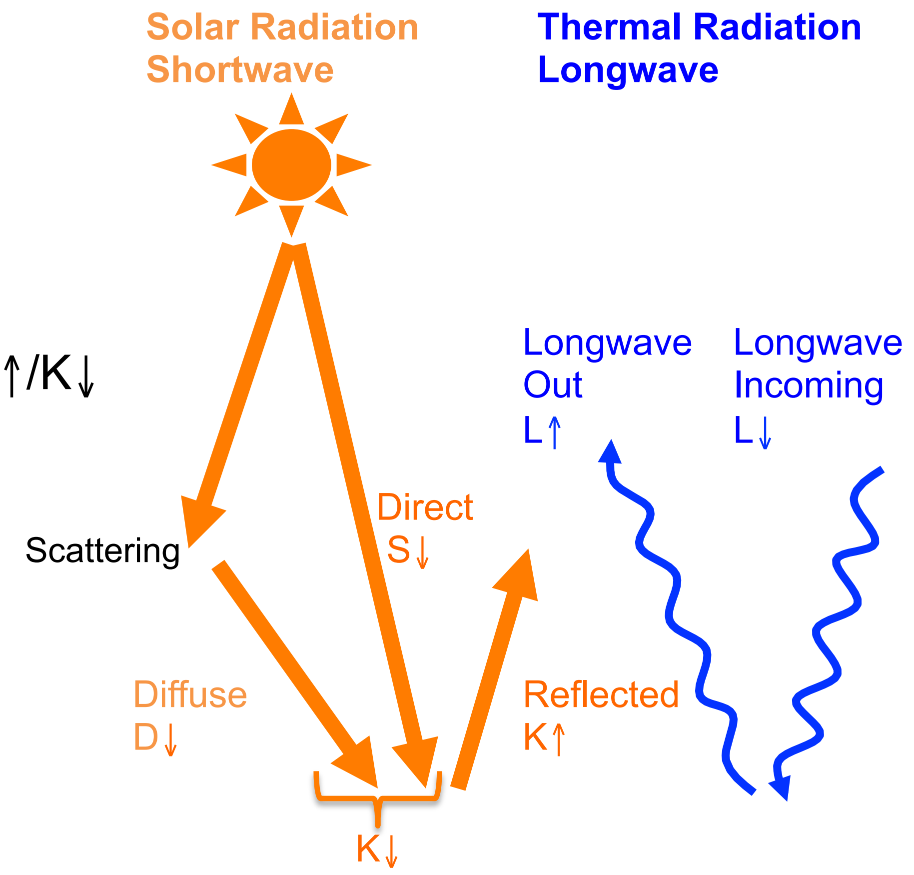
Albedo $\alpha = K\uparrow / K\downarrow$

Longwave Incoming L↓

Longwave Outgoing Radiation L↑

Longwave Net Radiation L*

Net Radiation Q*



$$Q^* = K^* + L^*$$

$$= K\downarrow - K\uparrow + L\downarrow - L\uparrow$$

$$= (1 - \alpha) * K\downarrow + L^*$$

$$L\uparrow = \varepsilon_{surf} \cdot \sigma \cdot T^4_{surf}$$

$$L\downarrow = \varepsilon_{atmos} \cdot \sigma \cdot T^4_{atmos}$$

Stefan-Boltzmann Constant
σ: $5.67 \cdot 10^{-8}$ J s^{-1} m^{-2} K^{-4}

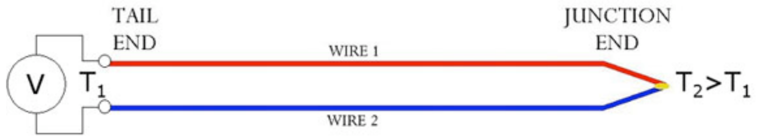
Measurement Principle

Thermopile

- converts thermal energy into electrical energy
- composed of thermocouples (usually in series)
- output voltage proportional to a local temperature difference
- range of tens or hundreds of millivolts.

Thermocouple

- temperature measurement based on the *Seebeck Effect*: a result of a difference in *thermoelectric power* of two materials



$$Emf = \int_{T_1}^{T_2} S_{12} \cdot dT = \int_{T_1}^{T_2} (S_1 - S_2) \cdot dT$$

- Emf is the Electro-Motive Force or Voltage; T_1 and T_2: Temperatures of reference (T_1) and measuring end (T_2)
- S_{12}, S_1, S_2: **Seebeck coefficients** of the thermocouple and thermo-elements
- null voltage:
  - same materials
  - no temperature difference

Radiation observations in Climate Science - Instrumentation

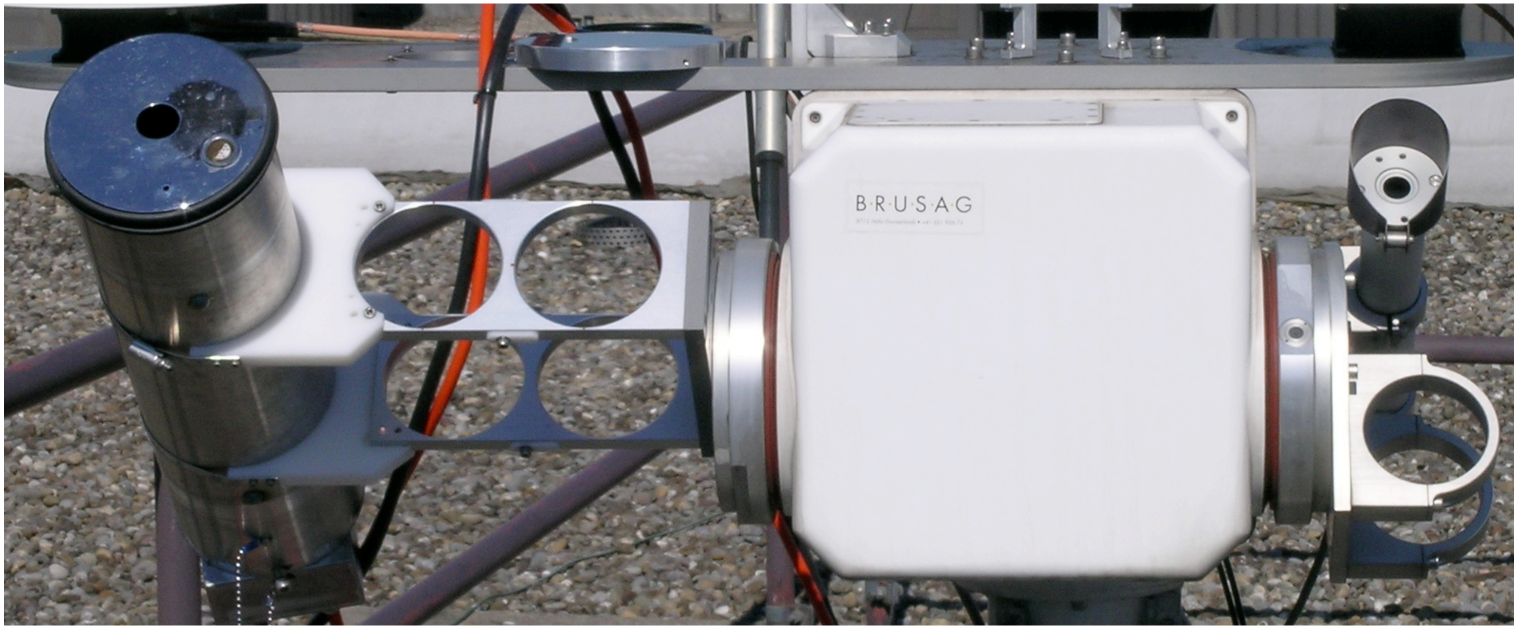
1. Pyrheliometer

Direct Solar Radiation
World Standard Instruments
(Compensation Type / Thermopile)
Open / with window ...

pyro-, pyr- +
(Greek: fire, burn; heat, produced by heating; and sometimes "fever")

Ἥλιος (Helios) is derived from the noun ἥλιος, "sun" in ancient Greek

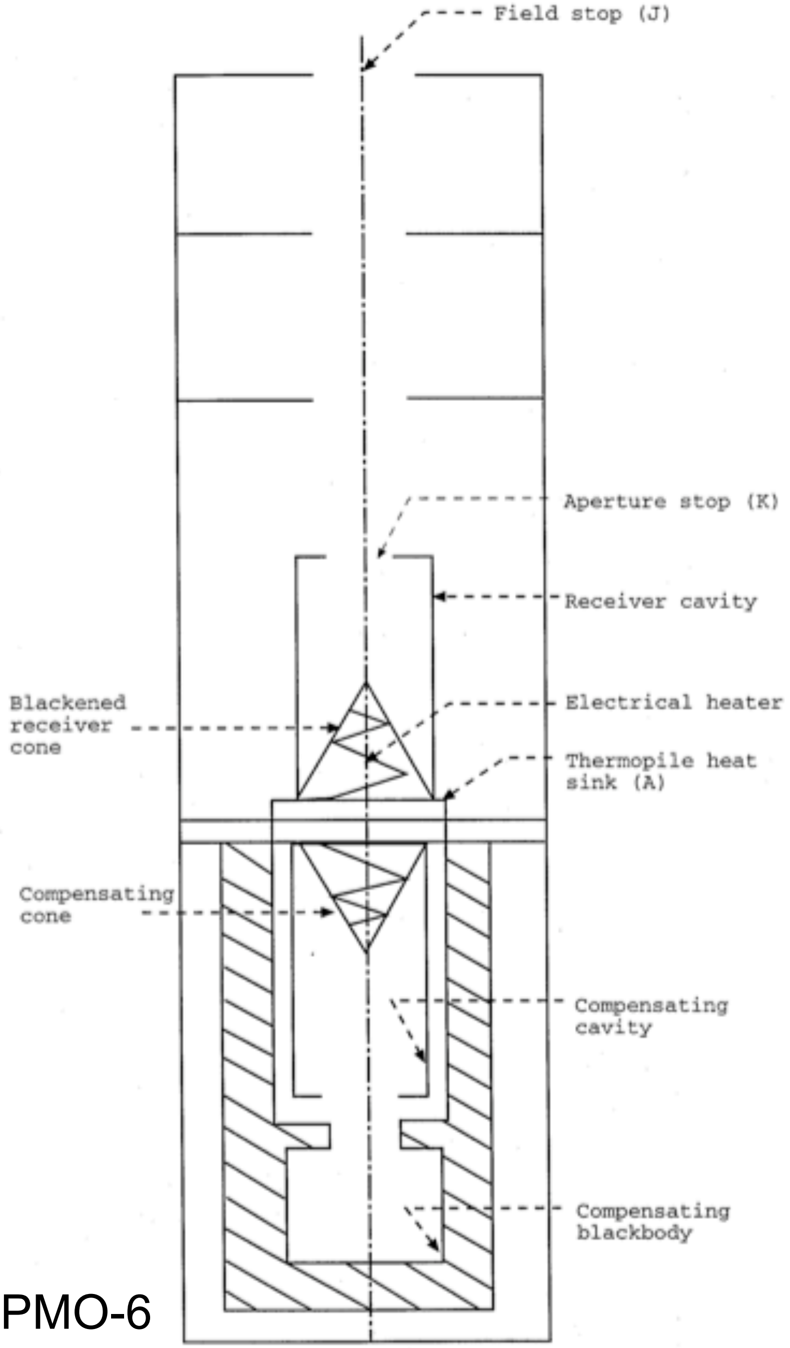
PMO-6



Kipp & Zonen
CH1

PMO-6 Absolute Cavity Radiometer

$S=k * (P_{closed}-P_{open})$



PMO-6

NREL-TP-463-20619

pmod/wrc

Other System:
Eppley Hickley-Frieden (HF)

Thermopile Pyrheliometer (NIP / CH1)

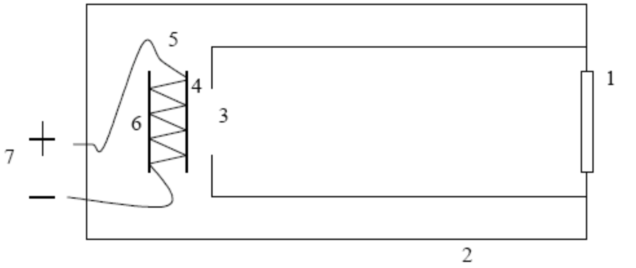
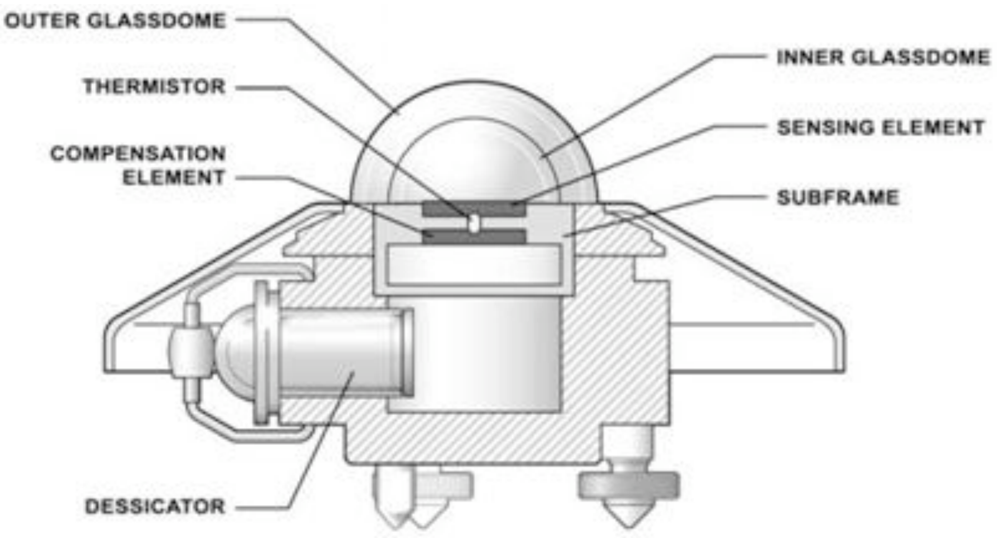


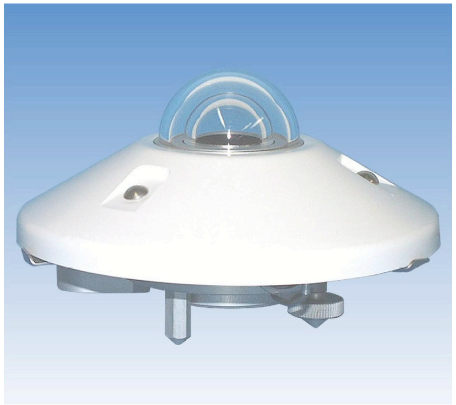
Fig. 1. Pyrheliometer schematic showing entrance window (1), thermal shield (2), detector aperture (3), light absorber (4), thermopile (5), heat sink (6), and thermopile output (7).

P. Thacher Sandia Labs

2. **Pyranometer**

- Global Radiation
- Shortwave Reflected Radiation
- Diffuse Radiation (in conjunction
  with a shading disk or shadow-band)
- Glass or quartz dome





Standard

Black & White Type

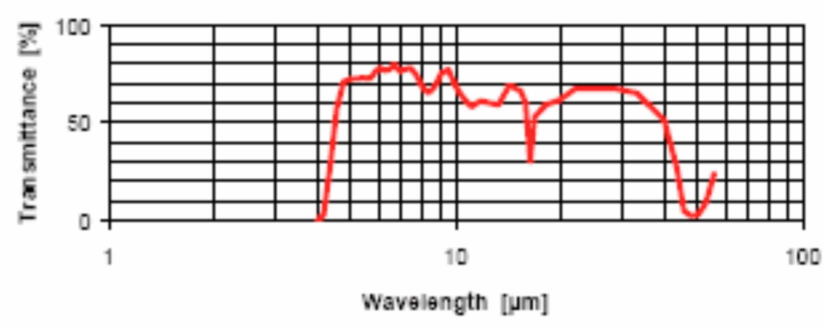
Photodiode Type

Shading – Shadowbands and Shading disks

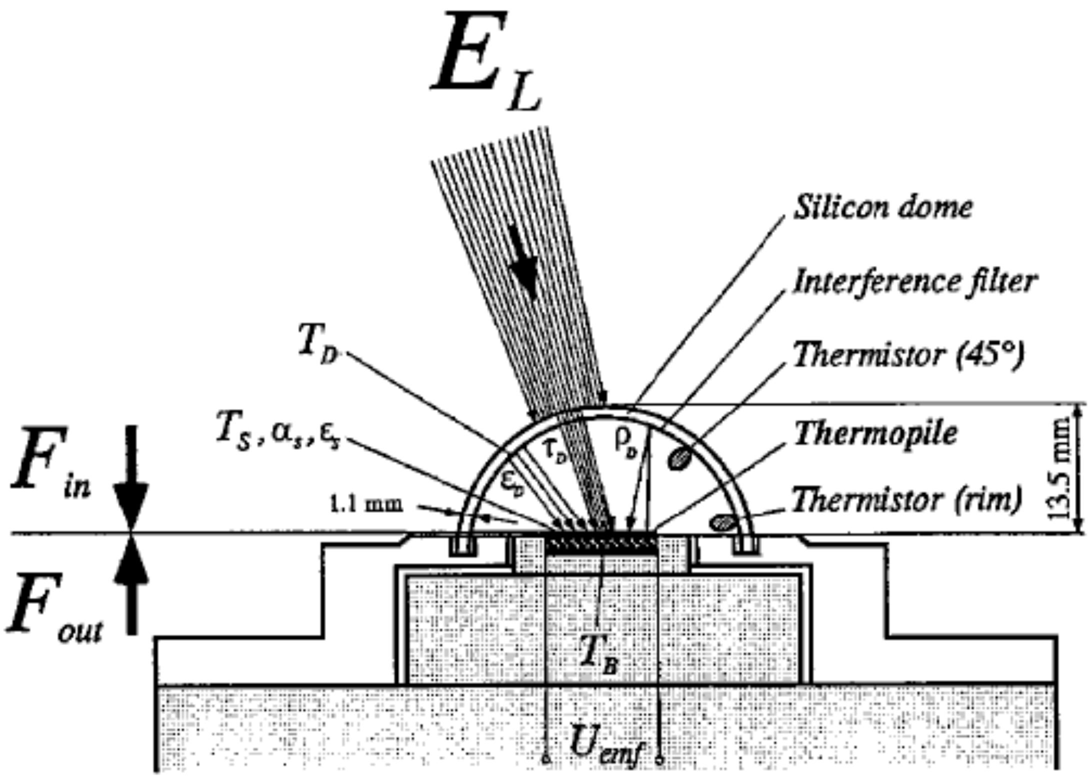
3. **Pyrgeometer**

geo-, ge- +
(Greek: earth, land,
soil; world)

Longwave Radiation
Thermopile, Silicon (Si) dome



Si-Dome and interference filters



Schematic view of Eppley PIR (Philipona et al. 1995)

Pyrgeometer Formula:

$$E_L = \underset{\text{LWin\_a}}{\frac{U_{\text{emf}}}{C}(1 + k_1\sigma T_B{}^3)} + \underset{\text{LWin\_b}}{k_2\sigma T_B{}^4} - \underset{\text{LWin\_c}}{k_3\sigma(T_D{}^4 - T_B{}^4)}.$$

We neglect k_1, set k_2 to 1.0, and k_3 to a mean value of 3.5.

4. **Pyrradiometer**

- “All-wave” Radiation
- Thermopile measurements
- Polyethylene Dome
- Double domes: Net-Radiometer
- “Wind Speed Error”

http://www.novalynx.com/

Different response to short- and longwave fluxes!

Birds like to destroy them, too...

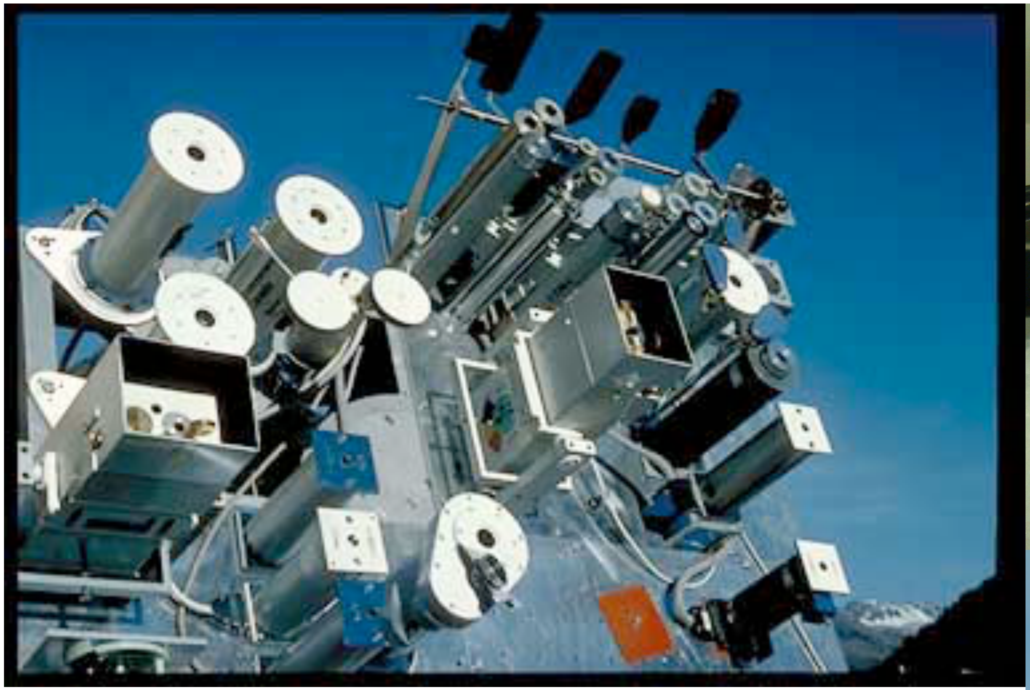
5. **Heliograph / Sunshine Duration Sensor**

Campbell-Stokes Sunshine Recorder

"Sunshine": Flux > 120 Wm^{-2}

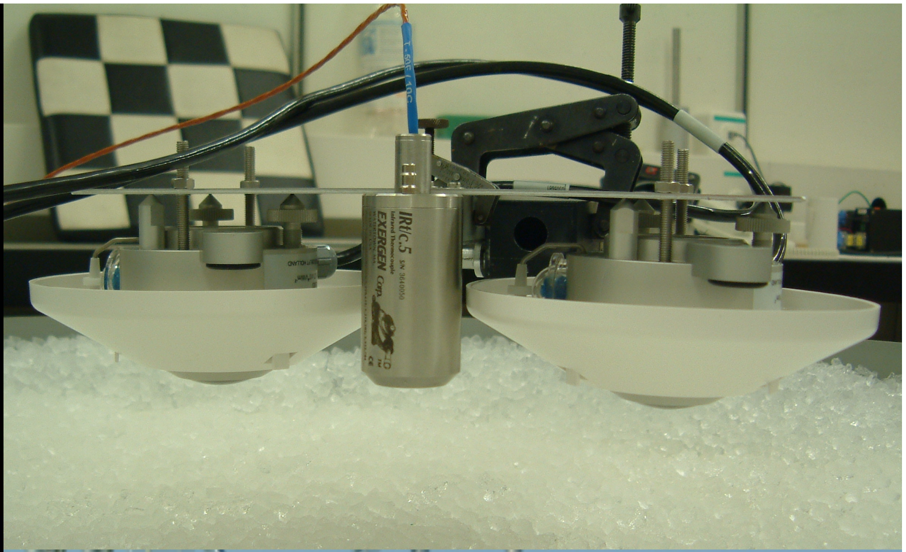
One end of an optical fiber revolves around the sun axis. The opening angle is limited by an optical diaphragm. At the other end, a photovoltaïc detector receives the light pulse when the fiber window meets the sun. The detected signal is compared to a threshold. A pulse is generated when the radiation intensity exceeds 120 W/m².

Calibrations and Errors



WSG (World Standard Group)
Davos, Switzerland

- Absolute Calibration Error
(Comparison to World Standard)



Spectral Response Errors

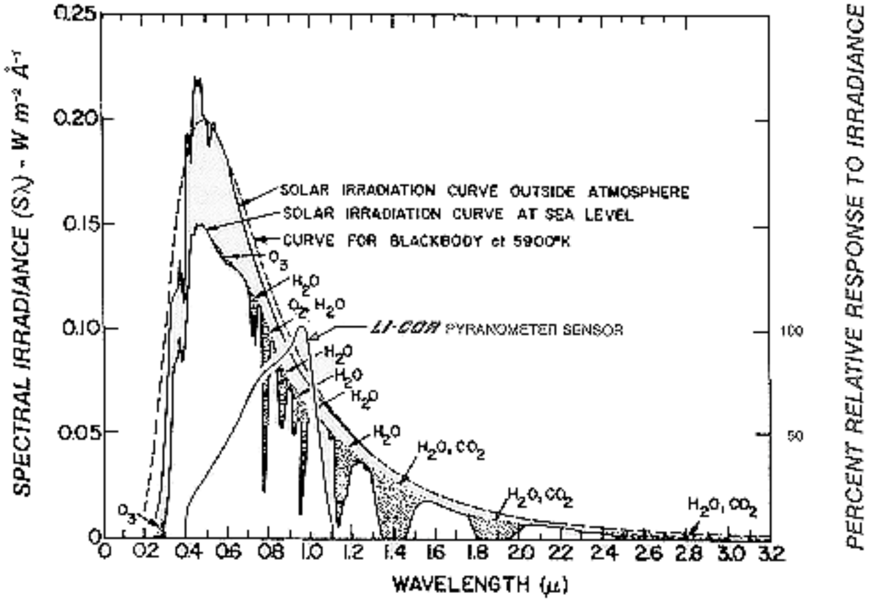
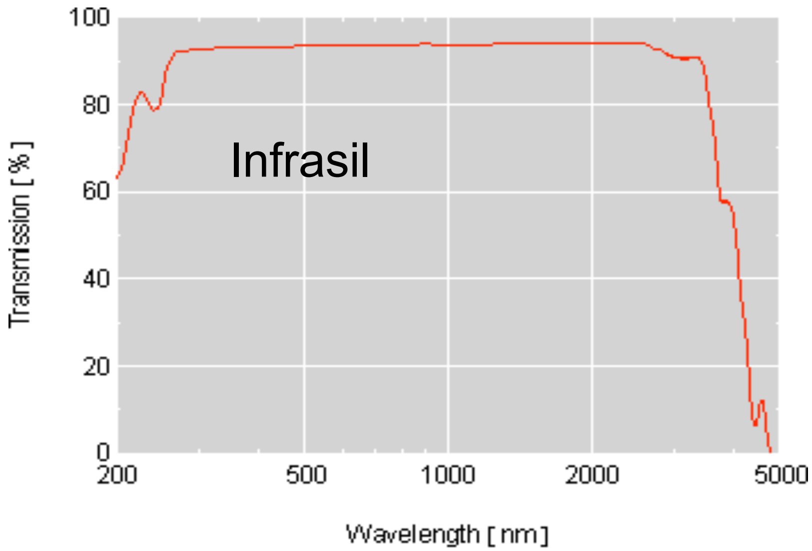
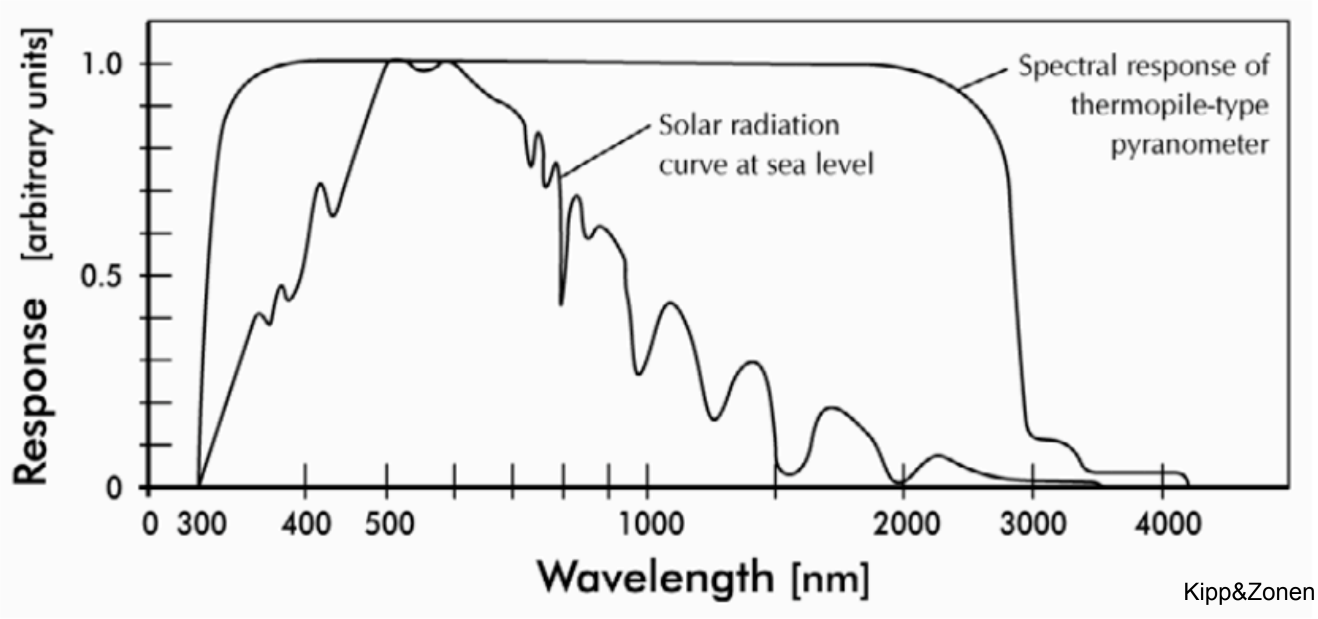


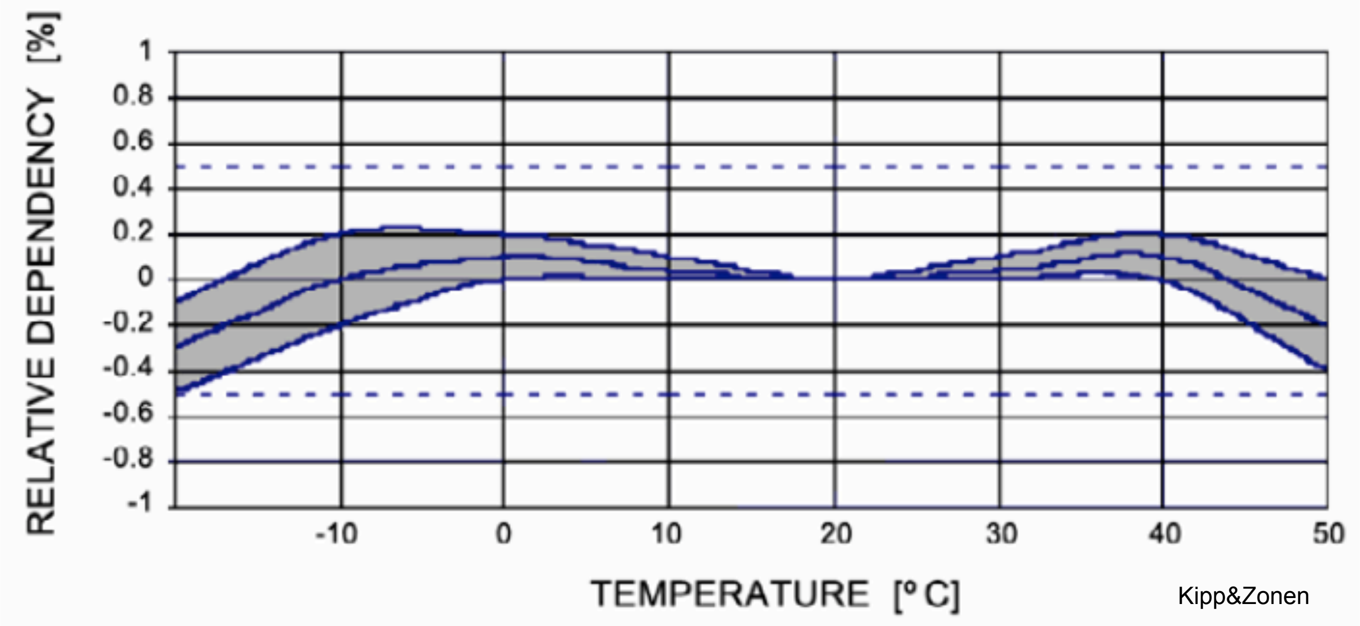
Figure 4. The LI-200SA Pyranometer spectral response is illustrated along with the energy distribution in the solar spectrum (8).



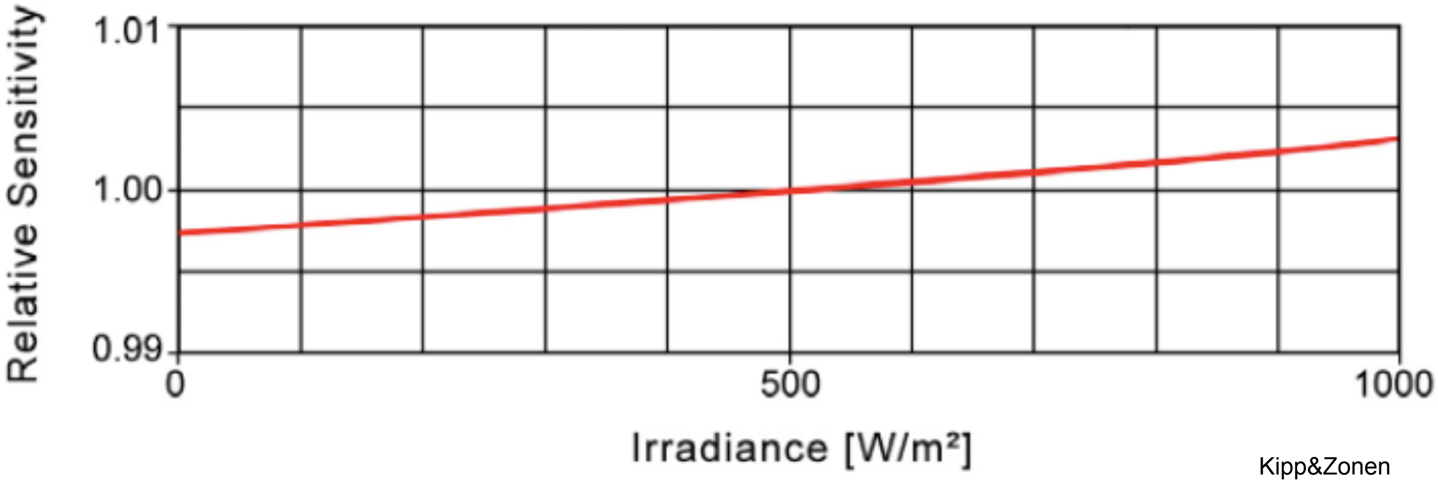


Kipp&Zonen

- Temperature Dependency



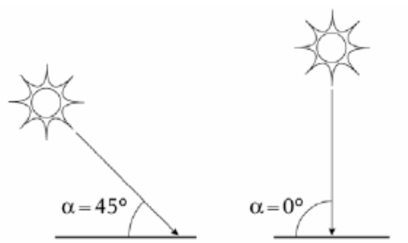
- Linearity

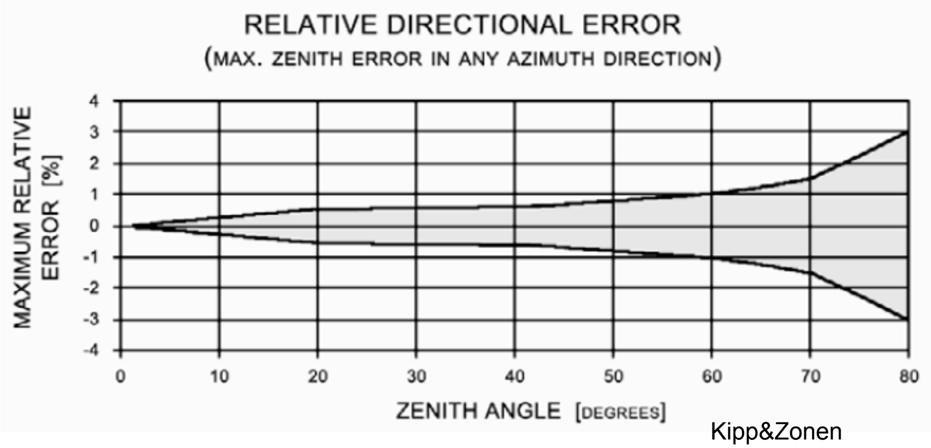


Geometric Errors:

- Cosine Response Error

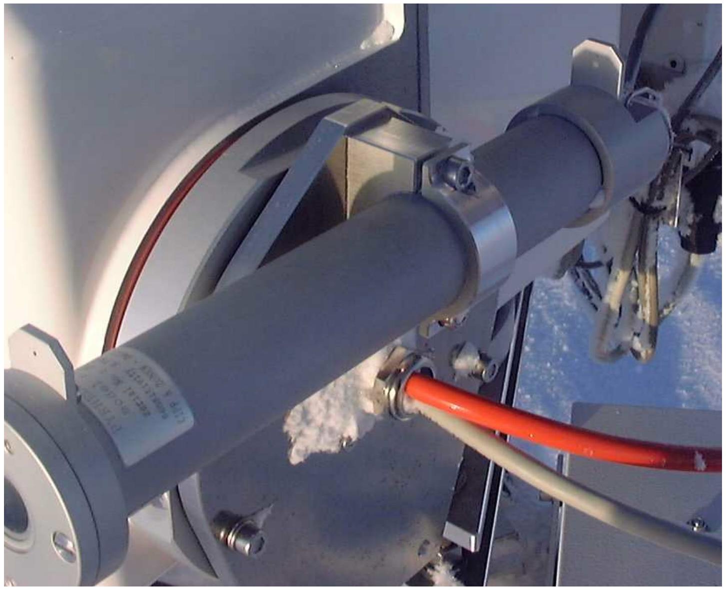
  (low vs high incident radiation)
- Azimuth error (sensor geometry)





Kipp&Zonen

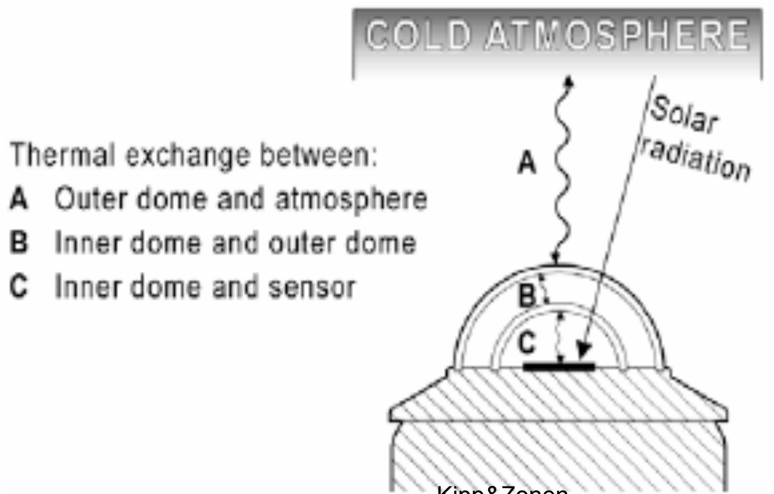
- Hysteresis
- Response Time Error
- Long Term Stability (aging of thermopile / paint / resistors / etc)



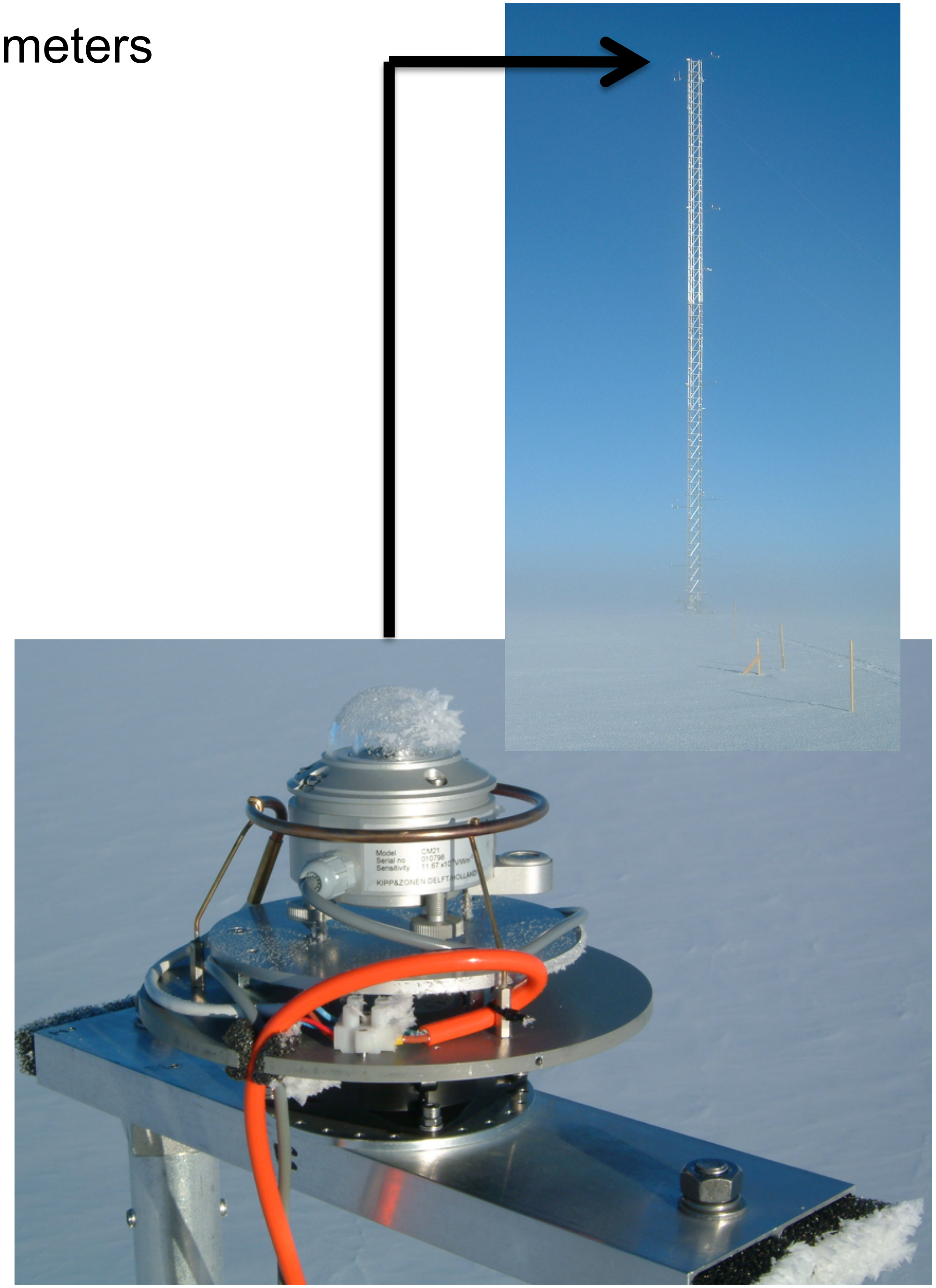
Pointing error

Condensation

Negative-Night-Time-Offset of Pyranometers



Kipp&Zonen



Ventilation and Heating!

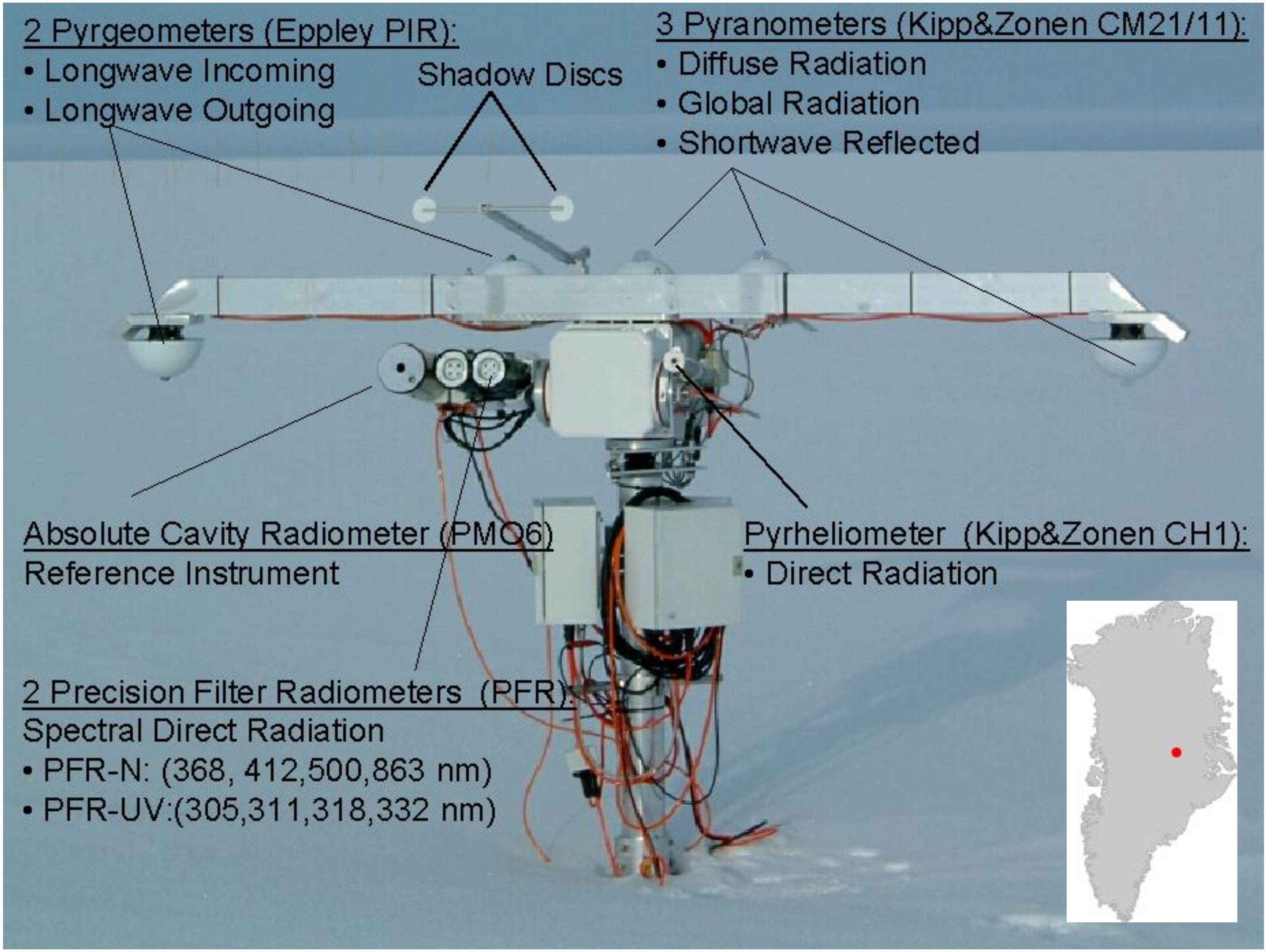
“Wind-Correction” of Pyrradiometers and Net-Radiometers

Dome material (polyethylene, lupolene) heats up. Ventilation reduces the heating effect.

Environmental impacts

IGLOS 2002

Radiation balance measurement at Summit, Greenland



2 Pyrgeometers (Eppley PIR):
- Longwave Incoming
- Longwave Outgoing

Shadow Discs

3 Pyranometers (Kipp&Zonen CM21/11):
- Diffuse Radiation
- Global Radiation
- Shortwave Reflected

Absolute Cavity Radiometer (PMO6)

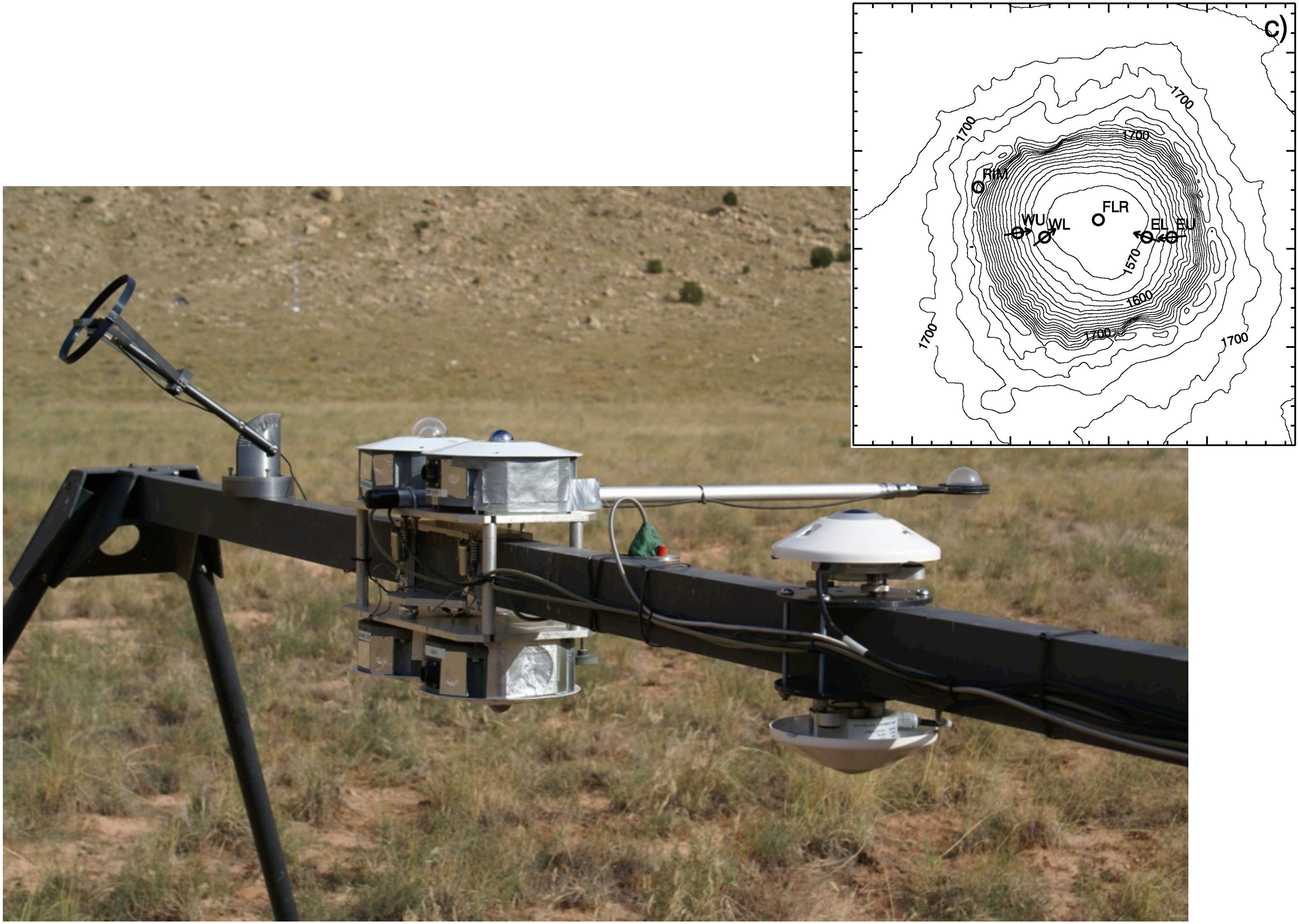
Reference Instrument

Pyrheliometer (Kipp&Zonen CH1):
- Direct Radiation

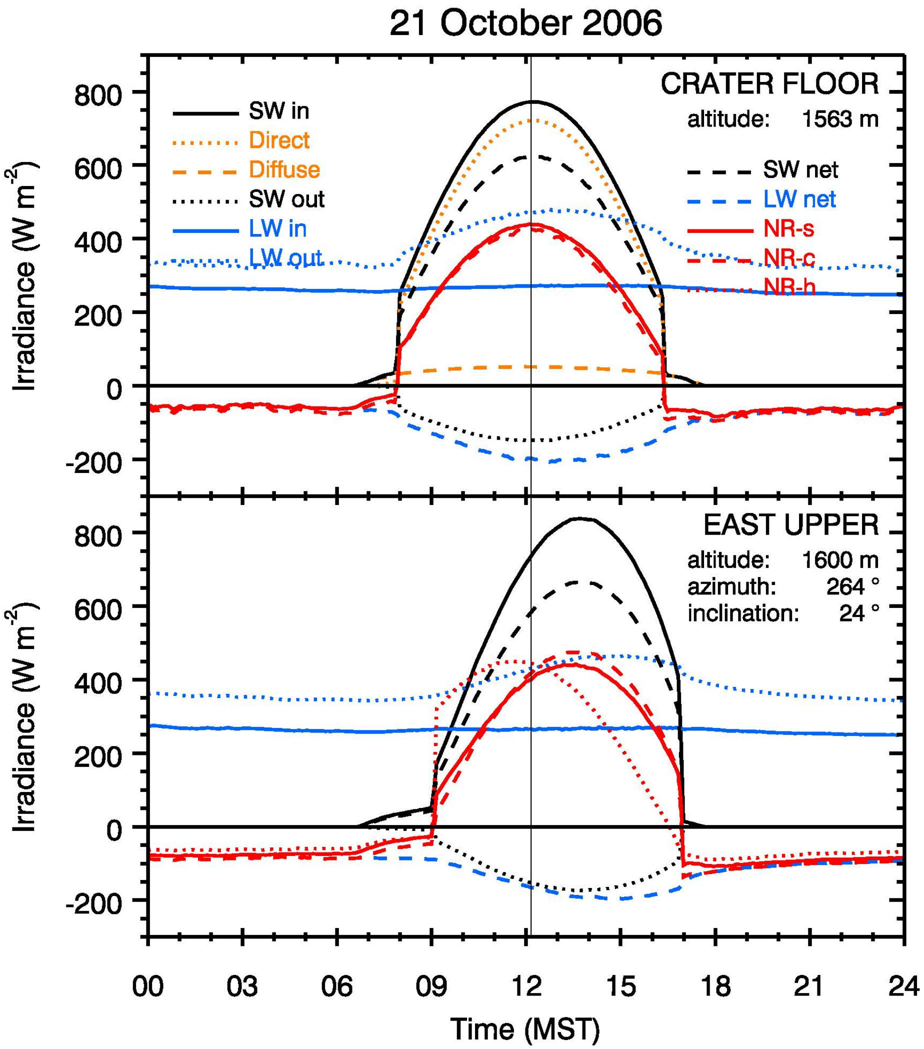
2 Precision Filter Radiometers (PFR):

Spectral Direct Radiation
- PFR-N: (368, 412,500,863 nm)
- PFR-UV:(305,311,318,332 nm)

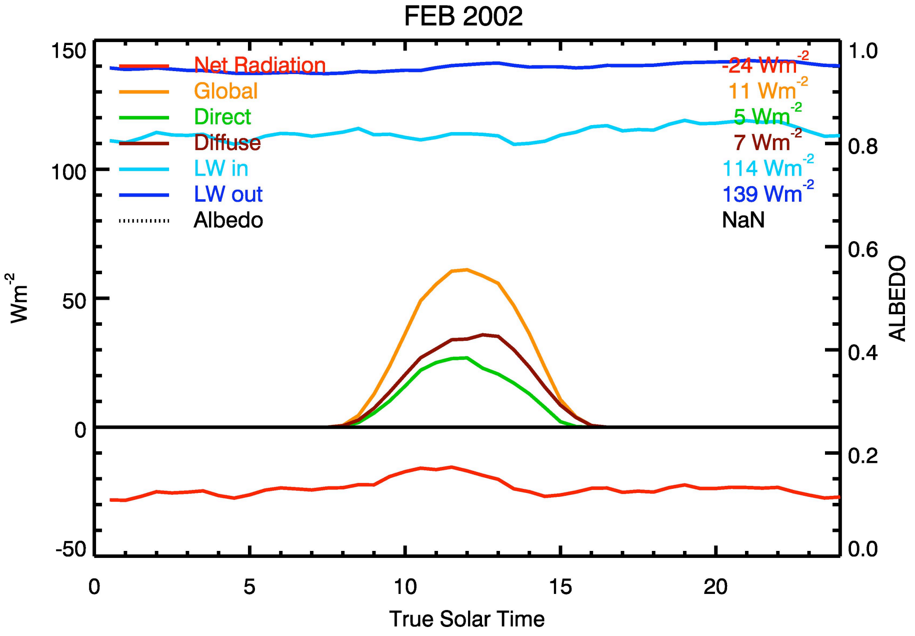
Radiation Balance Measurements during METCRAX 2006

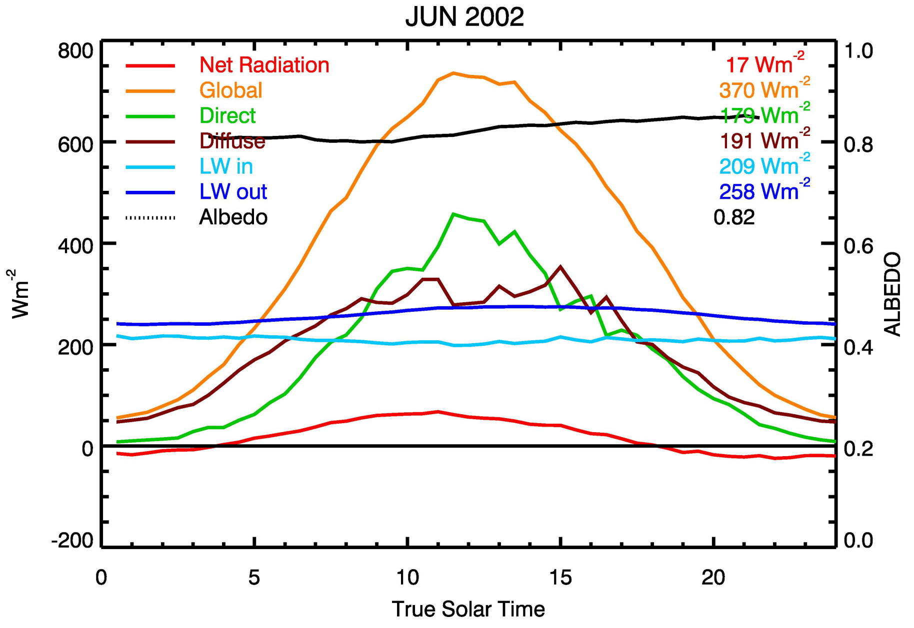


Meteor Crater, Arizona

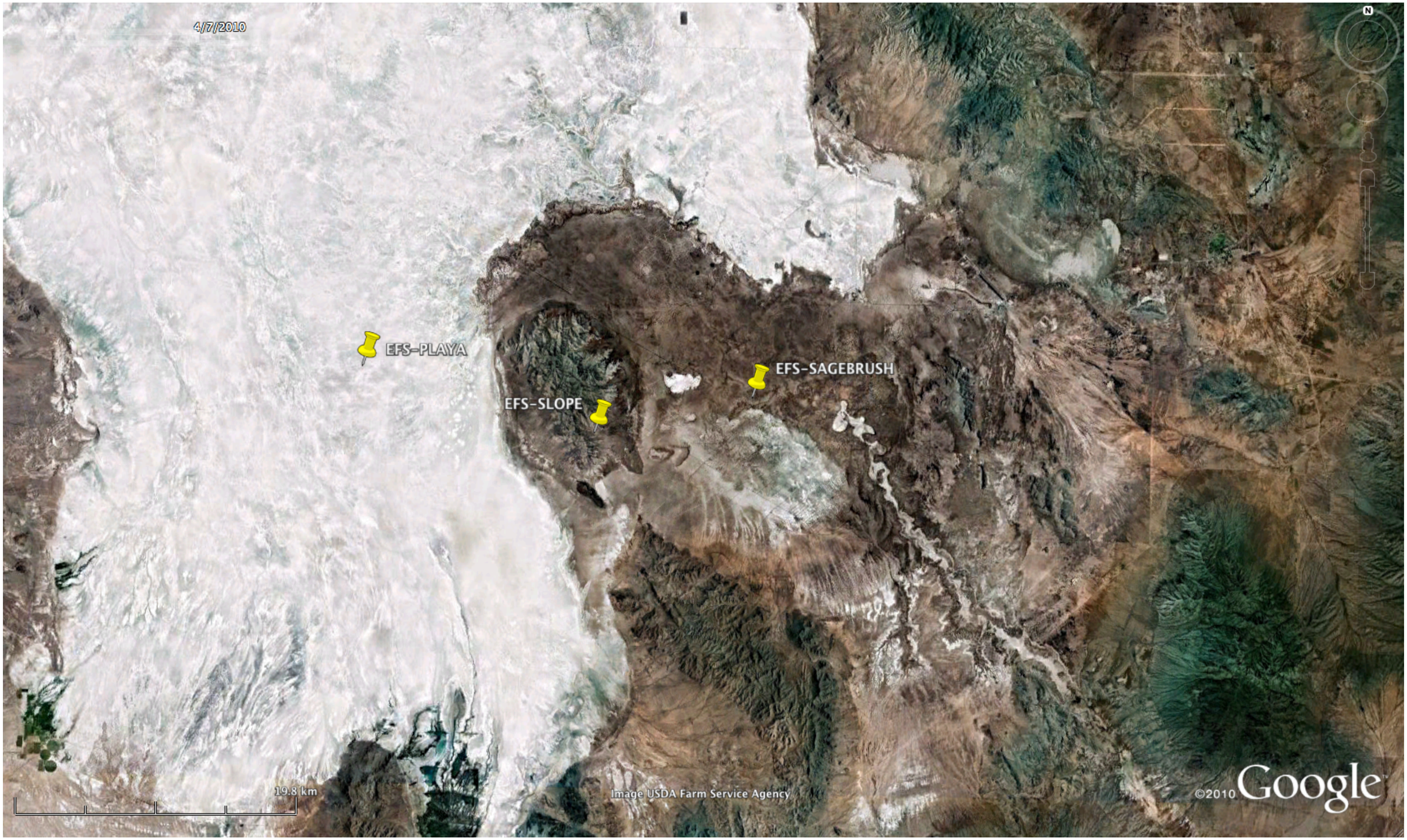


Summit, Greenland (3200 m)





MATERHORN (Mountain Terrain Modeling and Observation Program)



Radiation measurements during MATERHORN

EFS-Playa

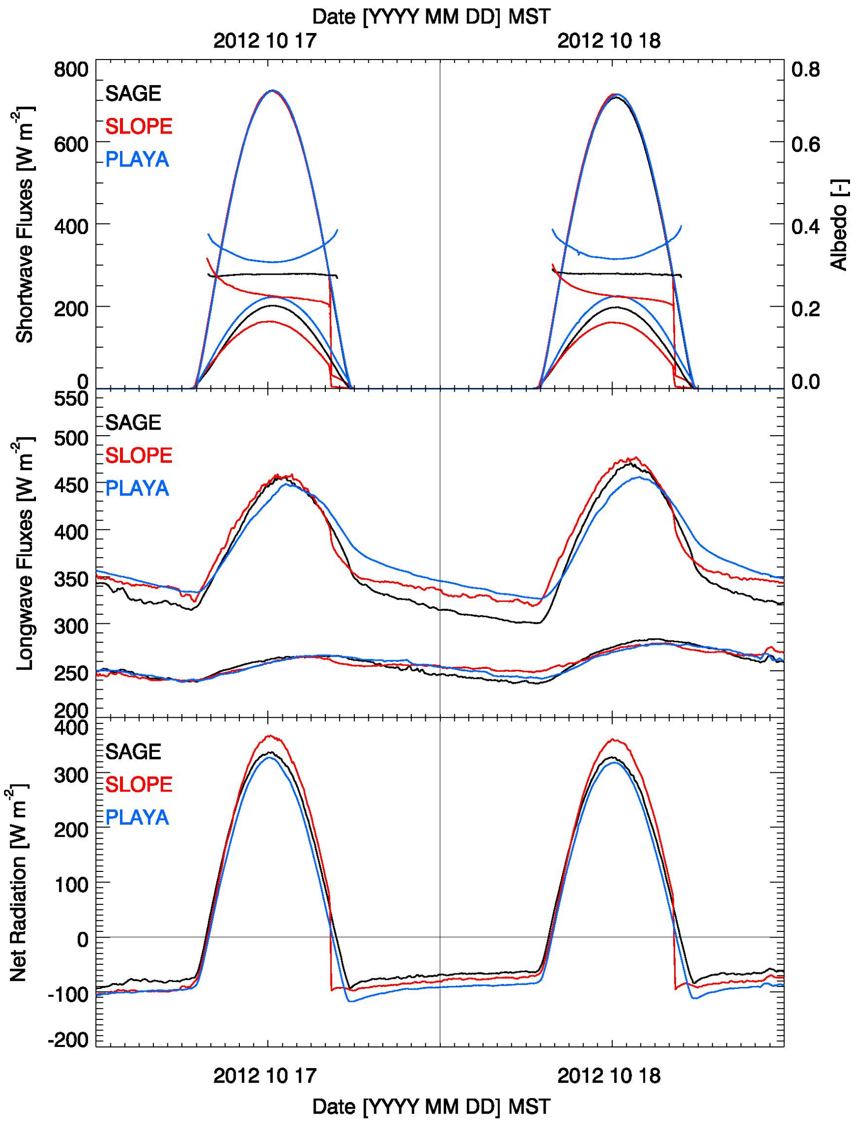
EFS-Sagebrush

EFS-Slope

Detailed View – 4 components

Radiation Balance at EFS-Sites

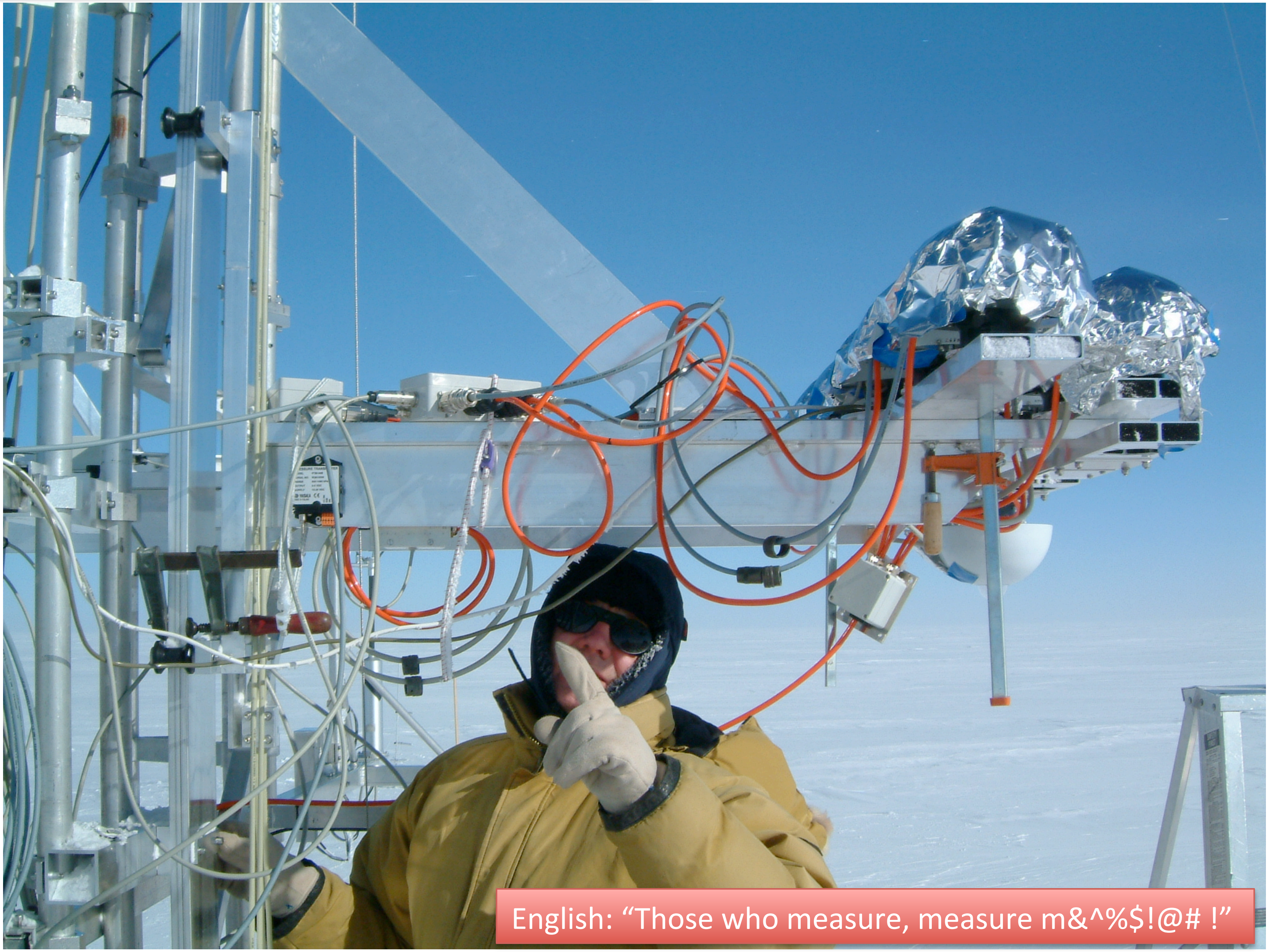
$$NR = SW^{\downarrow} - SW^{\uparrow} + LW^{\downarrow} - LW^{\uparrow}$$



- Same shortwave energy input SW↓
- Albedo controls SW↑
- Same daytime NR at EFS-Sage and EFS-Playa
- Differences in SW* are compensated by differences in LW↑
- NR differences (Playa – Sage) are larger at nighttime, pointing to differences in soil thermal properties.

	Albedo [-] (min & max daily means)	**Thermal Conductivity [W / (m K)]**
EFS-Sage	**0.27** (0.18-0.29)	0.58
EFS-Slope	0.23 (0.17-0.24)	0.44
EFS-Playa	**0.31** (0.24 -0.35)	0.89

“Wer misst, misst Mist!”

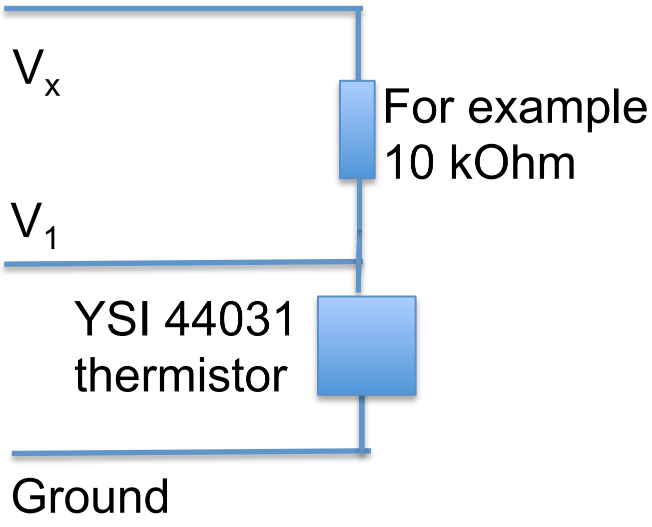


English: “Those who measure, measure m&^%$!@# !”

Additional discussion points …

- Build of instruments
- Thermistor measurements (YSI44031) – voltage drop across thermistor using known resistor (accuracy ?)
- Choice of voltage range / resistor / resolution / excitation voltage
- Measurements in different climates / elevations?

Considerations – LW measurements

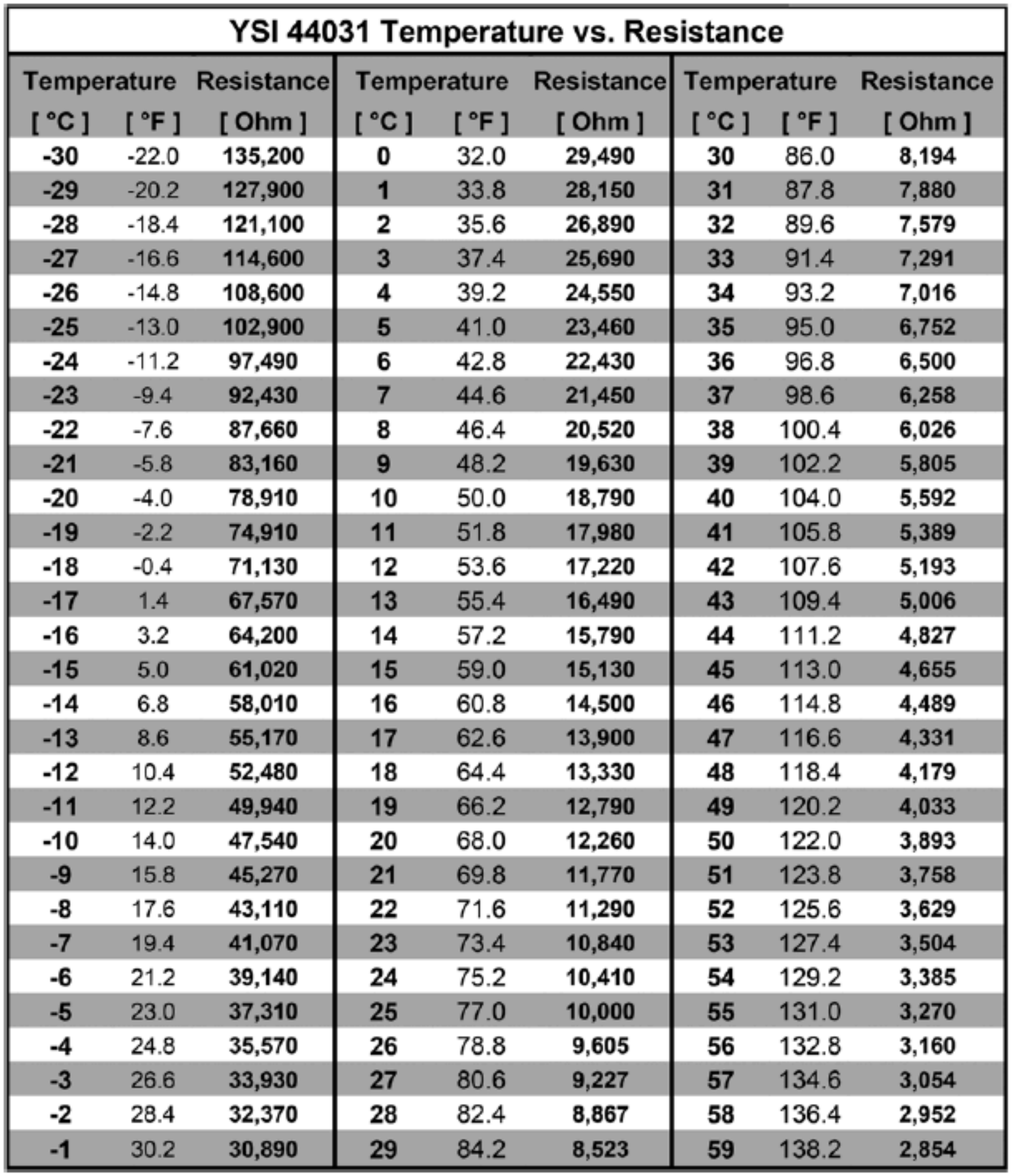


What temperature range do I expect? – What resistance will that mean?

What voltage range do I choose?

What is my best excitation voltage?

What will my resolution (W m^{-2}) be (cc ~ 10 uV / (W m^{-2}))?



YSI 44031 Temperature vs. Resistance

Temperature [°C]	Temperature [°F]	Resistance [Ohm]	Temperature [°C]	Temperature [°F]	Resistance [Ohm]	Temperature [°C]	Temperature [°F]	Resistance [Ohm]
-30	-22.0	135,200	0	32.0	29,490	30	86.0	8,194
-29	-20.2	127,900	1	33.8	28,150	31	87.8	7,880
-28	-18.4	121,100	2	35.6	26,890	32	89.6	7,579
-27	-16.6	114,600	3	37.4	25,690	33	91.4	7,291
-26	-14.8	108,600	4	39.2	24,550	34	93.2	7,016
-25	-13.0	102,900	5	41.0	23,460	35	95.0	6,752
-24	-11.2	97,490	6	42.8	22,430	36	96.8	6,500
-23	-9.4	92,430	7	44.6	21,450	37	98.6	6,258
-22	-7.6	87,660	8	46.4	20,520	38	100.4	6,026
-21	-5.8	83,160	9	48.2	19,630	39	102.2	5,805
-20	-4.0	78,910	10	50.0	18,790	40	104.0	5,592
-19	-2.2	74,910	11	51.8	17,980	41	105.8	5,389
-18	-0.4	71,130	12	53.6	17,220	42	107.6	5,193
-17	1.4	67,570	13	55.4	16,490	43	109.4	5,006
-16	3.2	64,200	14	57.2	15,790	44	111.2	4,827
-15	5.0	61,020	15	59.0	15,130	45	113.0	4,655
-14	6.8	58,010	16	60.8	14,500	46	114.8	4,489
-13	8.6	55,170	17	62.6	13,900	47	116.6	4,331
-12	10.4	52,480	18	64.4	13,330	48	118.4	4,179
-11	12.2	49,940	19	66.2	12,790	49	120.2	4,033
-10	14.0	47,540	20	68.0	12,260	50	122.0	3,893
-9	15.8	45,270	21	69.8	11,770	51	123.8	3,758
-8	17.6	43,110	22	71.6	11,290	52	125.6	3,629
-7	19.4	41,070	23	73.4	10,840	53	127.4	3,504
-6	21.2	39,140	24	75.2	10,410	54	129.2	3,385
-5	23.0	37,310	25	77.0	10,000	55	131.0	3,270
-4	24.8	35,570	26	78.8	9,605	56	132.8	3,160
-3	26.6	33,930	27	80.6	9,227	57	134.6	3,054
-2	28.4	32,370	28	82.4	8,867	58	136.4	2,952
-1	30.2	30,890	29	84.2	8,523	59	138.2	2,854

From Kipp & Zonen – CGR4 manual

Credits & Acknowledgements

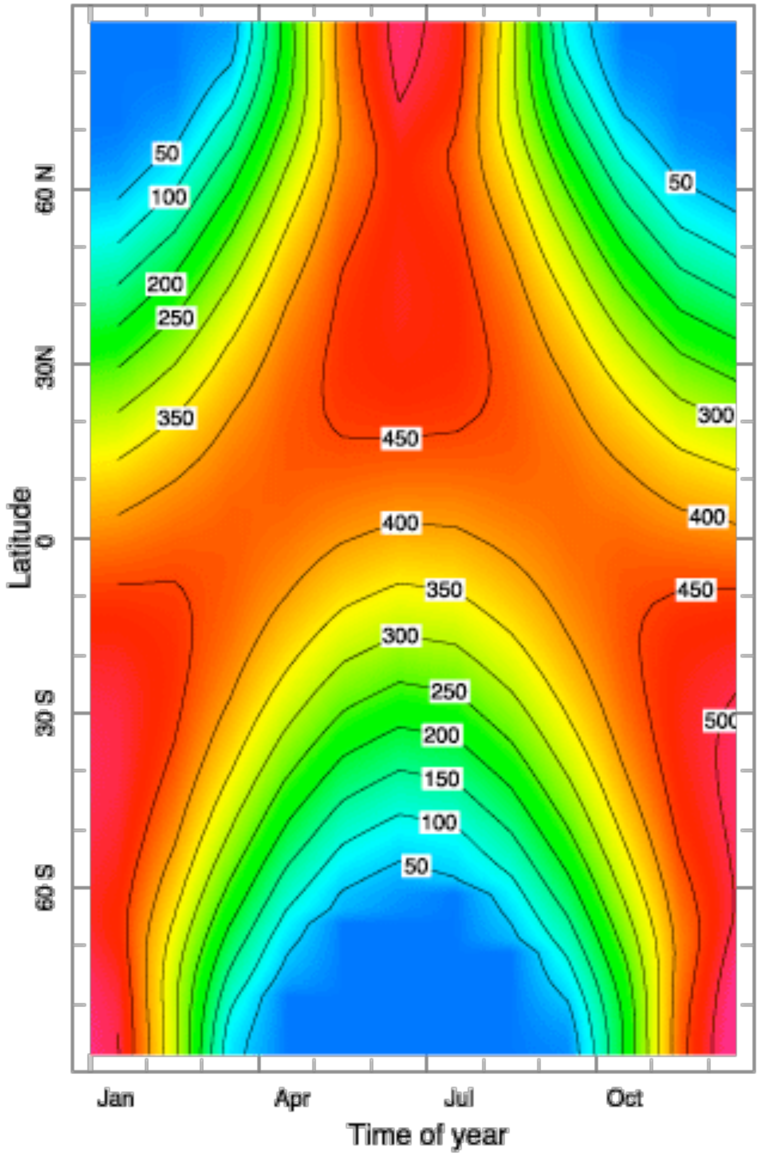
Lecture notes of Prof. Claus Froehlich, Davos: ftp://ftp.pmodwrc.ch/pub/Claus/Vorlesung2009/

Notes on ETH Feldkurs Rietholtzbach by Reto Stoeckli

Kipp & Zonen: http://www.kippzonen.com/?downloadcategory/551/Pyranometers.aspx

Wikipedia articles

Latitude-Time Distribution of Incoming Solar Radiation at the Top of the Atmosphere



Based on ERBE data. Units are W/m²